E* - DYNAMIC MODULUS
Test Protocol – Problems and Solutions

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16. Abstract

The Connecticut Department of Transportation is the lead state in a 13-state pooled funds project, to assess the Dynamic Modulus, E*, as a test method to characterize hot-mix asphalt mix designs. The project is a 30-month effort to: evaluate problems in implementing the protocol into DOT operations as part of the 2002 Pavement Design Guide; conduct a round robin test of the protocol; and, recommend changes or modifications to the protocol.

This report sets forth problems encountered with the protocol and offers recommendations on changes to the protocol and its use in DOT operations. The results of a 9-laboratory round robin series of tests are presented. E* test results for typical HMA mixes submitted by eight sponsor states are also presented in an appended CD.

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E*, DYNAMIC MODULUS

Test Protocol – Problems and Solutions

INTRODUCTION and BACKGROUND – NCHRP Project I-37A is producing the new 2002 Design Guide for New & Rehabilitated Pavements. The guide is based on mechanistic principles and requires a modulus, analogous to E for steel, to compute stress and strains in hot-mix asphalt (HMA) pavements. In 1999, the NCHRP Panel for Project 1-37A selected E* for this purpose. The selection was based on a paper authored by M. W. Witczak /7/ which compared E* to an Indirect Diametral Test (M_R). Both of these test procedures have been in use by the research community for over 30 years. Details on the methods can be found in Reference 12, pages 265 and 268.

Briefly, E* is the modulus of a visco-elastic material. The dynamic (complex) modulus of a visco-elastic test is a response developed under sinusoidal loading conditions. It is a true complex number as it contains both a real and imaginary component of the modulus and is normally identified by E* (or G*). In visco-elastic theory, the absolute value of the complex modulus |E*|, by definition, is the Dynamic Modulus. In the general literature, however, the term, "Dynamic Modulus", is often used to denote any type of modulus that has been determined under "non-static" load conditions.

The dynamic modulus protocol defines a linear visco-elastic test for asphaltic materials that was originally developed by Coffman and Pagen at Ohio State University in the 1960's. The test can be applied in a uniaxial (triaxial) condition in either compression or tension. Most of the test results obtained over the past 30-35 years have been in compression and are generally denoted as E*. The test has also recently been used in shear for both mixtures and binders during the SHRP and SuperPave research projects. These results are generally denoted as G* (orG*b). The E* test was adopted as the "Modulus Test of Choice" by the Asphalt Institute in the late 1960's by Kallas, Shook and Witczak. It subsequently became an ASTM test in the early 1970s, its designation is ASTM D3496. Most recently the E* protocol has been refined by Witczak and others at Arizona State University. The latest version of the protocol, dated June 2002, is appended.

The reasons for undertaking this project can be found in the shortcomings of the methodology used to obtain the Resilient Modulus (Mr), the parameter selected to characterize HMA mixes in the 1986 AASHTO Pavement Design Guide. The realization of problems with Mr, after several years and expenditures of millions of dollars in conducting and analyzing Mr test results, led to this initiative to look at the E* Protocol and address problems in the methodology so that 50 DOT materials testing laboratories would not have to do so. The project is designed to evaluate the Protocol and provide state DOTs with recommendations for the application of the Protocol in their operations. Specific project objectives are:

- determine the applicability of E* to characterize HMA mixes;
- determine the practical range of the E* protocol;
- determine any variations in E* values; and,
- evaluate the determination of E* for operational use in DOTs, using existing commercially available equipment.

THEORETICAL BASIS for E*

Dynamic Modulus – For linear visco-elastic materials such as HMA mixtures, the stress-strain relationship under a continuous sinusoidal loading is defined by its complex dynamic modulus (E*) This is a complex number that relates stress to strain for linear visco-elastic materials subjected to continuously applied sinusoidal loading in the frequency domain. The complex modulus is defined as the ratio of the amplitude of the sinusoidal stress at any given time, t, and the angular load frequency, ω, $\delta = \delta_o \sin(\omega t)$ and the amplitude of the sinusoidal strain $\varepsilon = \varepsilon_o \sin(\omega t - ø)$, at the same time and frequency, that results in a steady state response (Figure 1):

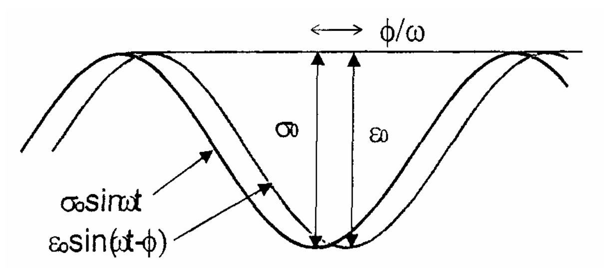
$$E^* = \delta/\varepsilon = \delta_o e^{i\omega t}/\varepsilon_o e^{i(\omega t - ø)} = \delta_o \sin\omega t/\varepsilon_o \sin(\omega t - ø) \qquad (1)$$

Where, δ_o = peak (maximum) stress
ε_o = peak (maximum) strain
ø = phase angle, degrees
ω = angular velocity
t = time, seconds
i = imaginary component of the complex modulus

Mathematically, the dynamic modulus is defined as the absolute value of the complex modulus, or:

$$|E^*| = \delta_o/\varepsilon_o \qquad (2)$$

Figure 1 – Dynamic (Complex) Modulus Test



For a pure elastic material, ø = 0, and it is observed that the complex modulus (E*) is equal to the absolute value, or dynamic modulus. For pure viscous materials, ø = 90º. The dynamic modulus testing of asphaltic materials is normally conducted using a uniaxially applied sinusoidal stress pattern as shown in Figure 1.

The primary output variables of the test are the dynamic modulus |E*|, and the phase angle (ø), which is a direct indicator of the elastic-viscous properties of the mix or binder material. The dynamic modulus in compression |E*| of the mix, is similar in principle to the G*, complex shear modulus of the binder, developed in the SHRP and SuperPave programs at the University of California, Berkley, and Penn State university. The two moduli, E* and G* are theoretically related through engineering mechanics by the relationship:

$$E^* = 2(1 + \mu)G^*$$
$$\mu = \text{Poisson's Ratio}$$

Master Curve Development – In the proposed "2002 Guide for the Design of Pavement Systems", currently under development in NCHRP Project 1-37A, the modulus of the asphalt concrete -at all analysis levels of temperature and time rate of load- is determined from a master curve constructed at a reference temperature, generally 70F. Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures should be shifted with respect to log of time until the curves merge into a single smooth function. The resulting master curve of the modulus, as a function of time, formed in this manner describes the time dependency of the material. The amount of shift required at each temperature required to form the master curve describes the temperature dependency of the material. In general, the master modulus curve can be mathematically modeled by a sigmoidal function described as:

$$\text{Log } |E^*| = \delta + \alpha \,/\, [1+e^{\beta + \gamma (\log tr)}] \qquad (3)$$

Where,
t_r = time of loading at reference temperature
δ = minimum value of E*
$\delta + \alpha$ = maximum value of E*
β, γ = parameters describing the shape of the sigmoidal function.
α = variable which is a function of gradation

The shift factor can be shown in the following form:

$$a(T) = t / t_r \qquad (4)$$

Where,
a(T) = shift factor, as a function of temperature
t = time of loading during test
t_r = time of loading at reference temperature (usually 70˚C)
T = temperature of loading cycle

The complex moduli relationship relating mixture moduli to temperature and time rate of loading has been an integral part of several mechanistic-empirical (M-E) design procedures used throughout the world. The basic protocol for characterizing HMA mixtures is used in: "The Asphalt Institute Airfield Design Procedure (MS-11)" and several technical manuals (TM) developed by the U. S. Army Corps of Engineers for use with M-E pavement designs for the U.S. military airfield and highway installations (e.g. TM 5-825). Additionally, complex moduli are widely used in the European community.

PROBLEMS ENCOUNTERED and SOLUTIONS - This report chronicles a series of problems encountered. They are separated into four categories: the protocol; specimen preparation; conducting the E* test; and presentation of the test results. Where available, photos of the problems and solution are presented.

(1) The Protocol – At the start of this project, we were working with an E* protocol dated 1999. In subsequent meetings and through other contacts we were made aware of protocol changes which were made since 1999. To resolve the various issues with the protocol a meeting was held at TRB headquarters in Washington, DC on April 17, 2002. The meeting was well attended by industry, TRB and NCHRP staff, university researchers, and the principal investigators on this project. The protocol was revised based on consensus input of the participants; the revisions reviewed, and the protocol finalized in June, 2002. It is attached hereto as Appendix 2 and was the basis for the round robin test conducted.

Recommendations developed from this project will be used to refine and streamline the E* protocol.

(2) Specimen Preparation – The protocol requires a 4-inch-diameter, 6-inch-high sample with 3 percent air voids. This section treats the sample preparation and instrumentation prior to entering the test chamber.

- Sample Compaction – Standard SuperPave mix procedures were employed to prepare the final test specimen. At the start of the project, the original E* protocol dated 1999 was used by the research team. This version of the protocol required production of a 7-inch high sample which forced our staff to over-fill and hand compact the loose height so the sample could be placed in a standard SuperPave compactor. Photo 1 illustrates this problem. In addition to producing the required specimen height, obtaining 3% air voids was also a problem.

- Solution - In 2002 the protocol revision used for most of the project reduced the finished height to nominally 6.7-inch. This revision alleviated the compaction problem as the gyratory compactor would accept the uncompacted sample. Given that there is no simple conversion for compaction of a 4-inch high, 6-inch diameter SuperPave sample to a 6.7-inch high, 6-inch diameter E* sample with 3 percent air voids, trial and error is used to obtain the 3 percent air voids

- Coring and Sawing Operations –After it is prepared, the gyratory sample is cored

Photo 1 – Sample Compaction

Overfilled Mold

Initial Compaction

Height 6.7 inch

Diameter 6.0 inch

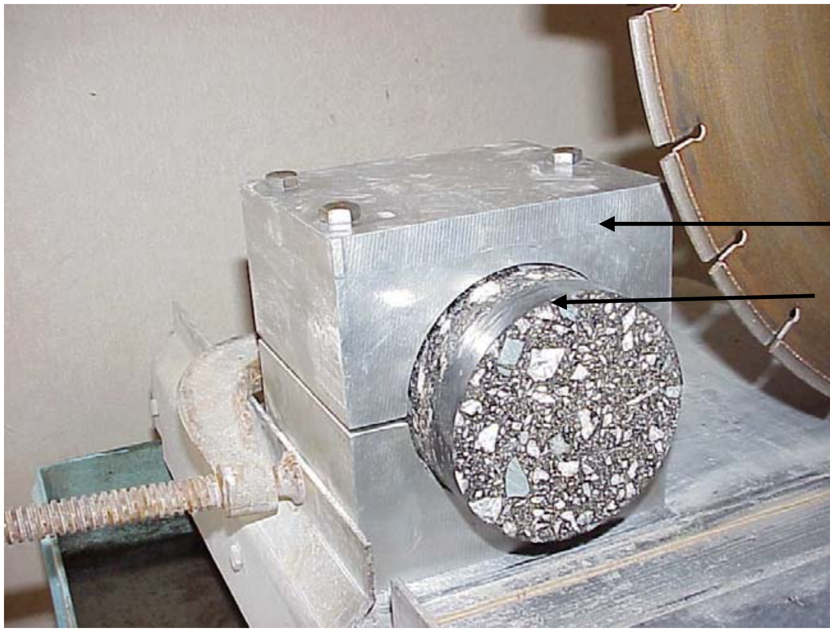
Finished Specimen

Photo 2 – Coring of Test Specimen

Restraining Collar

4 inch diameter by
6.7 inch height

Photo 3 – Sawing Operation



Restraining Device

Taped Sample Ends

Completed Test Specimen
4 inch diameter, 6 inch height

to produce a 4-inch diameter specimen. Photo 2 shows the coring device used. The collar shown in the photo was fabricated and used to hold the sample in place during the coring process. The final 6-inch high sample is achieved by trimming the 6.7-inch cored specimen, using a saw as shown in Photo 3. The sample must be held firmly in place and fraying of the edge of the cylinder as the saw blade breaks through the cut avoided.

Solution - The sample is placed in a restraining device, in our case, a six-inch aluminium cube was bored out and split, to prevent unwanted rotation and/or longitudinal movement during the sawing operations. Our devise avoided concentrated stresses when the restraining bolts were tightened by boring the hole slightly greater than 4-inch and placing a 3/32-inch rubber sheet around the specimen. Edge fraying of the sample was prevented during sawing, by placing two rounds of electrical tape on each end of the test specimen. Photo 3 presents the finished test specimen and also shows the taped sample resting on half of the restraining device prior to sawing.

- Instrumentation – Final instrumentation of the test specimen is accomplished by gluing gauge plugs onto the side of the specimen and attaching a Linear Variable Differential Transducer (LVDT) to the plugs to measure displacements. Table 2 of the protocol presents information on the recommended number of test specimens and LVDTs required per specimen. In our work we employed two specimens with three LVDTs per specimen.

Table 2 - Recommended Number of Specimens

LVDTs per Specimen	**Number of Specimens**	**Estimated Limit of Accuracy**
2	2	18.0
2	3	15.0
2	4	13.4
3	2	13.1
3	3	12.0
3	4	11.5

A problem encountered was misalignment of the gauge plugs, resulting in the LVDT separating from the test specimen. Stress caused by forcing the guiding rod through misaligned brackets caused failure at higher temperatures. A ruined sample is shown in Photo 4.

Solution - This problem was overcome by using a template fabricated from aluminum stock to position and secure the gauge plugs as they were glued to the sides of the specimen. Photo 5 shows the jigs held in place with rubber bands, while the epoxy adhesive sets.

(3) Conducting the E* Test - This section addresses the conduct of the E* test in an environmental chamber. The test chamber must be capable of producing and maintaining the test temperatures shown in Table 3 of the protocol.

Photo 4 – Ruined Test Specimen

Photo 5 – Aluminum Jig Used to Secure Gauge Plugs on Test Specimens

Aluminum Jig

- <u>Temperature Conditioning of the Test Specimen</u> – Each test sample must be conditioned at the test temperature so that the test temperature is uniform throughout the mass of the specimen. Table 3 of the protocol presents time estimates to achieve specimen temperature equilibrium. During our work we were unable to achieve the temperature in the time frames shown. This is due to the thermodynamic properties of

Table 3 - Recommended Equilibrium Times

Specimen Temperature, C (F)	Time from room temperature, hrs 25 C (77 F)	Time from previous test temperature, hrs
-10 (14)	overnight	-
4.4 (40)	overnight	4 hrs or overnight
21.1 (70)	1	3
37.8 (100)	2	2
54.4 (130)	2	1

** Note that the temperature equilibrium times may vary depending on the type of environmental chamber in use. Some testing laboratories reported as much as 6 hours to reach the equilibrium temperature.*

the sample, which are in large part affected by the heat exchange properties of the aggregate. The recommended times in Table 3, based on our experience, are impossible to achieve and can not be used. Each temperature increase from test to test is about the same number of degrees and can be expected to take the same length of time to reach equilibrium throughout the test specimen.

During our work, we found that a dummy specimen with a centrally located thermocouple is the most accurate means of determining sample temperature. Without an instrumented dummy, there is no good way to determine the temperature throughout the sample. It is thought that Table 3 was an attempt to supply conditioning times for set ups without such an instrumented dummy. Table 3 implies that heat transfer takes place faster as the temperature rises thus estimating shorter equilibrium times at higher temperatures. Table 3 does not recognize data showing that bituminous concrete is a poor conductor of heat. In fact, Table XXVII in "Asphalts and Allied Substances by Abraham", 1962 lists the specific heat of the asphalt at 0 degrees F as 0.388 Btu/lb and at 140 F is 0.451 Btu/lb, which is exactly opposite the tacit assumption of Table 3.

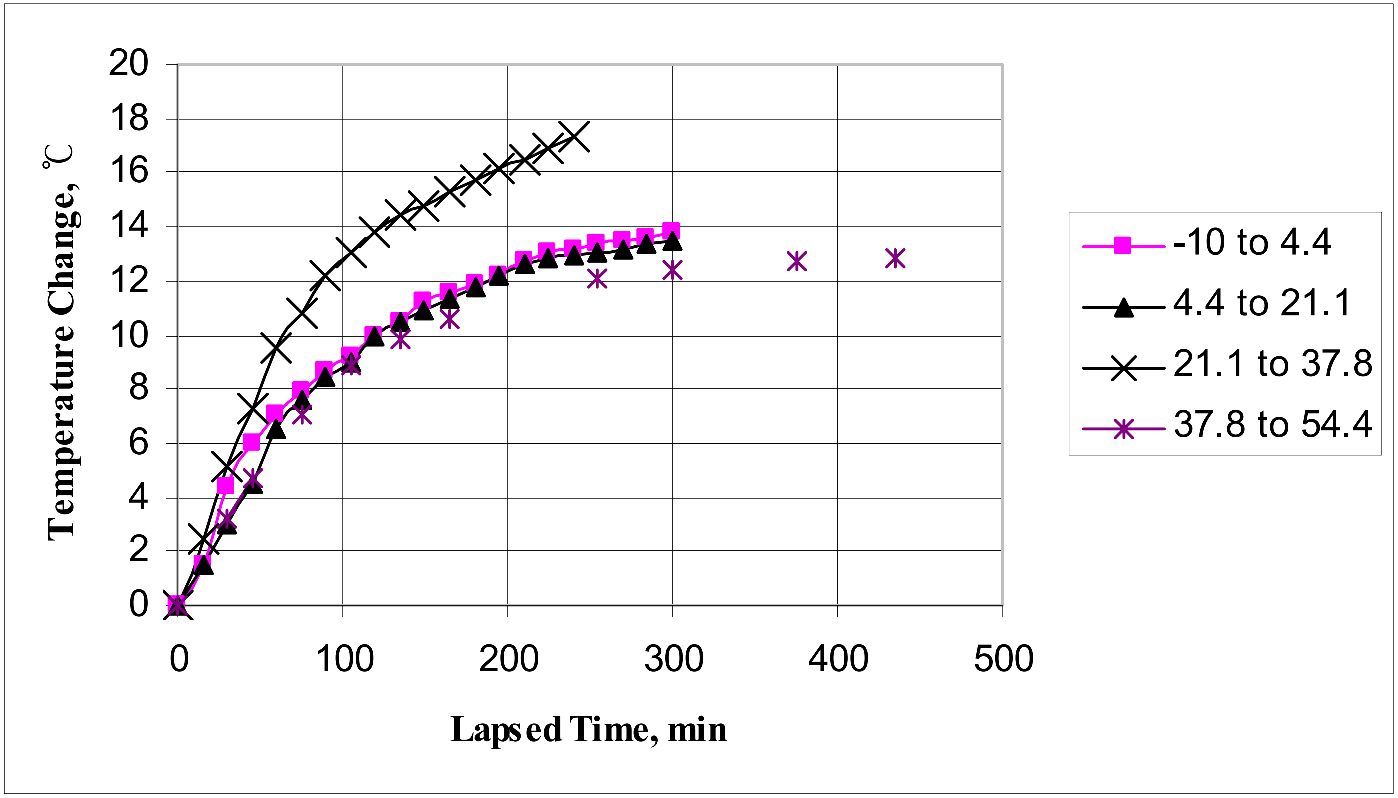
Table 3A presents temperature changes over time observed by the CAPLab staff who were monitoring the environmental chamber. These data are shown graphically in Figure 2. They were measured using a dummy specimen containing a thermocouple. The temperature changes have been plotted to show the similarity in rate of change. As the number of degrees for each temperature change is about the same, the conditioning time should be about the same. Three of the four had not reached the new temperature by the time the lab closed in the afternoon. In fact, the change to 54.4C from 37.8C wasn't accomplished overnight.

Table 3A – Changes in Temperature with Time, (℃)

Elapsed conditioning time, min.	**-10 to 4.4**	**4.4 to 21.1**	**21.2 to 37.8**	**37.8 to 54.4**
0	0	0	0	0
15	1.5	1.5	2.5	
30	4.4	3	5.1	3.2
45	6	4.5	7.3	4.7
60	7.1	6.5	9.5	
75	7.9	7.6	10.8	7.1
90	8.7	8.4	12.2	
105	9.2	9	13	8.9
120	10	9.9	13.8	
135	10.5	10.5	14.4	9.8
150	11.2	10.9	14.8	
165	11.6	11.3	15.3	10.6
180	11.9	11.8	13.7	
195	12.2	12.2	16.1	
210	12.7	12.6	16.5	
225	13	12.8	16.9	
240	13.2	12.9	17.3	
255	12.4	13.1		12.1
270	13.5	13.2		
285	13.6	13.4		
300	13.8	13.5		12.4
315				
330				
345				
360				12.7
375				
390				
405				
420				
435				
Temp @ Total Elapsed time	3.8	17.9	38.4	50.5
Over night	4.4	21.1		51.5
Time to reach Temp	6 hr plus	6 hr plus	3 hr 45 min	7 hr plus

* Temperatures at center of 4 inch puck

Figure 2 – Conditioning Time versus Temperature



It would appear that the most practical approach would be to condition the sample overnight and test the specimen first thing in the morning. Setting the chamber to a higher temperature than required for the next test in order to accelerate the temperature change doesn't appear prudent. This action may not result in any time savings. When the chamber temperature is lowered to the desired temperature; a long wait will be necessary to equalize temperature in the heart of the test specimen. If the chamber door is opened between tests as several samples are being conditioned simultaneously and tested in sequence, additional time is required for the test specimen to achieve equilibrium at the specified test temperature again. If samples are taken out to transfer gauges, the thermal dummy should also be taken out otherwise its temperature does not reflect the temperature of the test specimen.

<u>Solution</u> – To resolve the issue of sample temperature a dummy specimen containing a thermocouple is mounted in the test chamber adjacent to the test specimen. Photo 6 shows this system in place. Testing should be delayed until the thermocouple indicates the desired temperature.

If several samples are in the test chamber at one time, when changing LVDTs to the next sample, it is critical to have the door open only for a short time. At 54.4C the LVDTs should not be placed in the brackets until the sample temperature has been reached and testing is imminent as tension on the cables can pull the gauge plugs from the side of the test specimen since the tensile strength of the asphalt is low at this temperature.

- <u>Loading of the Test Specimen</u>- The protocol requires 200 cycles of load conditioning, but does not state whether this is at the contact load of five percent of test load or at the 25 Hz test load. Table 4 of the protocol suggests dynamic stress levels for this test. If at any time during the conditioning load process the recoverable axial strain in the sample exceeds 1500 microstrain the sample is to be discarded. The strain level range should be 50-150 microstrain. Experience with the E* test procedure and the HMA mixes being tested is required in order to select the proper stress level that complies with the sample strain limitation.

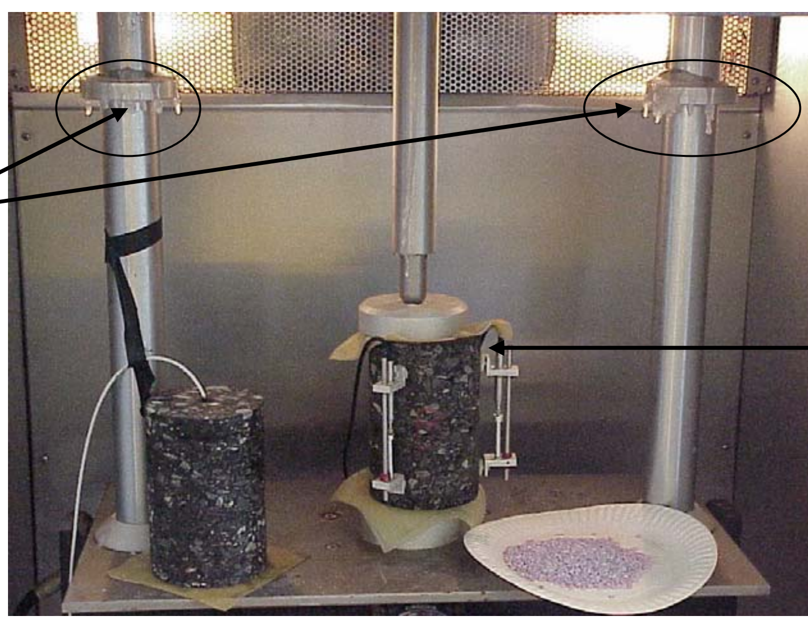
Table 4 - Typical Dynamic Stress Levels

Temperature, ^oC (^oF)	Range, kPa	Range, psi
-10 (14)	1400 - 2800	200 - 400
4.4 (40)	700 - 1400	100 - 200
21.1 (70)	350 - 700	50 - 100
37.8 (100)	140 - 250	20 - 50
54.4 (130)	35 - 70	5 - 10

<u>Solution</u> - We are aware of test systems which employ strain-control as a criteria for conducting load-deformation tests. Conducting a few cycles under strain control and then converting to stress control appears to offer promise for this test protocol.

Photo 6 – Instrumented Specimen in the Testing Machine

Photo 7 – Ice Formation on Testing Machine



- Test Chamber and Environment - Moisture in the laboratory must be controlled. Humidity was a severe problem in the summer of 2002. The test chamber's cooling system circulates the air in the test chamber and apparently the door gasket and the gasket at the test frame column allowed lab air to enter the test chamber. At low temperature settings and high humidity, moisture was condensed on the metal surfaces of the test chamber and the test specimen. At –10 C the moisture froze and the position of the test specimen shifted under load (see Photo 7). The loading faces were coated with ice and during the load cycling the sample moved laterally and eventually fell off the loading plate.

Solution – Frequently check the test chamber to perceive unwanted moisture in the chamber and maintain a low level of humidity in the lab itself.

(4) Presentation of Test Results – The results of the tests performed must be reported to a user. Section 14 of the protocol presents five reporting requirements. Our review and use of this protocol has prompted several questions about these five elements. The following discussion presents our thoughts on the reporting requirements. It is predicated on the reported data being clear concise, and easily used in the upcoming 2002 Pavement Design Guide. This concept has been endorsed by the project advisory panel.

Section 14.1 "For each individual specimen report the dynamic modulus ($|E^*|$) and phase angle (ø) for each temperature–frequency combination tested."

We had difficulty determining the individual LVDT phase angles from our testing machines printout. Further, who is going to use the 90 E* and 90 ø values reported? From a DOT's purview this volume of data is impractical.

Section 14.2 "Report the average peak stress (δ) and strain (ε_o) for each temperature–frequency combination tested." There are 30 of each. Is this to be reported as an average for the last five cycles for each LVDT? Or, an average of the average of each five cycles? The protocol is unclear. Clarification is needed. We believe that, for each specimen the peak stress and phase angle should be reported for each temperature/frequency sweep as an average of the LVDTs used.

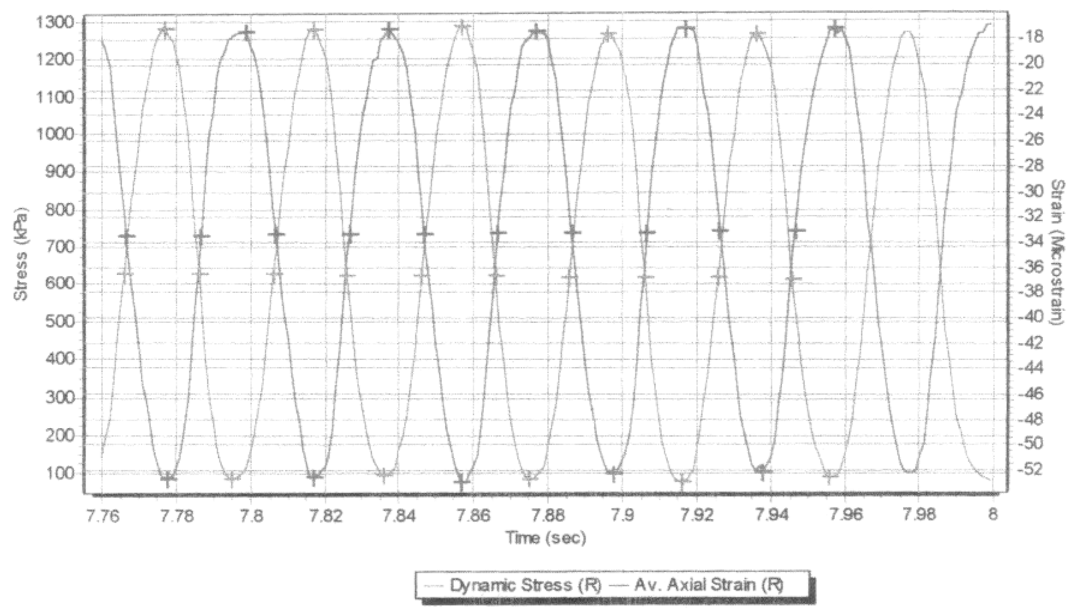
Section 14.3 "Report, for each temperature-frequency combination tested, the dynamic modulus and phase angle for each replicate test specimen along with the average, standard deviation and coefficient of variation of the three replicates."

Table 2 presented alternatives of two or four replicates as well as for three. We tested two replicates and believe the protocol should state the coefficient of variation of the replicates tested.

On the sample printout from the testing machine (Figure 3) the E* and ø values shown is the average of 3 LVDTs over 5 test cycles at a fixed temperature. The value of reporting all individual values of the standard deviation and the coefficient of

Figure 3 – Sample E* Test Output

FileName: C:\UTM4\UTM_38\Datafiles\Round Robin\CT\Tilcon_RR_10_10C_Oct_22.B38



Sweep 1 (25Hz)

Test Date and Time: Tuesday, October 22, 2002, at 1:44 PM	Temperature (Deg.C): -10.0
Data Filtering: Not used	Confining Pressure (kPa): -0.0
Curve fitting: Not used	Axial Gauge Length (mm): 101.6
Phase angle: Calculated from mid point values	Radial Gauge Length (mm): 50

	Cycle #195	Cycle #196	Cycle #197	Cycle #198	Cycle #199	Average
Loading stress (kPa)	1191.8	1182.3	1197.0	1185.1	1173.2	1185.9
Recoverable axial micro-strain	35.3	35.3	35.6	35.1	34.9	35.3
Permanent axial micro-strain	17	17	17	17	17	
Dynamic modulus (MPa)	33715.3	33452.4	33666.8	33718.8	33572.0	33625.1
Phase angle (Deg)	5.80	5.59	5.92	5.45	5.79	5.71
Dyn Modulus/sine(phase angle)	666657.8	686375.4	652387.4	709724.1	665131.0	676055
Poisson's ratio						
Recoverable radial micro-strain						
Permanent radial micro-strain						
Dynamic load (kN)	9.738	9.661	9.781	9.684	9.586	9.690
Maximum load (kN)	10.468 (7.777s)	10.443 (7.817s)	10.515 (7.857s)	10.336 (7.896s)	10.326 (7.936s)	10.417
Minimum load (kN)	0.729 (7.795s)	0.782 (7.836s)	0.734 (7.875s)	0.652 (7.916s)	0.739 (7.956s)	0.727
Maximum averaged axial (mm)	-0.002 (7.799s)	-0.002 (7.837s)	-0.002 (7.877s)	-0.002 (7.917s)	-0.002 (7.957s)	-0.002
Minimum averaged axial (mm)	-0.005 (7.778s)	-0.005 (7.817s)	-0.005 (7.857s)	-0.005 (7.898s)	-0.005 (7.938s)	-0.005
Maximum axial #1 (mm)	-0.001 (7.796s)	-0.001 (7.837s)	-0.001 (7.876s)	-0.001 (7.916s)	-0.001 (7.956s)	-0.001
Minimum axial #1 (mm)	-0.003 (7.777s)	-0.003 (7.817s)	-0.003 (7.858s)	-0.003 (7.898s)	-0.003 (7.938s)	-0.003
Maximum axial #2 (mm)	-0.001 (7.798s)	-0.001 (7.837s)	-0.001 (7.876s)	-0.001 (7.915s)	-0.001 (7.957s)	-0.001
Minimum axial #2 (mm)	-0.003 (7.778s)	-0.003 (7.816s)	-0.003 (7.857s)	-0.003 (7.896s)	-0.003 (7.938s)	-0.003
Maximum axial #3 (mm)	-0.003 (7.795s)	-0.003 (7.837s)	-0.003 (7.877s)	-0.003 (7.916s)	-0.003 (7.957s)	-0.003
Minimum axial #3 (mm)	-0.009 (7.778s)	-0.009 (7.817s)	-0.010 (7.857s)	-0.009 (7.898s)	-0.009 (7.936s)	-0.009

Operator: Jack and Gilly

Notes/comments: E* Round Robbin Test
Temperature = -10C

Specimen Information

Identification: #08Tilcon, CT

Core/Sample Number:

Dimensions (mm)	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev.
Diameter (mm)	102	102	102	102	102	102	102	
Height (mm)	150	150	150	150	150	150	150	

Cross-Sectional Area: 8171.282
Volume: 1225692

Comments/Properties:

1/1/02 3:21:14 PM   UTM_38 V1.01 Beta (22/05/2002) Dynamic Modulus Test variation is questionable. We believe this requirement should be refined to provide adequate statistical information in a simplified form.

Section 14.4 In addition, report the dynamic modulus replicate results in a format compatible with Table 6 of this protocol. This is the format of data entry required for the computer program "Asphalt Pavement Analysis and Design System" (APADS) that was developed under the 2002 Design Guide for the design of new and rehabilitated pavement structures. This is merely a tabulation of the data in Section 14.3, but in the form employed in the 2002 Guide.

Section 14.5 "Report the constructed master curve." Construction of the master curve requires reading the time of maximum stress and maximum strain from the graphic output, Figure 3. To assure accuracy, maximum stress and strain should be read five times each and then averaged, respectively. This is 150 readings each for each test, determining the difference for each data pair, and calculating the average of each group of five readings. This activity is extremely labor intensive and should be automated.

Solution – The reporting requirements were simplified by this research team. Figure 4 presents the format developed by the research team to report, needed test results.

ROUND ROBIN TEST of the E* PROTOCOL – Based on our experience gained in obtaining and using the E* equipment, a round robin test of the Protocol was undertaken. The data obtained would be used as justification for the AASHTO Subcommittee on Materials to approve the Protocol for use by state DOTs. Ten laboratories were contacted to participate in the round robin and eight of the ten, plus the Advanced Pavement Laboratory at the University of Connecticut participated. They are listed in Table 5.

Table 5 – Listing of E* Round Robin Participants

Laboratory	Location	Contact
University of Maryland	College Park, Maryland	Dr. Charles Schwartz
Applied Asphalt Technology	Sterling, Virginia	Dr. Ramon Bonaquist
North Carolina State University	Raleigh, North Carolina	Dr. Richard Kim
Arizona State University	Tempe, Arizona	Dr. Matthew Witczak
Purdue University	W. Lafayette, Indiana	Dr. Terri Pellinen
National Center for Asphalt Technology	Auburn, Alabama	Dr. Ray Brown
University of Nevada-Reno	Reno, Nevada	Dr. Peter Sebaaly
Federal Highway Administration	McLean, Virginia	Kevin Stuart
University of Connecticut	Storrs, Connecticut	Dr. Jack E. Stephens

Figure 4– Suggested Reporting Format

Results From Dynamic Modulus Frequency Tests

Tests Performed at Connecticut Advanced Pavement Laboratory

Material Supplied by: Connecticut

Test Temperature = -10 C

Gauge Length = 101.6 mm

Location Identifiers

Project Number
Route
Mileage

	Averages of Last Five Cycles											
	Sweep 1 (25Hz)		Sweep 2 (25Hz)		Sweep 3 (25Hz)		Sweep 4 (25Hz)		Sweep 5 (25Hz)		Sweep 6 (25Hz)	
Specimen	1	2	1	2	1	2	1	2	1	2	1	2
Actual Temperature Deg C =	-10	-10	-10	-9.9	-10	-9.9	-10	-9.9	-10	-9.9	-10.1	-9.9
Average Peak Load, KN =	17.696	9.69	18.056	9.537	17.352	8.847	16.028	8.086	14.527	7.382	13.058	5.74
Average Peak Stress, kPa =	2165.9	1185.9	2209.7	1167.2	2123.6	1082.6	1961.5	989.6	1777.8	903.4	1598	702.5
Dynamic Modulus(E*)= Average E*/Sweep	27,389	33,625 XX	25,619	31,560 XX	24,202	30,213 XX	20,883	26,989 XX	19,599	25,353 XX	16,710	21,714 XX
Average Phase AngleØ (Deg) = Average Ø/Sweep	14.36	5.71 XX	16.98	7.54 XX	17.27	7.04 XX	16.66	8.82 XX	17.21	9.65 XX	18.29	11.34 XX
LVDT #1 Average Peak Strain =	59.06	196.85	88.58	19.69	88.58	19.69	98.43	19.69	98.43	19.69	98.43	196.85
LVDT # 2 Average Peak Strain =	59.06	19.69	68.90	29.53	68.90	19.69	78.74	19.69	68.90	19.69	78.74	196.85
LVDT # 3 Average Peak Strain =	88.58	29.53	88.58	59.06	108.27	68.90	108.27	68.90	108.27	68.90	118.11	59.06
Coefficient of Variation of LVDTs												

For the round robin, CAPLab staff chose a HMA surface course mix, commonly used in Connecticut. Appendix 1 presents instructions issued to the round robin participants, particulars on the aggregate for the mix design, and data sheets to record details on sample preparation and the results of the tests performed. Each laboratory was sent two one-gallon cans containing 6962 gm of blended and dry mixed aggregate, the amount to prepare one specimen, and a one quart can of binder. These components were needed to prepare two 170 mm high by 150 mm diameter specimens with an asphalt content of approximately 5.3 percent. Data for a sample mixture are presented in Table 6. All materials were sent with a copy of the mix design, a copy of the E* Protocol dated 6/02, (See Appendix 2) and a request to report any deviations or problems encountered in using the Protocol.

Table 6 – Sample Mixture Data

Mix Property	Average of Two Specimens
Binder Content (%)	5.3
Binder Weight (gm)	389.6
Total Aggregate Weight (gm)	6961.8
Total Specimen Weight (gm)	7351.4
Theoretical Maximum Specific Gravity (Gmm)	2.651

Specimen Preparation - Participants prepared duplicate test specimens, instrumented and tested the specimens in accordance with the Protocol. In summary, the specimens were prepared by first heating the binder and aggregates to 157C (≈ 315F) and mixing them. The mixtures were then short-term oven aged for four hours at 135C (295F) and compacted in a standard gyratory compactor. The specimens were compacted in a 6-in. mold at 600 kPa (≈ 87 psi) with the final height of the gyratory set at 170.2 mm (≈ 6.7 in.). Air voids of the uncored specimens were determined by AASHTO T269-94. 100 mm (4 in.) diameter test specimens were cored from the center of the 6-in. compacted samples and approximately 9 mm (≈ 0.35 in.) were sawn from each end to produce a nominal 150 mm by 100 mm diameter (6-in. x 4-in.) specimen. Air voids of the final test specimens were then determined using AASHTO 269-94.

Dynamic Modulus Testing – E* tests were conducted on the two specimens in accordance with the Protocol shown as Appendix 2. The test conditions are summarized in Table 7.

Table 7 – Summary of E* Test Conditions

Test Temp. (F)	Frequency (Hz)	Test Cycles
14, 40, 70, 100, 130	25	200
	10	200
	5	100
	1	20
	0.5	15
	0.1	15

Axial deformation of the specimens was measured via LVDTs placed on the specimen's side. Brass studs were glued onto the surface of the test specimen and used to secure the LVDTs in place. CAPLab staff sent a set of templates to locate the mounting plugs 101.6 mm apart and 25 mm from the top and bottom of the specimen (Appendix 2, Figure B-1). Pairs of rubber membrane with vacuum grease between the layers were placed on the top and bottom of each specimen during testing to minimize end friction. Figure 2 in the Protocol shows a schematic of the gauge point instrumentation of the test samples used.

All tests were to be conducted in temperature-controlled chamber capable of maintaining temperatures from 14 to 140 F (-10 to 60 C). The specimens were tested using a set of stress levels expected to yield resilient strains more than 50 micro strain at low test temperatures and less than 150 micro strain at higher temperatures. This ensured, to the degree possible, a linear response of the material for the temperature regimens used in this work.

<u>Results of Precision and Bias Analysis</u> – As stated previously, eight laboratories as well as the CAPLab were contacted and agreed to participate in a round robin test of the protocol. Table 8 presents the results of our Precision and Bias analysis, which was conducted in accordance with ASTM C802-96. The data show strong indications of testing variations at the participating laboratories. These results are for one mix tested in accordance with the E* Protocol dated 6/02. All data received from the participating laboratories are presented on the enclosed CD.

It is interesting to note that not all of the participating laboratories could provide test results for each temperature and sweep required in the protocol. Two laboratories could not do Sweep 1 at -10C and 4.4C and eight labs provided data on Sweeps 2-6 at these temperatures. For tests at 21.1 C and 37.8 C 8 of 9 provided data for Sweep 1 and all labs provided data for Sweeps 2-6. The high temperature test, 54.4 C, 8 of 9 labs provided data for Sweep 1, and each lab contributed data in Sweeps 2-6.

It is obvious from the data in Table 8 that there is a wide variation in laboratory capability to provide the data required in the E* protocol. In one case the laboratory experienced equipment problems with the test chamber and could not comply with the full suite of tests required. We have no explanation for the remainder of the missing data.

In a parallel effort, FHWA tested several materials being evaluated at the ALF facility at McLean, Virginia. For this work the aggregate type and gradation were held constant and the asphalt binder varied. Figure 5 shows the E* values obtained for the various binders tested. The code designations for the eight modified binders tested is presented in Table 8A. All tests were performed at a temperature of 50 C, 10 Hz. Figure 6 shows the coefficient of variation of the E* data by binder values, in particular, the modified binders. There is substantial variation in E* value, especially among the modified binders. The large differences in the coefficient of variation of E* values obtained by FHWA while testing ALF mixes with the same equipment, at a single

Table 8 – Summary of Test Results for Precision and Bias

Temp	Variables	Mean	S.D.	Minimum	Maximum	Count	Temp	Variables	Mean	S.D.	Minimum	Maximum	Count
	δ	1399.45	477.08	857.21	2121.81	7		δ	1028.09	339.17	496.43	1401.95	7
-10 °C	E*	31870.39	5737.47	23662.44	42245.99	7	4.4 °C	E*	19677.27	2865.06	15613.38	22922.22	7
Sweep 1	ø	10.20	3.31	6.43	15.32	7	Sweep 1	ø	14.13	3.06	10.07	18.83	7
	ε	44.08	12.59	26.15	57.20	7		ε	54.11	20.92	22.14	74.90	7
	δ	1583.33	613.27	851.63	2455.99	8		δ	1056.31	367.92	507.78	1637.87	8
-10 °C	E*	28848.39	4892.03	21981.86	36610.88	8	4.4 °C	E*	17004.68	2751.14	13951.88	20751.52	8
Sweep 2	ø	8.42	3.78	2.00	13.55	8	Sweep 2	ø	14.91	2.42	12.71	19.52	8
	ε	56.22	23.08	26.33	87.73	8		ε	65.27	29.01	25.13	110.40	8
	δ	1474.31	515.32	845.44	2266.43	8		δ	959.90	286.84	496.88	1360.11	8
-10 °C	E*	26973.22	4048.17	21090.53	32274.20	8	4.4 °C	E*	14214.33	4150.68	6293.49	19287.77	8
Sweep 3	ø	9.70	4.04	3.61	17.05	8	Sweep 3	ø	14.93	5.24	4.16	20.74	8
	ε	55.85	21.08	28.68	84.18	8		ε	78.59	47.12	26.78	176.67	8
	δ	1394.43	507.30	828.43	2275.61	8		δ	873.83	239.39	486.08	1121.35	8
-10 °C	E*	23615.45	3174.83	18339.26	27927.20	8	4.4 °C	E*	11133.70	3138.90	5708.12	14959.72	8
Sweep 4	ø	12.15	4.50	5.88	21.95	8	Sweep 4	ø	18.24	5.16	11.01	26.66	8
	ε	59.39	20.73	33.05	97.63	8		ε	89.73	51.01	32.57	196.45	8
	δ	1347.35	517.75	825.97	2261.99	8		δ	783.72	217.01	483.35	1123.25	8
-10 °C	E*	21868.33	3715.14	16185.90	27653.65	8	4.4 °C	E*	10649.05	1989.94	8222.98	13386.77	8
Sweep 5	ø	12.67	4.31	5.66	21.09	8	Sweep 5	ø	21.58	3.52	16.28	28.58	8
	ε	62.02	22.24	36.34	104.48	8		ε	75.73	23.23	36.37	104.34	8
	δ	1280.33	561.56	780.00	2264.50	8		δ	737.46	225.87	460.00	1125.90	8
-10 °C	E*	18474.19	3004.45	14104.66	23590.45	8	4.4 °C	E*	7658.95	1571.08	5465.99	10011.78	8
Sweep 6	ø	13.66	4.60	8.91	24.19	8	Sweep 6	ø	24.99	3.87	19.00	32.83	8
	ε	68.78	26.89	43.53	126.45	8		ε	99.27	32.37	47.95	149.60	8

δ = Peak Stress (kPa)
ø = Phase Angle (degrees)
ε = Peak Strain (micro)

S.D.= Standard Deviation
Count=Number of Laboratories providing test data
E* = Dynamic Modulus (kPa)

Table 8 – Summary of Test Results for Precision and Bias (Continued)

Temp	Variables	Mean	S.D.	Minimum	Maximum	Count	Temp	Variables	Mean	S.D.	Minimum	Maximum	Count
	δ	521.49	222.15	280.87	961.95	8		δ	200.07	119.64	49.70	398.00	8
21.1 °C	E*	8024.27	1580.58	5635.73	11100.29	8	37.8 °C	E*	2383.90	564.99	1585.60	3266.40	8
Sweep 1	ø	25.32	7.59	17.95	42.90	8	Sweep 1	ø	31.37	7.11	25.86	46.92	8
	ε	68.60	33.54	25.30	123.97	8		ε	86.94	54.13	24.51	173.31	8
	δ	480.59	139.29	283.71	669.70	9		δ	171.64	94.02	49.57	314.95	9
21.1 °C	E*	6360.27	1329.55	4551.90	9279.91	9	37.8 °C	E*	1721.24	215.31	1504.06	2196.06	9
Sweep 2	ø	24.90	3.12	20.95	30.65	9	Sweep 2	ø	29.53	2.29	26.87	33.89	9
	ε	79.36	29.00	30.57	121.68	9		ε	100.81	58.61	32.96	199.05	9
	δ	423.49	126.34	245.00	556.69	9		δ	149.20	79.92	49.33	244.68	9
21.1 °C	E*	5435.98	1194.03	3857.39	7918.59	9	37.8 °C	E*	1455.39	251.65	1235.50	1936.12	9
Sweep 3	ø	24.24	6.39	8.83	31.98	9	Sweep 3	ø	27.73	2.59	23.60	32.03	9
	ε	80.19	24.56	35.07	109.80	9		ε	100.69	50.64	39.25	182.25	9
	δ	343.06	108.04	165.50	512.47	9		δ	124.78	67.60	41.00	221.55	9
21.1 °C	E*	3495.10	894.89	2471.97	5503.79	9	37.8 °C	E*	911.52	143.38	760.90	1257.65	9
Sweep 4	ø	28.29	5.14	17.86	34.68	9	Sweep 4	ø	26.29	3.23	20.94	31.45	9
	ε	101.00	31.04	49.48	134.64	9		ε	135.98	73.07	53.88	237.98	9
	δ	294.89	114.78	110.50	497.98	9		δ	105.20	60.25	30.00	217.69	9
21.1 °C	E*	2812.48	738.40	2027.00	4605.77	9	37.8 °C	E*	744.39	123.95	626.30	1042.75	9
Sweep 5	ø	30.84	3.56	25.44	35.83	9	Sweep 5	ø	26.51	3.03	22.34	31.52	9
	ε	107.07	39.70	48.45	161.49	9		ε	141.88	82.12	47.90	281.75	9
	δ	254.46	129.69	72.00	506.06	9		δ	90.91	62.06	20.50	222.19	9
21.1 °C	E*	1685.44	562.86	970.74	2961.54	9	37.8 °C	E*	525.36	108.55	391.72	758.51	9
Sweep 6	ø	30.05	4.14	22.52	36.03	9	Sweep 6	ø	23.53	3.14	19.49	28.28	9
	ε	154.46	69.47	49.72	251.88	9		ε	162.34	117.40	48.67	402.82	9

δ = Peak Stress (kPa)
ø = Phase Angle (degrees)
ε = Peak Strain (micro)

S.D.= Standard Deviation
Count=Number of Laboratories providing test data
E* = Dynamic Modulus (kPa)

Table 8 – Summary of Test Results for Precision and Bias (Continued)

Temp	Variables	Mean	S.D.	Minimum	Maximum	Count
54.4 °C Sweep 1	δ	51.37	30.12	15.66	96.31	8
	E*	898.781	273.92	461.0454	1368.852	8
	ø	29.26	7.06	21.70	43.65	8
	ε	64.50	46.98	12.20	147.81	8
54.4 °C Sweep 2	δ	50.91	25.37	15.74	93.60	9
	E*	681.134	112.82	515.981	842.3237	9
	ø	26.15	3.68	20.23	31.74	9
	ε	73.46	32.73	30.51	121.18	9
54.4 °C Sweep 3	δ	44.94	19.09	15.38	74.10	9
	E*	558.962	101.1	426.4227	679.6436	9
	ø	25.80	6.71	21.29	42.30	9
	ε	79.18	30.58	36.07	118.30	9
54.4 °C Sweep 4	δ	37.21	14.52	13.00	52.25	9
	E*	392.698	103.46	264.4237	542.695	9
	ø	25.19	9.78	17.55	49.96	9
	ε	94.94	34.69	43.25	138.69	9
54.4 °C Sweep 5	δ	33.99	14.54	11.00	54.06	9
	E*	337.753	95.374	219.6001	511.1726	9
	ø	19.38	4.72	9.55	25.88	9
	ε	101.64	44.30	44.40	184.61	9
54.4 °C Sweep 6	δ	28.88	13.17	8.00	44.78	9
	E*	292.152	118.94	163.0107	546.5141	9
	ø	19.53	3.65	11.76	24.06	9
	ε	99.67	38.33	42.72	157.50	9

δ = Peak Stress (kPa)
ø = Phase Angle (degrees)
ε = Peak Strain (micro)
S.D.= Standard Deviation
Count=Number of Laboratories providing test data
E* = Dynamic Modulus (kPa)

Table 8 A – Abbreviations for Eight Polymer-Modified Asphalt Binders in Figures 5 and 6

Binder	**Abbreviation**
Styrene-Butadiene-Styrene Linear	SBS L
Styrene-Butadiene-Styrene Linear Grafted	SBS LG
Styrene-Butadiene-Styrene Radial Grafted	SBS RG
Ethylene Vinyl Acetate	EVA
Ethylene Vinyl Acetate Grafted	EVA G
Elvaloy	Elvaloy
Ethylene Styrene Interpolymer	ESI
Chemically Modified Crumb Rubber Asphalt	CMCRA

Figure 5 – FHWA-ALF
E* Values for Various Asphalt Binders

(3 Replicates, 50 ℃, 10 Hz)

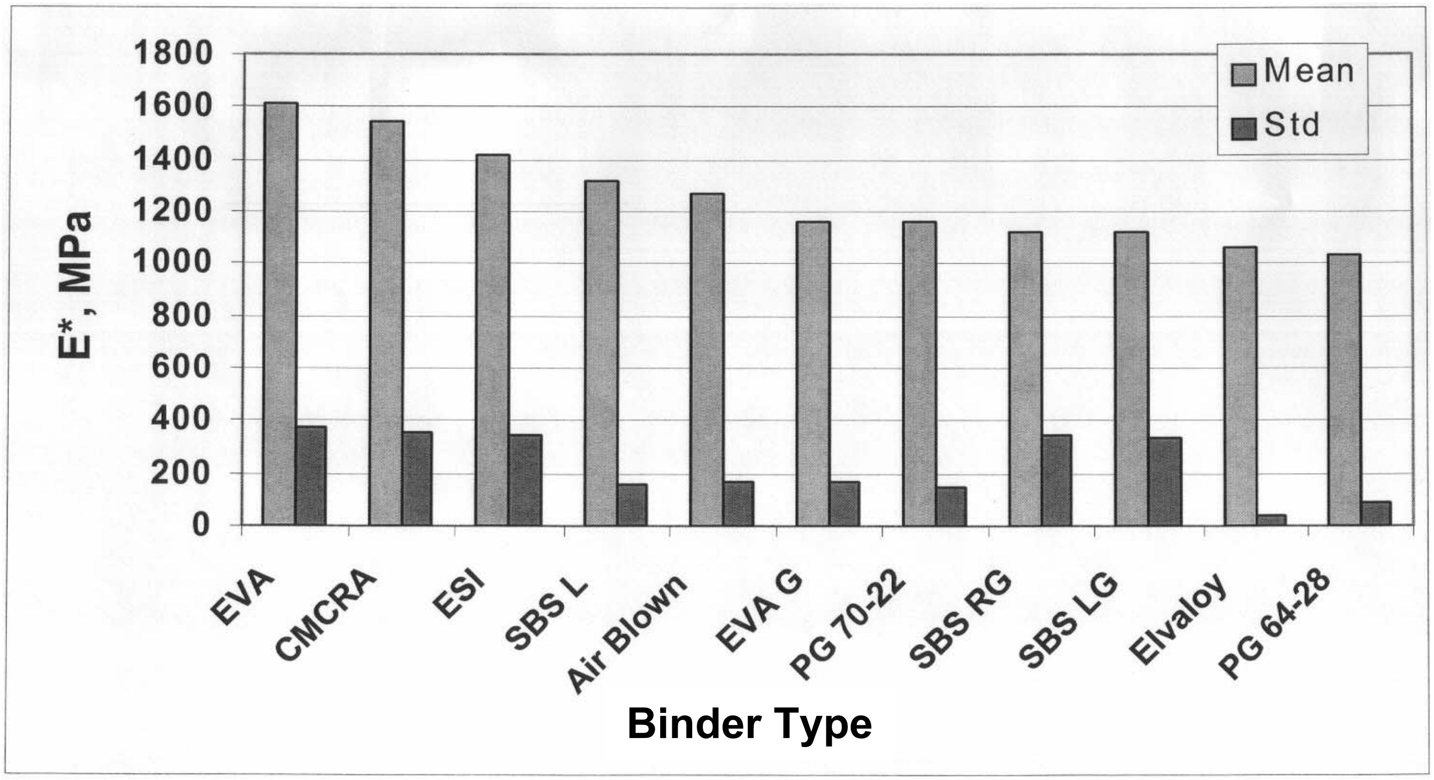
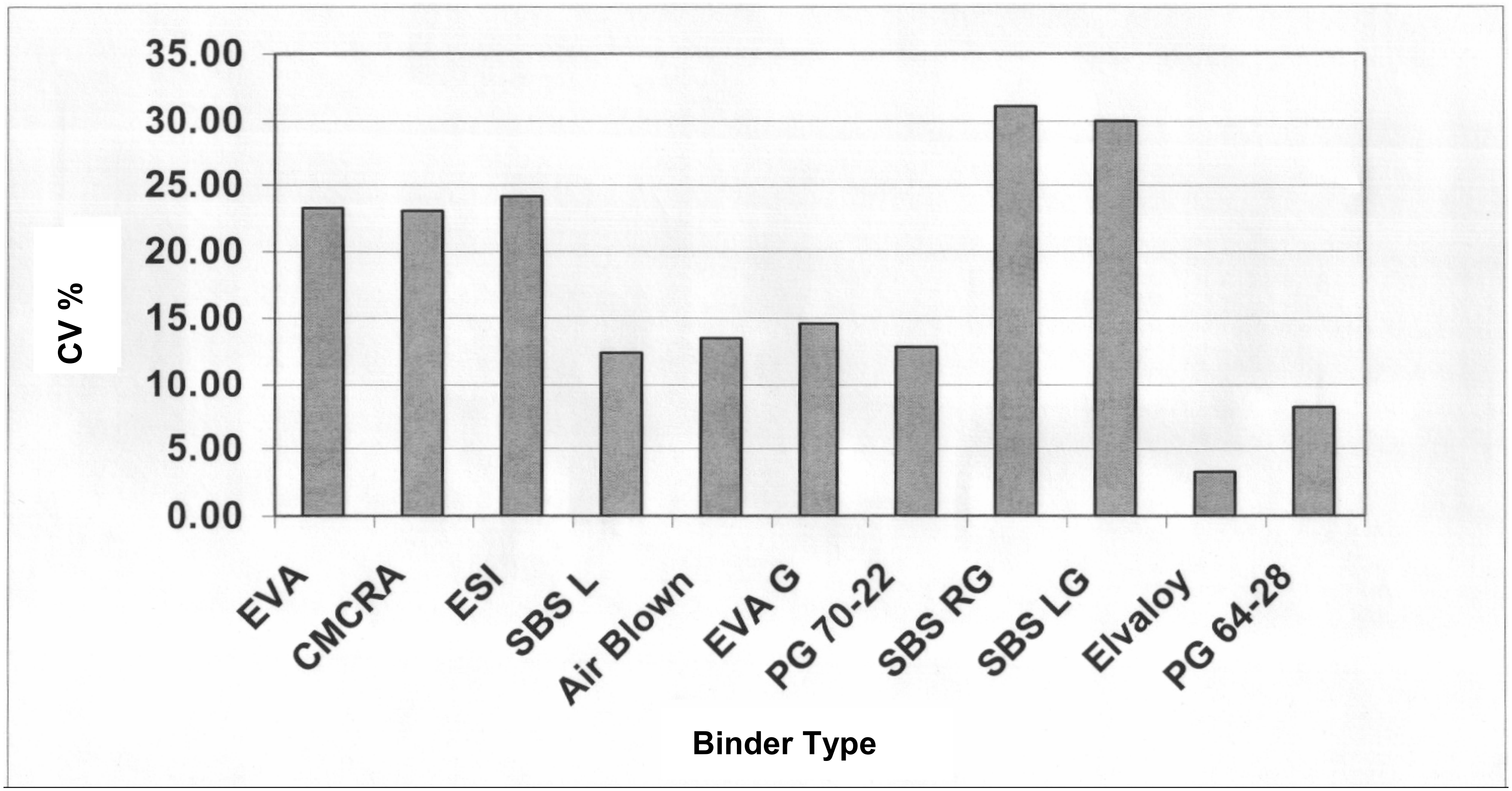


Figure 6 –FHWA-ALF
Coefficient of Variation of Measured E* for Various Asphalt Binders

(3 Replicates, 50 ℃, 10 Hz)



frequency and temperature, holding aggregate type constant but varying the binder, suggest that other factors beyond variation among laboratories affect E* values.

E* TESTS on STATE DOT's HMA MIXES – E* tests were conducted on HMA mixes from eight sponsoring states. For this activity, each participant sent to CAPLab the binder, coarse and fine aggregate, gradation and other mix design information. The mix was then prepared and tested by CAPLab staff in accordance with the E* Protocol and the results were sent to each state. The enclosed CD presents the results of all E* tests on state mixes, with the respective states being coded.

CONCLUSIONS – The dynamic modulus test, E*, provides modulus values which can be used to predict stress levels in HMA pavement systems. A round robin test of the E* protocol produced Precision and Bias results which indicate that a strong variation in E* values can be obtained among laboratories. These tests were performed on one mix only, holding aggregate type, gradation and binder constant.

Other factors affect E* values. For Example, FHWA E* tests on ALF mixes, for a single test speed, temperature, and type of aggregate produced different E* values when the type binder was changed. This statement is based on the large differences in the coefficient of variation of the FHWA E* data.

The variation is, in part, due to the stress levels used. As E* is inversely related to strain, the 50 to 150 micron strain range permits a wide range of stress levels and a wide range of E* results. Table 9, a summary of recoverable strain data for the round robin tests and the E* tests conducted for eight state sponsors, was prepared to illustrate this point. Please note the wide variation in recovered strain outside the limits in the protocol of 50-150 microstrain. A procedure is needed to reduce the potential range of results for a given material. A portion of the variation is due to the recoverable strain permitted. This variation could be sharply reduced, if E* values were converted to a single strain. A logical conversion is to 100 microstrain.

Concerning the protocol, recommendations are presented below to improve the protocol and hopefully shorten the overall time required to conduct the test. Our experience is that a full week is required to test a single material. If the test fails the permanent strain limitations in the protocol, it must be discarded and a new sample used to finish the test. This time frame appears to be excessive, given a DOT's contract requirements to place a HMA pavement in a limited window of time.

RECOMMENDATIONS – The following recommendations are presented to: (a) clarify and refine the current test protocol; and, (b) shorten the time of test and focus its results for use in the 2002 Pavement Design Guide.

(1) Sample preparation – Use a restraining device to prevent sample movement during sawing of the ends. Friction tape the specimen ends to prevent end fraying.

(2) Instrumentation – Use a template when positioning gauge plugs.

Table 9 – Summary of Recoverable Strain Data

For Round Robin

Laboratory	A	B	C	D	E	F	G	H	I
< 50 [(1)] micro	0	1	20	27	12	43	0	5	3
> 150 [(2)] micro	0	0	0	2	9	0	25	18	8
% Outside [(3)] Limits	0	2% < 50	33% < 50	45% < 50	21% < 50	72% < 50	0% < 50	8% < 50	5% <50
	0	0% > 150	0% > 150	3% > 150	16% > 150	0% > 150	42% > 150	30% > 150	13% > 150
Total % - Outside Limits	0%	2%	33%	48%	37%	72%	42%	38%	18%

For State HMA Mixes

State	1	2	3	4	5	6	7	8
< 50 [(1)] micro	39	9	32	5	7	5	7	5
> 150 [(2)] micro	1	10	0	9	8	19	11	13
% Outside [(3)] Limits	65% < 50	16% < 50	53% < 50	8%< 50	12% < 50	8% < 50	12% < 50	8% < 50
	2% > 150	18% > 150	0% > 150	15% > 150	13% > 150	32%> 150	18% > 150	13% > 150
Total % - Outside Limits	67%	34%	53%	23%	25%	40%	30%	21%

(1) Total # of values recommended below limit of 50 microstain
(2) Total # of values recommended upper limit of 150 microstain
(3) % outside of recommended limits

(3) Conducting the E* test – Use a dummy specimen instrumented with a thermal couple to establish the test specimen's temperature. Frequently check for unwanted moisture in the test chamber. This is particularly important when conducting the low temperature tests during high humidity periods.

(4) Presentation of test results – Simplify the amount of data reported. A suggested format is presented in the text. The resultant format should be directly useable in the 2002 Pavement Design Guide.

(5) E* test should be simplified and the time to conduct the test should be significantly reduced. This problem has been recognized and is being addressed in NCHRP Project 9-29. The output of the NCHRP project should be carefully reviewed and applied to aid operational DOTs, in conducting the E* test. An alternative to a simplified E* test is to conduct an adequate number of E* tests to define the modulus for the various mixes commonly used in a state. This requires that any factors affecting the E* test results be defined.

(6) Specific recommendations to improve the Protocol dated 6/2002 are:

(a) Section 6.3 – Add the following to Note 1: The saw shall be equipped with a restraining device to hold the test specimen without developing stress concentrations in the sample.

(b) Section 6.4 – Add the following to Note 2: A restraining device to hold the specimen is helpful.

(c) Section 9.1 – Correct the heights to 149.86 and 155.90 mm (5.91 and 6.09 inch).

(d) Section 10.1 – Note 5 belongs at the end of Section 10.2.

(e) Section 11.2 – Revise Table 3 as follows:

Temp C	Time from Room Temp, (hrs) 25C	Time from Previous Test Temp, (hrs)
-10	Overnight	6 hrs or Overnight
4.4	Overnight	6 hrs or Overnight
21.1	2 hrs	6 hrs or Overnight
37.8	6 hrs or Overnight	6 hrs or Overnight
54.4	Overnight	6 hrs or Overnight

(f) Section 12.5 – This computation appears meaningless, as the strain for each LVDT depends on the location of the button. Strain measured between two coarse aggregate particles will be very different from strain measured between two areas of fine aggregate. E* calculated from the average LVDT strain appears to be the most appropriate value of E*. The computation should be changed to:

$$E^* = \delta/\text{Average strain per cycle}$$

Insert a new section – E* value adjusted to a common strain. 100 microstrain is recommended.
E* @ 100mm = (E* X 100) / Average of last 5 cycles of recoverable strain

(g) Section 12.6 – Change the statement to: "calculate the phase angle individually for each temperature/ frequency of each specimen."

$$\phi = \frac{t_i}{t_p} * (360)$$

Where: t_i = average lag time for last five cycles and for (# of) LVDTs.
t_p = average time for a stress cycle (sec).

(h) Section 13.2 and 13.3 – Add some way to develop the E* Master Curves. Appendix 3 is a spread sheet system developed by Arizona State University staff to prepare these curves.

(i) Section 14.1- Delete this requirement and replace it with Section 14.2.

(j) Section 14.3 – Change end of sentence to: "coefficient of variation of the replicates tested."

(k) Section 14.5 – Change the statement to: "Report the constructed master curve using Appendix 3." If Appendix 3 is not specified in the protocol, the user has no way of knowing how the curve was constructed.

Selected References

1– Akhter, G. F., and Witczak, M. W., “Sensitivity of Flexible Pavement Performance to Bituminous Mix Properties”, TRB Record 1034.

2 – Fonseca, O. A., and Witczak, M. W., “A Prediction Methodology for the Dynamic Modulus of In-Place Aged Asphalt Mixtures”, Proceedings, Association of Asphalt Paving Technologists, Volume 65, 1996.

3 – Miller, J. S., Uzan, J., and Witczak, M. W., “Modification of the Asphalt Institute’s Bituminous Mix Modulus Predictive Equation”, TRB Record 911.

4 – Mirza, M. W., and Witczak, M. W., “Development of a Global Aging System for Short and Long Term Aging of Asphalt Cements”, Proceedings, Association of Asphalt Paving Technologists, Volume 64, 1995.

5 – Pellinen, T. K., and Witczak, M. W., “Stress Dependent Master Curve Construction for Dynamic (Complex) Modulus”, Journal of the Association of Asphalt Paving Technologists, Volume 71, 2000, PP. 281-309.

6 – Shook, J. F., and Kallas, B. F., “Factors Influencing the Dynamic Modulus of Asphalt Concrete”, Proceedings, Association of Asphalt Paving Technologists, AAPT, Los Angeles, CA, 1969.

7 – Witczak, M. W., “A Comparison of the Dynamic (Complex) Modulus Test (E*) and Indirect Diametral Test (Mr) for AC Mixtures”, 2/12/99, Unpublished.

8 – Witczak, M. W., “Design of Full-Depth Asphalt Airfield Pavements”, Proceedings, 3rd International Conference on Structural Design of Asphalt Pavements, Volume I, London, England, 1972.

9 – Witczak, M. W., and Fonseca, O. A., “Revised Predictive Model for Dynamic (Complex) Modulus of Asphalt Mixtures”, TRB Record 1540, 1996.

10 – Witczak, M. W., and Root, R. E., “A Summary of Complex Modulus Laboratory Test Proceeures and Results”, Proceedings, Symposium on Fatigue Testing of Bituminmous Mixtures, ASTM Annual Meeting, Philadelphia , PA, 1973.

11 – Witczak, M. W., et. al., “The Universal Airport Pavement Design System, Report II: Asphalt Mixture Material Characterization”, University of Maryland Report, May 1989.

12 – Yoder, E., “Principles of Pavement Design”, J. Wiley and Sons, 1975.

APPENDIX 1

Round Robin Test

1 – Instructions to Participants issued 6/17/02.

2 – Listing of Aggregate Weights for Connecticut 12.5 mm Mix

3 – Data Sheet for Samples Prepared by Participants

4 – Data Sheet (Excel) to record E* Test Results

To: Round Robin Participants
From: Charles E. Dougan

Subject: Round Robin Test of Dynamic Modulus (E*) Test Protocol

We have completed all arrangements for the subject testing. On or about Monday June 17, 2002 we will ship binder, aggregate and current protocol to you. The aggregate (proportioned in a quantity for a 170.2 mm high by 150.0 mm diameter specimen) will be dry mixed and shipped in a gallon plastic jar. One container per specimen.

The binder is a PG 64-28 and one quart will make two specimens.

Test samples are to be prepared following Protocol section 9 page 5.

The mix is a 12.5 mm Superpave mix.

Some pointers on simplifying the mix process:

1. Use the entire contents of the gallon can of aggregate to keep the gradation consistent.
2. Binder content should be 5.3% of the total mix which is 390.0 grams for this specimen.
3. Heat the binder and aggregate to 157C for mixing. About an hour in the oven set at 157 C.
4. Age for 4 hrs as per AASHTO PP2.
5. Condition to 146 C for compaction.
6. Set the gyratory compaction pressure at 600 kPa and a height of 170.2 mm (6.7 inches). This has generally been reached at less than 150 gyrations based on our experience.

Determine the air voids before and after coring. Maximum Specific Gravity is 2.651. While wet from coring , weigh in water, then obtain the saturated surface dry weight. We dry overnight in an oven set about 65 C and obtain the dry weigh the next morning.

All tests are to be conducted in accordance with the attached test protocol. This protocol is the latest version and represents a consensus of the best minds working with this test method. If you encounter any problems with the protocol, please record these problems and pass this information back with your final results. We have experienced problems with the time to reach temperatures shown in table 3 page 8 of the protocol. We recommend that a thermal couple in a dummy specimen the same size as the E* specimens be used to assure that the temperature requirement has been met.

We will e-mail an excel sheet for results shortly and request that you e-mail your test results to us on or before July 30, 2002. It is our intention to discuss these results at an upcoming Advisory Panel meeting scheduled for August 22, 2002. If you can’t meet this target date, please advise me.

Your participation in this effort is greatly appreciated.

The Lab e-mail is james.mahoney@uconn.edu
Phone: 860-486-5956,
FAX:860-486-2294

For your convenience, metal templates shown on last page of Protocol are included.

Aggregate Weights for First E* Round Robin

Total Sample weight = 6972.2 gm

Heigth at 100 gyratory cycles = 170.2 mm or 6.7 inch

Binder content = 5.3% =390.2 gm

Sieve mm	inch	1/2 inch Traprock	Cumulative	3/8 inch Traprock	Cumulative	Traprock Sand	Cumulative	Natural Sand	Cumulative	Size Weight	Cumulative
19	3/4"	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	313.7	313.7	0.0	0.0	0.0	0.0	0.0	0.0	313.7	313.7
9.5	13/8"	784.3	1098.0	104.9	104.9	10.5	10.5	1.4	1.4	901.1	1214.8
4.75	#4	592.6	1690.6	1993.5	2098.4	14.6	25.1	23.0	24.4	2623.7	3838.5
2.36	#8	17.4	1708.0	224.5	2322.9	594.0	619.1	80.2	104.6	916.1	4754.6
1.18	#16	0.0	1708.0	68.3	2391.2	573.1	1192.2	76.7	181.3	718.1	5472.7
0.6	#30	0.0	1708.0	0.0	2391.2	288.6	1480.8	108.1	289.4	396.7	5869.4
0.3	#50	0.0	1708.0	0.0	2391.2	215.4	1696.2	170.1	459.5	385.5	6254.9
0.15	#100	0.0	1708.0	0.0	2391.2	167.3	1863.5	147.8	607.3	315.1	6570.0
0.075	#200	14.0	1722.0	12.2	2403.4	113.0	1976.5	52.3	659.6	191.5	6761.5
Pan	Pan	20.9	1742.9	36.6	2440.0	115.0	2091.5	37.6	697.2	210.1	6971.6
Totals		1742.9		2440.0		2091.5		697.2		6971.6	

Preparation of samples for E*

Sample Number ______________ Source ______________________ Technician _______________ Date ___________

GYRATORY MOLDED 6"			CORED 4"		
Wt of sample put in gyratory mold	A	__________			
Weight of Molded Sample	B	__________	Weight of 4" Sample	__________	BB
Number of gyrations	C	__________			
Height of sample	D	__________	Height of sample	__________	DD
Wt of SSD 6" plug	E	__________	Weight of SSD 4" plug	__________	EE
Wt of 6" plug in water	F	__________	Wt of SSD 4" plug in water	__________	FF
Volume of 6" plug (E - F)	G	__________	Vol Sample of 4" plug (EE-FF)	__________	GG
Volume of solids (B/h)	H	__________	Volume of solids (BB/h)	__________	HH
Volume of air voids (G – H)	I	__________	Volume of air voids (GG-HH)	__________	II
% Air Voids (I/g)*100	J	__________	% Air Voids (II/GG)*100	__________	JJ

RICE

Weight, Sample + Alum Can	__________	a	Comments:	____________________
Weight of Alum Can	__________	b		____________________
Wt of sample (a-b)	__________	c		____________________
Wt of sample + Alum Can & Water	__________	d		____________________
Wt Alum can + water	__________	e		____________________
Wt of sample in water (d-e)	__________	f		____________________
Vol Sample (c-f)	__________	g		____________________
Max Sp Gr (c/g)	__________	h		____________________

Sweep 1 (25Hz)

Target Temperature: ____°C

Gage Length:_____(mm)

		Average of Last 5 Cycles			
		Specimen			
		1	2	3	4
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

Sweep 2 (10Hz)

		Average of Last 5 Cycles			
		Specimen			
		1	2	3	4
Actual Test Temperature, C =					
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

Sweep 3 (5Hz)

Target Temperature: ____°C

Gage Length:_____(mm)		Average of Last 5 Cycles Specimen 1	2	3	4
Actual Test Temperature, C =					
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

Sweep 4 (1Hz)

		Average of Last 5 Cycles Specimen 1	2	3	4
Actual Test Temperature, C =					
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

Sweep 5 (0.5Hz)

		Average of Last 5 Cycles			
		Specimen			
		1	2	3	4
Actual Test Temperature, C =					
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

Sweep 6 (0.1Hz)

		Average of Last 5 Cycles			
		Specimen			
		1	2	3	4
Actual Test Temperature, C =					
Average Peak Load, kN =					
Average Peak Stress, kPa =					
Dynamic Modulus =					
LVDT-1					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-2					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				
LVDT-3					
Average peak deformation	(mm)				
Average peak Strain (ε_o)	micro				
Average Phase angle	(Deg)				
ti (if Available)	(Sec)				
tp (if Available)	(Sec)				

APPENDIX 2

Dynamic Modulus (E*) Protocol (6/02)

1. Scope

1.1 This test method covers procedures for preparing and testing asphalt concrete mixtures to determine the dynamic modulus and phase angle over a range of temperatures and loading frequencies.

1.2 This standard is applicable to laboratory prepared specimens of mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.48 in).

1.3 *This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 AASHTO Standards

T312 Method for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.

PP2 Practice for Mixture Conditioning of Hot Mix Asphalt (HMA).

T166 Bulk Specific Gravity of Compacted Bituminous Mixtures.

T209 Maximum Specific Gravity of Bituminous Paving Mixtures.

T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures.

3. Definitions

3.1 *Complex Modulus* – E^*, a computed value that defines the relationship between stress and strain for a linear viscoelastic material.

3.2 *Dynamic Modulus* – $|E^*|$, the absolute value of the complex modulus calculated by dividing the maximum (peak-to-peak) stress by the recoverable (peak-to-peak) axial strain for a material subjected to a sinusoidal loading.

3.3 *Phase angle* – ϕ, the angle in degrees between a sinusoidal applied (peak to peak) stress and the resulting (peak to peak) strain in a controlled-stress test.

3.4 *Linear viscoelastic* – within the context of this test, refers to behavior in which the dynamic modulus is independent of stress or strain amplitude.

4. Summary of Method

4.1 A sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle.

4.2 Figure 1 presents one schematic of the dynamic modulus test that is in use.

5. Significance and Use

5.1 Dynamic modulus values measured over a range of temperatures and frequencies of loading can be shifted into a master curve for characterizing asphalt concrete for pavement thickness design and performance analysis.

5.2 The values of dynamic modulus and phase angle can also be used as performance criteria for asphalt concrete mixture design.

6. Apparatus

6.1 Dynamic Modulus Test System – A dynamic modulus test system consisting of a testing machine, environmental chamber, and measuring system.

6.1.1 *Testing Machine* – A servo-hydraulic testing machine capable of producing a controlled haversine compressive loading. The testing machine should have a capability of applying load over a range of frequencies from 0.1 to 25 Hz and stress level up to 2800 kPa (400 psi).

6.1.2 *Environmental Chamber* – A chamber for controlling the test specimen at the desired temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from -10 to 60 ^{o}C (14 to 140 ^{o}F) to an accuracy of ± 0.5 ^{o}C (1 ^{o}F). The chamber shall be large enough to accommodate the test specimen and a dummy specimen with thermocouple mounted at the center for temperature verification.

6.1.3 *Measurement System* - The system shall be fully computer controlled capable of measuring and recording the time history of the applied load, and the axial deformations. The system shall be capable of measuring the period of the applied sinusoidal load and resulting deformations with a resolution of 0.5 percent.

6.1.3.1 *Load* - The load shall be measured with an electronic load cell in contact with one of the specimen caps. The load cell shall be calibrated in accordance with AASHTO T67. The load measuring system shall have a minimum range of 0 to 25 kN (0 to 5600 lb) with a resolution of 5 N (1 lb).

6.1.3.2 *Axial Deformations* – Axial deformations shall be measured with linear variable differential transformers (LVDT) mounted between gauge points glued to the specimen as shown in Figure 2. The deformations shall be measured at a minimum of two locations 180^o apart; however, three locations located 120^o apart is recommended to minimize the number of replicate specimens required for testing. The LVDTs shall have a range of ± 0.5 mm (0.02 in). The deformation measuring system shall have auto zero and selectable ranges as defined in Table 1.

Table 1 - Deformation Measuring System Requirements.

Range, mm (in)	Resolution, mm (in)
±0.5 (0.01969)	0.0100 (0.00039)
±0.25 (0.00984)	0.0050 (0.00020)
±0.125 (0.00492)	0.0025 (0.00010)
±0.0625 (0.00246)	0.0010 (0.00004)

6.1.4 *Loading Platens* – Platens, with a diameter equal to or greater than that of the test specimen are required above and below the specimen to transfer the load from the testing machine to the specimen. Generally, these platens should be made of hardened or plated steel, or anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used.

6.1.5 *End Treatment* – Friction reducing end treatments shall be placed between the specimen ends and the loading platens. The end treatments shall consist of two 0.5 mm (0.02 in) thick latex sheets separated with silicone grease.

6.2 *Superpave Gyratory Compactor* – A gyratory compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO T312.

6.3 *Saw* – A machine for sawing test specimens ends to the appropriate length is required. The saw shall have a diamond cutting edge and shall be capable of cutting specimens to the prescribed dimensions without excessive heating or shock.

Note 1 – A diamond masonry saw greatly facilitates the preparation of test specimens with smooth, parallel ends. Both single or double-bladed diamond saws should have feed mechanisms and speed controls of sufficient precision to ensure compliance with paragraphs 9.5 and 9.6 of this method. Adequate blade stiffness is also important to control flexing of the blade during thin cuts.

6.4 *Core Drill* - A coring machine with cooling system and a diamond bit for cutting nominal 101.6 mm (4.00 in) diameter test specimens.

Note 2 – A coring machine with adjustable vertical feed and rotational speed is recommended. The variable feeds and speeds may be controlled by various methods. A vertical feed rate of approximately 0.05 mm/rev (0.002 in/rev) and a rotational speed of approximately 450 RPM has been found to be satisfactory for several of the Superpave mixtures.

7. Hazards

Observe standard laboratory safety precautions when preparing and testing HMA specimens.

8. Testing Equipment Calibration

8.1 The testing system shall be calibrated prior to initial use and at least once a year thereafter or per manufacturer requirements.

8.1.1 Verify the capability of the environmental chamber to maintain the required temperature within the accuracy specified.

8.1.2 Verify the calibration of all measurement components (such as load cell and specimen deformation measurement device) of the testing system.

8.2 If any of the verifications yield data that does not comply with the accuracy specified, correct the problem prior to proceeding with testing.

9. Test Specimens

9.1 *Size* – Dynamic modulus testing shall be performed on test specimens cored from gyratory compacted mixtures. The average diameter of each test specimen shall be between 100 and 104 mm (3.94 and 4.09 in). The average height of each test specimen shall be between 147.5 and 152.5 mm (5.81 and 6.00 in).

9.2 *Aging* – Mixtures shall be aged in accordance with the 4-hours short-term oven aging procedure in AASHTO PP2.

9.3 *Gyratory Specimens* – Prepare 170 mm (6.69 in) high specimens to the required air void content in accordance with AASHTO T312.

Note 3 – Testing should be performed on test specimens (101.6 mm (4.00 in) diameter) meeting specific air void tolerances. The gyratory specimen (152.4 mm (6.00 in) diameter) air void content required to obtain a specified test specimen air void content must be determined by trial and error. Generally, the test specimen air void content is 1.5 to 2.5 percent lower than the air void content of the gyratory specimen when the test specimen is removed from the middle as specified in this test method.

9.4 *Coring* – Core the nominal 101.6 mm (4.00 in) diameter test specimens from the center of the gyratory specimens. Both the core drill and the gyratory specimen should be adequately supported to ensure that the resulting test specimen is cylindrical with sides that are smooth, parallel, and free from steps, ridges, and grooves.

9.5 *Diameter* – Measure the diameter of each test specimen at the mid height and third points along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm (0.04 in). Calculate the average and the standard deviation of the six measurements. If the standard deviation is greater than 2.5 mm (0.01 in) discard the specimen. For acceptable specimens, the average diameter, reported to the nearest 1 mm (0.04 in), shall be used in all material property calculations.

9.6 *End Preparation* – The ends of all test specimens shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the specimen by sawing with a single or double bladed saw. The prepared specimen ends shall meet the tolerances described below. Reject test specimens not meeting these tolerances.

9.6.1 The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm (0.002 in) across any diameter. This requirement shall be checked in a minimum of three positions at approximately 120° intervals using a straight edge and feeler gauges approximately 8 - 12.5 mm (0.32 - 0.49 in) wide or an optical comparator.

9.6.2 The specimen end shall not depart from perpendicular to the axis of the specimen by more than 1 degree This requirement shall be checked on each specimen using a machinists square and feeler gauges.

9.7 *Air Void Content* – Determine the air void content of the final test specimen in accordance with AASHTO T269. Reject specimens with air voids that differ by more than 0.5 percent from the target air voids.

Note 4 – Considerable time can be saved if the cored test specimens were treated as wet, and the weights in water and saturated surface dry were measured immediately or within a short time period after coring. The test specimens can then be left to dry overnight, the dry weight can be measured the next day, and then they can be immediately prepared for testing.

9.8 *Replicates* – The number of test specimens required depends on the number of axial strain measurements made per specimen and the desired accuracy of the average dynamic modulus. Table 2 summarizes the replicate number of specimens that should be tested to obtain a desired accuracy limit (e.g., less than ±15 percent).

Table 2 - Recommended Number of Specimens

LVDTs per Specimen	**Number of Specimens**	**Estimated Limit of Accuracy**
2	2	18.0
2	3	15.0
2	4	13.4
3	2	13.1
3	3	12.0
3	4	11.5

9.9 *Sample Storage* – If test specimens will not be tested within 24 hours, wrap specimens in polyethylene and store in an environmentally protected storage area at temperatures between 5 and 26.7°C (40 and 80°F).

Note 4 – To eliminate effects of aging on test results, it is recommended that specimens be stored no more than two weeks prior to testing.

10. Test Specimen Instrumentation

10.1 Attach mounting studs for the axial LVDTs to the sides of the specimen with epoxy cement. Figure 3 shows details of the mounting studs and LVDT mounting hardware. A detailed drawing of the LVDT mounting hardware that is currently in use is shown in Attachment A.

10.2 The gauge length for measuring axial deformations shall be 101.6 mm ±1 mm (4.00 in ± 0.04 in). Suitable alignment and spacing fixture shall be used to facilitate mounting of the axial deformation measuring hardware. The gauge length is measured between the stud centers

Note 5 – Quick setting epoxy such as Duro Master Mend Extra Strength Quick Set QM-50 has been found satisfactory for attaching studs. Additional guidance for stud alignment is outlined in Attachment B.

11. Procedure

11.1 The recommended test series for the development of master curves for use in pavement response and performance analysis consists of testing at –10, 4.4, 21.1, 37.8, and 54.4 ^{o}C (14, 40, 70, 100 and 130^{o}F) at loading frequencies of 0.1, 0.5, 1.0, 5, 10, and 25 Hz at each temperature. Each test specimen, individually instrumented with LVDT brackets, should be tested for each of the 30 combinations of temperature and frequency of loading 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.

11.2 Place the test specimen in the environmental chamber and allow it to equilibrate to the specified testing temperature ± 1F. A dummy specimen with a thermocouple mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, minimum recommended equilibrium temperature times are provided as a guideline.

Table 3 - Recommended Equilibrium Times.

Specimen Temperature, ^{o}C (^{o}F)	**Time from room temperature, hrs 25 C (77 F)**	**Time from previous test temperature, hrs**
-10 (14)	overnight	-
4.4 (40)	overnight	4 hrs or overnight
21.1 (70)	1	3
37.8 (100)	2	2
54.4 (130)	2	1

** Note that the temperature equilibrium times may vary depending on the type of environmental chamber in use. Some testing laboratories reported as much as 6 hours to reach the equilibrium temperature.*

11.3 Place one of the friction reducing end treatments on top of the hardened steel disk at the bottom of the loading frame. Place the specimen on top of the lower end treatment, and mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

11.4 Place the upper friction reducing end treatment and hardened steel disk on top of the specimen. Center the specimen with the hydraulic load actuator visually in order to avoid eccentric loading. Allow a time period for the test specimen to reach the test temperature equilibrium. (This time period may vary between 10 and 30 minutes after changing and reconnecting the next test specimen).

11.5 Apply a contact load (P_{min}) equal to 5 percent of the dynamic load that will be applied to the specimen.

11.6 Adjust and balance the electronic measuring system as necessary.

11.7 Apply sinusoidal (haversine) loading ($P_{dynamic}$) to the specimen in a cyclic manner. The dynamic load should be adjusted to obtain axial strains between 50 and 150 microstrain.

Note 6 – The dynamic load depends upon the specimen stiffness and generally ranges between 15 and 2800 kPa (2 and 400 psi). Higher load is needed at colder temperatures. Table 4 presents typical dynamic stress levels based on temperature.

Table 4 - Typical Dynamic Stress Levels

Temperature, ^oC (^oF)	Range, kPa	Range, psi
-10 (14)	1400 - 2800	200 - 400
4.4 (40)	700 - 1400	100 - 200
21.1 (70)	350 - 700	50 - 100
37.8 (100)	140 - 250	20 - 50
54.4 (130)	35 - 70	5 - 10

11.8 Test the specimens from lowest to highest temperature; that is from -10 ^oC (14 ^oF) to 54.4 ^oC (130 ^oF). At each temperature apply the loading from highest to lowest frequency; that is from 25 Hz to 0.1 Hz. At the beginning of testing, precondition the specimen with 200 cycles at 25 Hz. Then load the specimen as specified in Table 5. A typical rest time period between each frequency run is 2 minutes. This rest period shall not exceed 30 minutes for any two-frequency runs.

Table 5 - 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

11.9 At the end of any testing period, if the cumulative un-recovered deformation was found to be greater than 1500 micro units of strain, keep the test data up to this last testing period and discard the specimen. Use a new specimen for the rest of the testing periods. The loading stress level should be reduced by fifty percent.

12. Calculations

12.1 Determine the average amplitude of the sinusoidal load from the load cell and deformation measured from each axial LVDT over the last 5 loading cycles for each test condition.

12.2 Determine the average lag time (t_i) between the peak load and the peak deformation from each LVDT over the last 5 loading cycles for each test condition.

Note 7 – Different approaches are available to determine these. The approach is highly dependent upon the number of data points collected per cycle. Approaches that have been used include peak search algorithms, various curve fitting techniques, and Fourier Transform

12.3 Over the last 5 loading cycles and for each test condition, calculate the loading stress, σ_o, as follows:

$$\sigma_o = \frac{\overline{P}}{A}$$

Where:

$\overline{P}$ = average peak load
A = area of specimen
σ_o = average peak stress.

12.4 Over the last 5 loading cycles and for each test condition, calculate the recoverable axial strain individually for each LVDT, ε_o , as follows:

$$\varepsilon_o = \frac{\overline{\Delta}}{GL}$$

Where:

$\overline{\Delta}$ = average peak deformation
GL = gauge length
ε_o = average peak strain

12.5 Over the last 5 loading cycles and for each test condition, calculate the dynamic modulus, |E*| individually for each LVDT as follows:

$$Dynamic\ Modulus, |E^*| = \frac{\sigma_o}{\varepsilon_o}$$

12.6 Over the last 5 loading cycles and for each test condition, calculate the phase angle individually for each LVDT:

$$\phi = \frac{t_i}{t_p} * (360)$$

Where:

t_i = average lag time between a cycle of stress and a cycle of strain (sec)
t_p = average time for a stress cycle (sec)

13. Master Curve Development

13.1 The mechanical behavior of viscoelastic materials such as asphalt mixtures is dependent on the temperature and time of load (frequency) at which the material is tested. In order to compare test results of various mixes, it is important to normalize one of these variables. Data collected at different temperatures can be "shifted" relative to the time of loading, so that the various curves can be aligned to form a single *master curve*.

13.2 The shift factor, a(T), defines the required shift (as log of time) at a given temperature, i.e., a constant by which the loading times must be divided to get a reduced time, t_r, for the master curve:

$$t_r = \frac{t}{a(T)}$$

Where:

t_r = reduced time, time of loading at the reference temperature
t = time of loading , the reciprocal of the loading frequency
$a(T)$ = shift factor as a function of temperature
T = temperature

The master curve development can be found in numerous documents on pavement materials characterization. The concept is illustrated in Figure 4, which presents the shifting of laboratory measured dynamic modulus test data to the reference temperature T_0 of 21.1 C (70F). A sigmoidal fitting function is used to construct the master curve.

13.3 Using the shift factors, the master curve can be constructed using a selected reference temperature of 70F to which all data are shifted.

13.4 Various computer programs can be used to define relationships with a(T) and temperature. One method is to use the numerical optimization (Solver) provided in the Microsoft Excel program.

13.5 Different functions are used to mathematically model the material response and create the master curve for asphalt mixtures. For time or frequency dependency, the generalized power law is most widely accepted at low to intermediate temperatures. As higher temperature data is included, a polynomial and sigmoidal functions have been used. Caution should be exercised when employing polynomial fitting functions due to the polynomial swing in low and high temperatures, when extrapolating outside the range of data. The generalized power law and sigmoidal functions will approach asymptotically the limiting stiffness values, thus, allowing the prediction outside the measured range of data.

14. Report

14.1 For each individual LVDT report the dynamic modulus ($|E^*|$) and phase angle (ϕ) for each temperature-frequency combination tested.

14.2 Report the average peak stress (σ_o) and strain (ε_o) for each temperature-frequency combination tested.

14.3 Report, for each temperature-frequency combination tested, the dynamic modulus and phase angle for each replicate test specimen along with the average, standard deviation and coefficient of variation of the three replicates.

14.4 In addition, report the dynamic modulus replicate results in a format compatible with Table 6. This is the format of data entry required for the computer program "Asphalt Pavement Analysis and Design System" (APADS) that was developed under the 2002 Design Guide for the design of new and rehabilitated pavement structures.

14.5 Report the constructed master curve.

Table 6 - Required Input Data for APADS 2002.

Temperature, F	Replicate	Mixture |E*|, psi (or MPa) @ Frequency Noted					
		0.1	0.5	1	5	10	25
14	1						
	2						
	3						
	4						
40	1						
	2						
	3						
	4						
70	1						
	2						
	3						
	4						
100	1						
	2						
	3						
	4						
130	1						
	2						
	3						
	4						

Figure 1 - General Schematic of Dynamic Modulus Test.

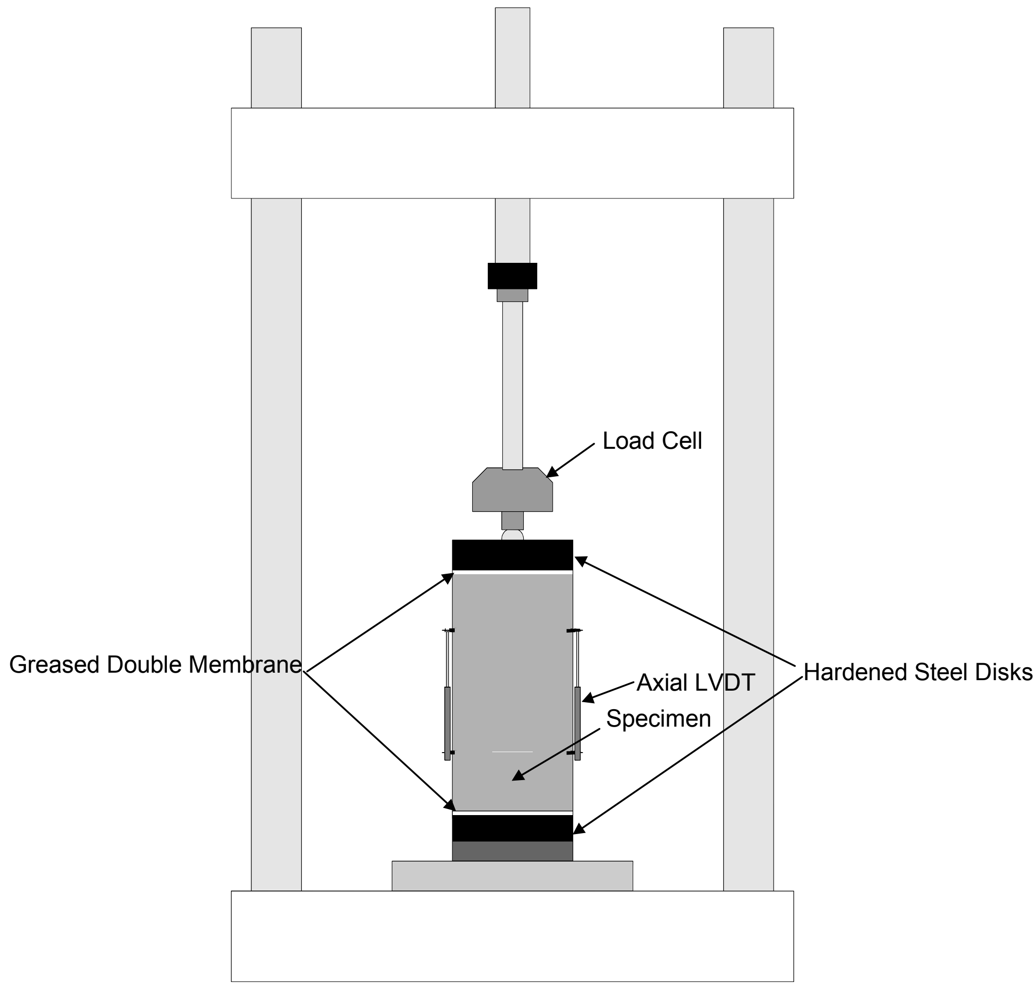


Figure 2 - General Schematic of Gauge Points (*Not to scale*).

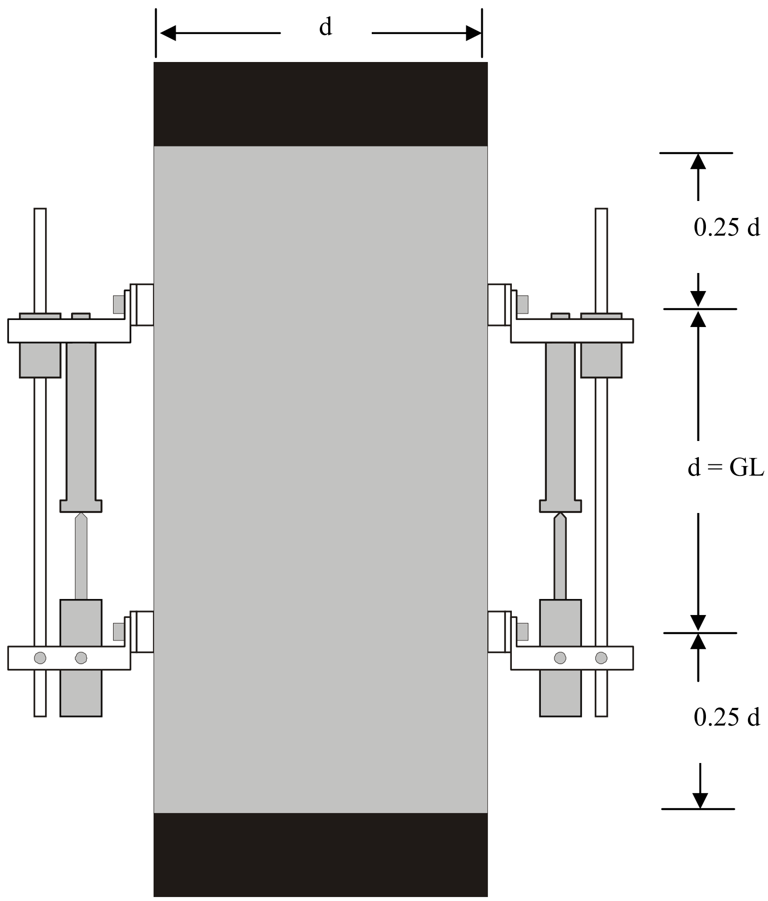


Figure 3 - Mounting Hardware Details
(See Attachment A for drawings details)

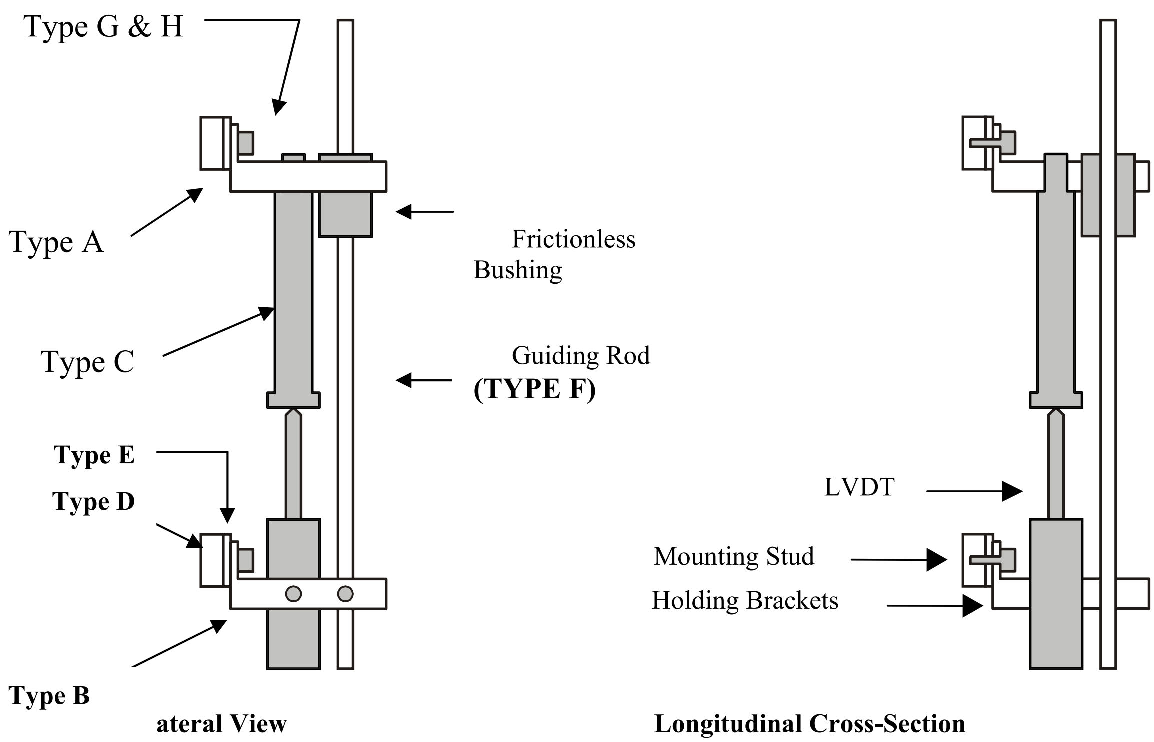
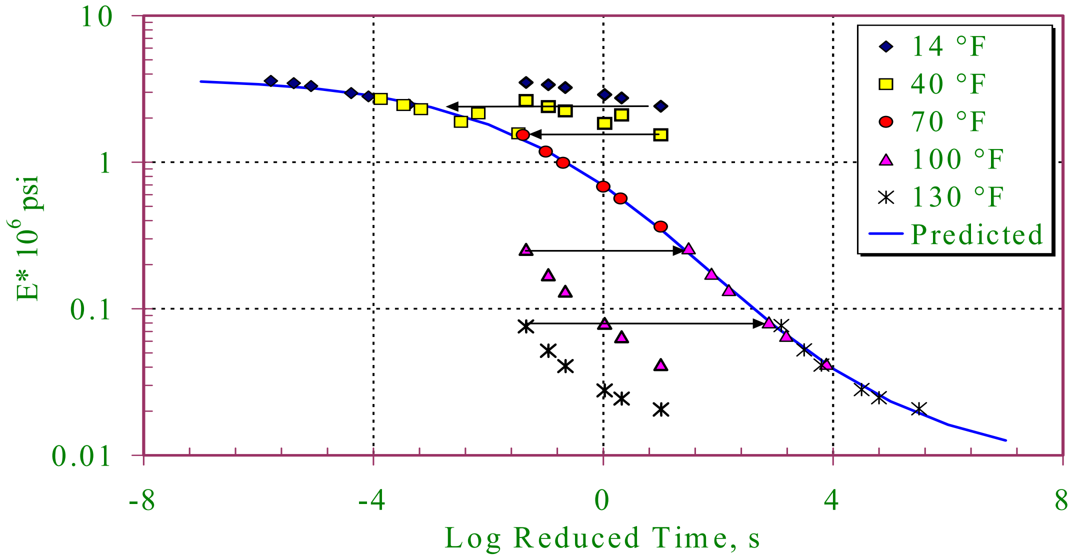
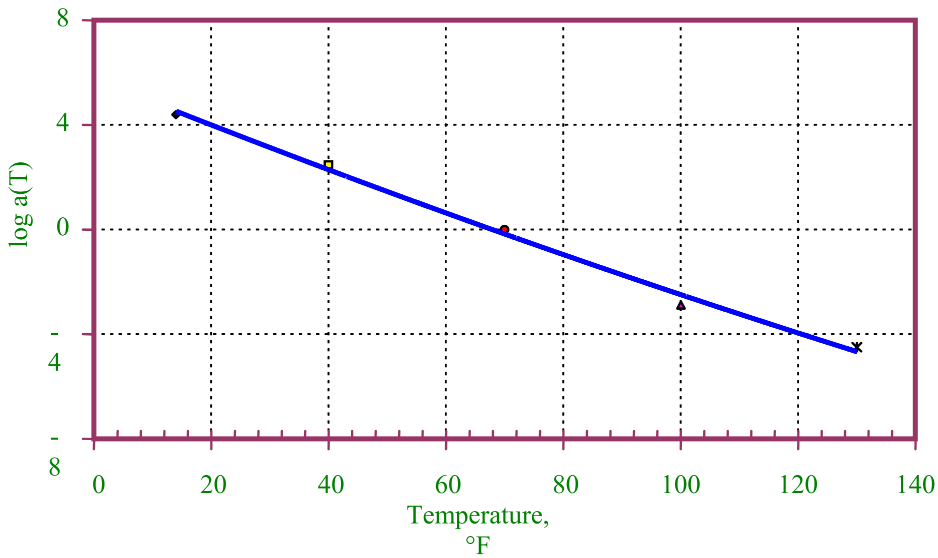


Figure 4 - Example of Master Curve Construction





ATTACHMENT A

LIST OF LVDT BRACKETS DETAILS USED BY ARIZONA STATE UNIVERSITY

LIST OF DRAWING ITEMS

- Type A Aluminum Bracket*
- Type B Aluminum Bracket*
- Type C Aluminum Bracket*
- Type D Brass Button
- Type E Brass Ring
- Type F Steel Bar
- Type G Screw (4-40 x ¼ cap screw)
- Type H Screw (4-40 x ¼ cap screw)
- Plastic Washer (4-40 plastic Washers)
- Super Ball Bushing Bearing, diameter 0.188 in, length 0.562 in**

<u>NOTES</u>

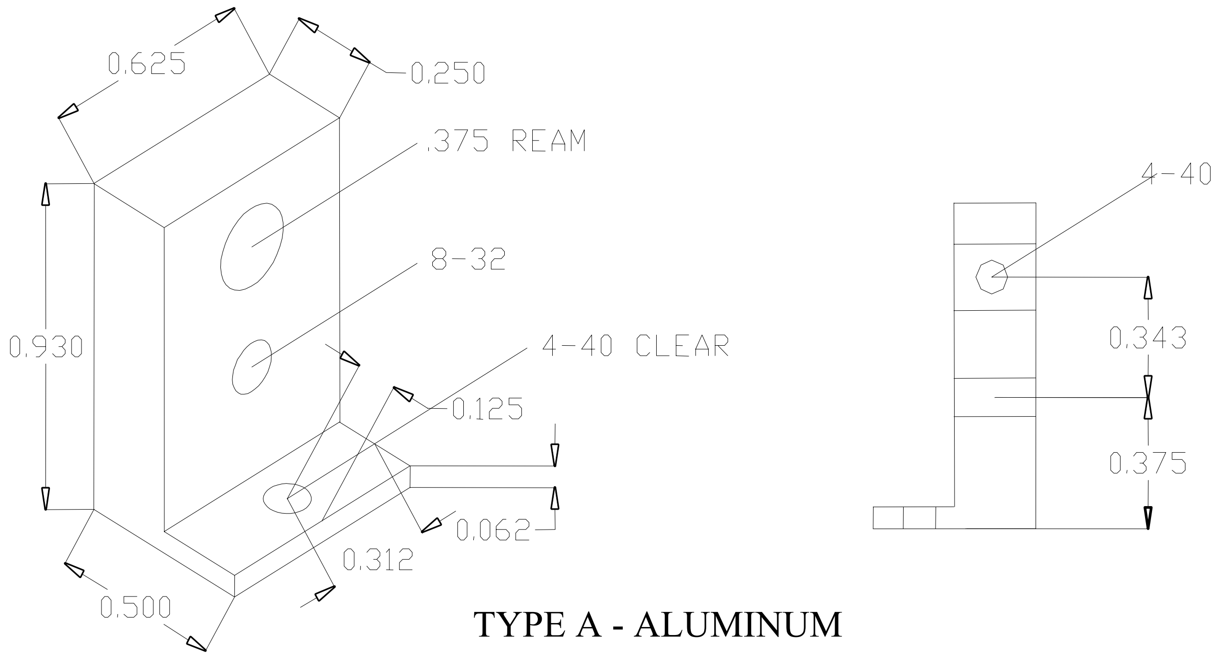
* Half of the screw holes are mirror images

** Bushing information

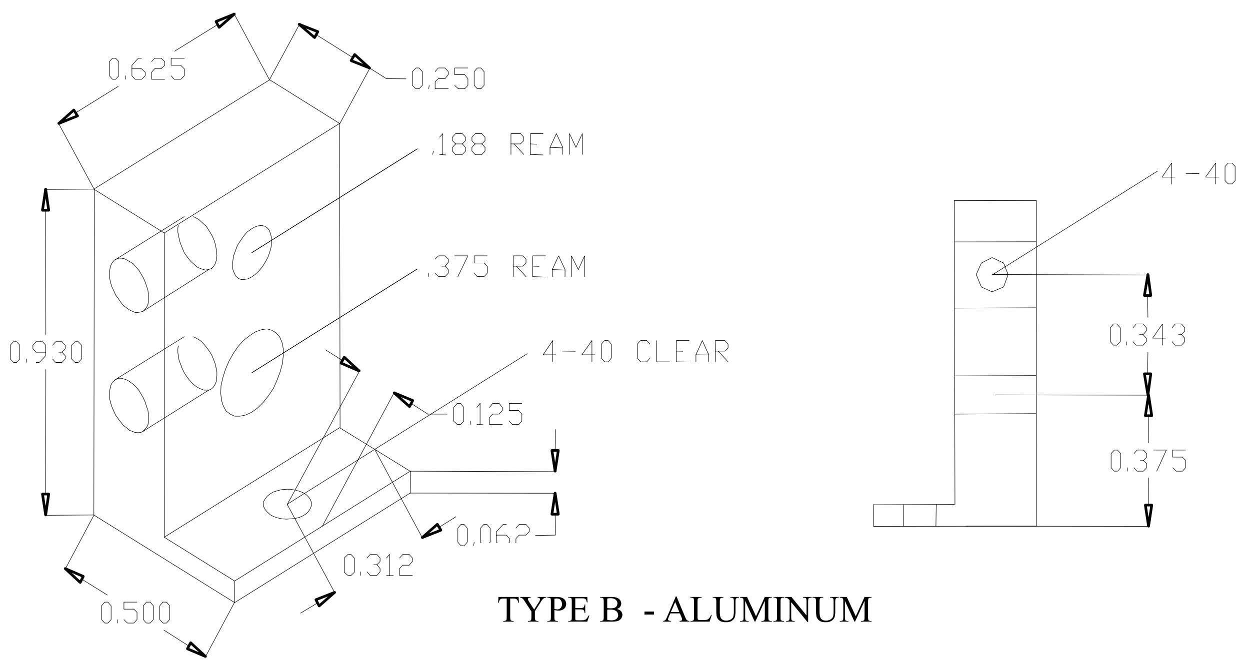
Description: Super Ball Bushing Bearing
Nominal Diameter: 0.188 in
Length: 0.562 in

Supplier: *MSC Industrial Supply Co*
555 W. Hoover, Suite #4
Mesa AZ 85210
Tel: 480-9641-500
1-888-203-5226, 1-800-645-7270

Catalog Number: 35-5-28009

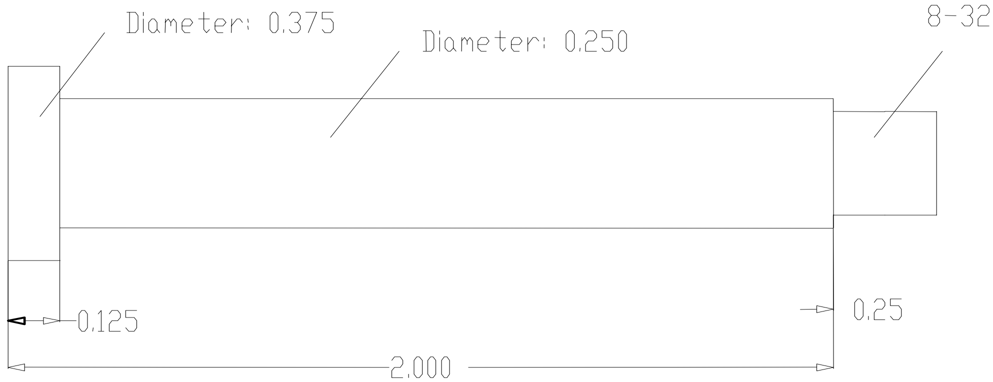


TYPE A - ALUMINUM

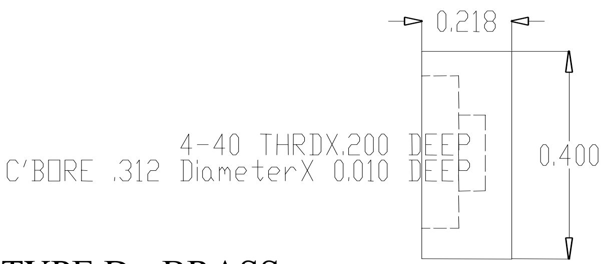


TYPE B - ALUMINUM

** All Units are in Inches*

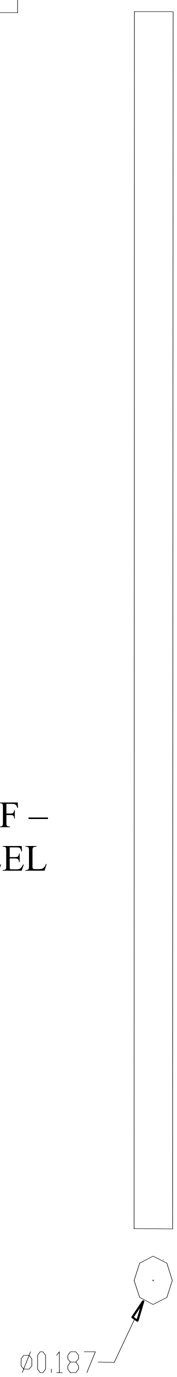


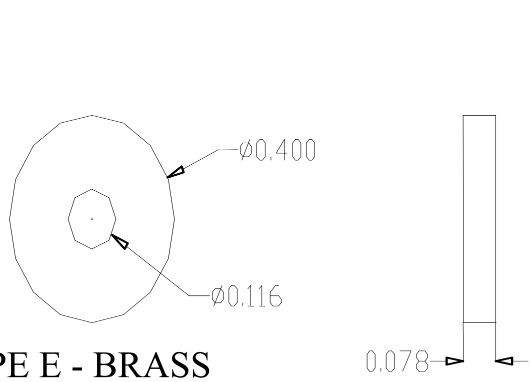
TYPE C - ALUMINUM



TYPE D - BRASS

TYPE F – STEEL





TYPE E - BRASS

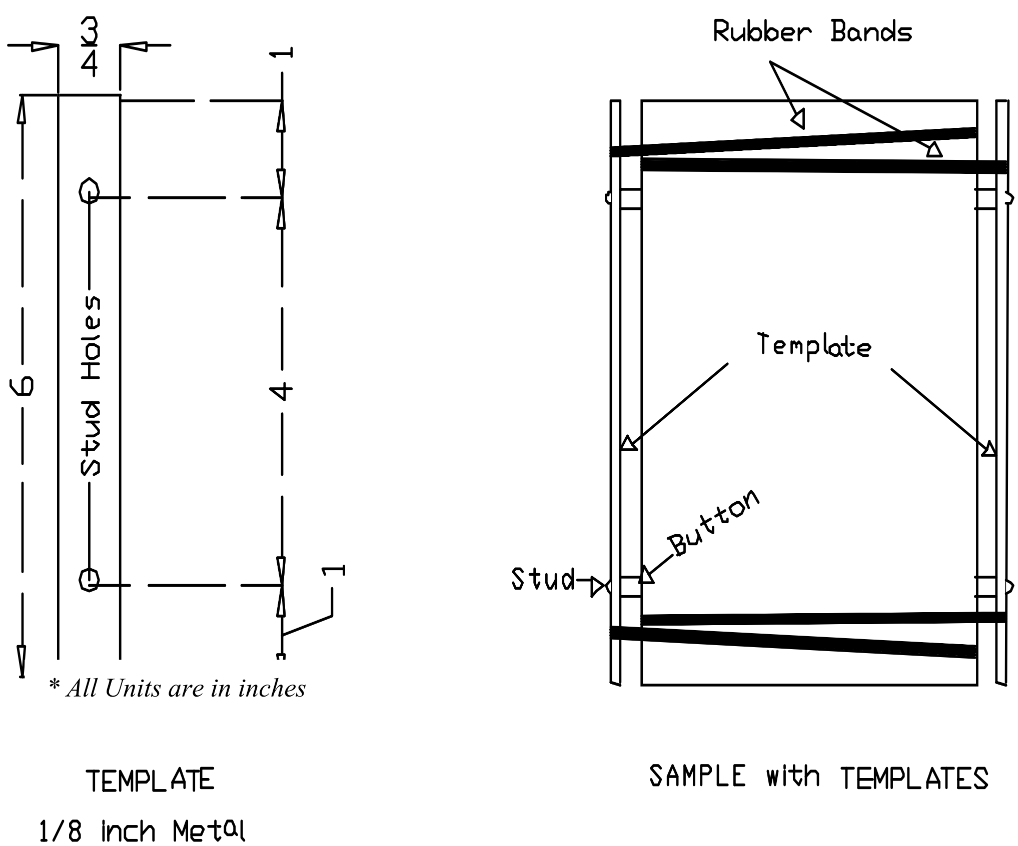
** All Units are in Inches*

ATTACHMENT B

TEMPLATE FOR LOCATING MOUNTING PLUGS WHEN USING LVDT

The spacing and parallelism of the glued buttons is important when using the LVDT's. The figure below shows a simple flat metal bar with holes for the studs that hold the brackets. The bar must be flat and the holes exactly 101.6 mm (4 in) apart (25.4 mm (1 in) form each end). The holes should fit the studs closely. The mounting buttons are screwed to the bar and epoxy glue put on the buttons. Each bar is then lined up with an axial line on the specimen and two rubber bands put around as shown in Figure B-1. Keeping the rubber bands near the ends of the specimen permits applying all bars without waiting for glue to dry.

Figure B-1 - Template for Locating LVDT Mounting Buttons.



APPENDIX 3

EXAMPLE EXCEL SPREADSHEET

For

E* MASTER CURVE

Instructions for use of an Excel Spreadsheet to develop a Master Curve.

- The green columns, in both the mix data and binder data sheets, are the input cells.

- Use the "Excel Solver" in the mix data sheet to minimize the sum of error^2.

- Do this at least twice to prepare a Master Curve.

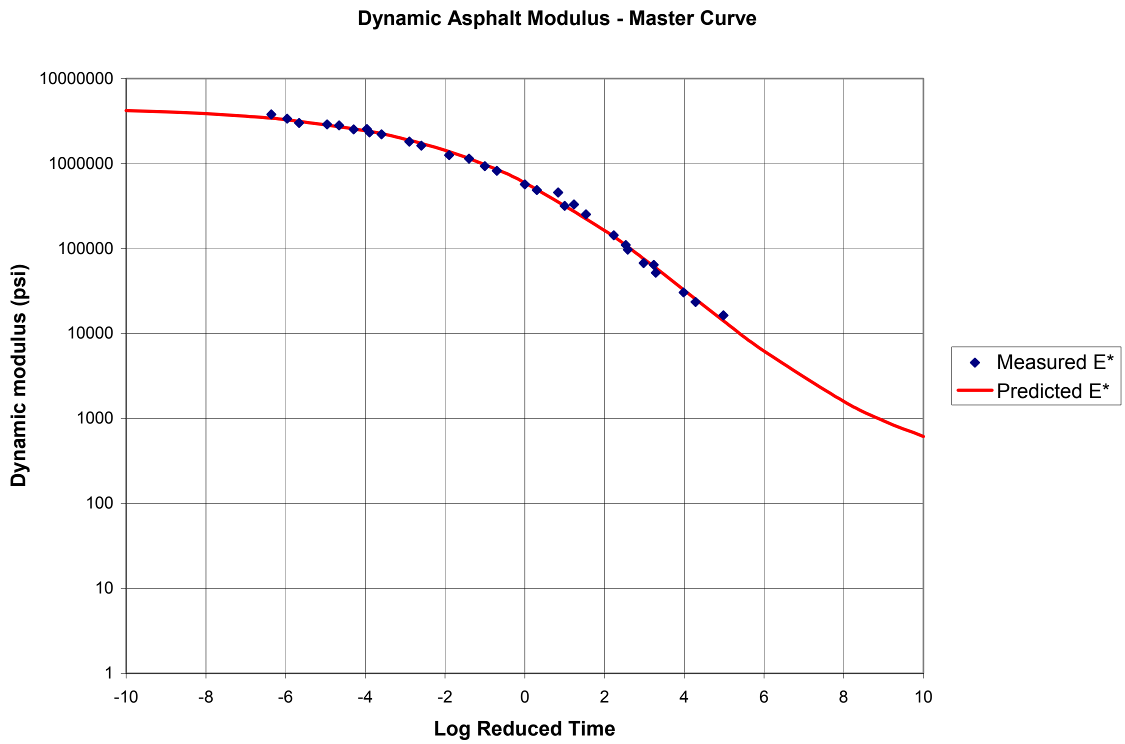
Reference Temperature F =	70

Sum of Error^2 =	3.732E-02

Temp. °F	Frequency Hz	E* psi	Viscosity (cpoise)	Reduced T	Log EMeasured	Epredicted (psi)	Log EPredicted	Error^2
10	0.1	2540000	2.700E+12	-3.9598	6.4048	2415272	6.3830	4.782E-04
10	0.5	2810000	2.700E+12	-4.6587	6.4487	2741342	6.4380	1.154E-04
10	1	2890000	2.700E+12	-4.9598	6.4609	2873135	6.4584	6.461E-06
10	5	3000000	2.700E+12	-5.6587	6.4771	3155927	6.4991	4.843E-04
10	10	3360000	2.700E+12	-5.9598	6.5263	3267166	6.5142	1.481E-04
10	25	3780000	2.700E+12	-6.3577	6.5775	3404268	6.5320	2.067E-03
40	0.1	1250000	9.222E+10	-1.8947	6.0969	1380397	6.1400	1.857E-03
40	0.5	1620000	9.222E+10	-2.5936	6.2095	1729209	6.2378	8.027E-04
40	1	1810000	9.222E+10	-2.8947	6.2577	1882382	6.2747	2.900E-04
40	5	2210000	9.222E+10	-3.5936	6.3444	2235461	6.3494	2.475E-05
40	10	2320000	9.222E+10	-3.8947	6.3655	2383670	6.3772	1.383E-04
40	25	2520000	9.222E+10	-4.2926	6.4014	2573734	6.4106	8.396E-05
70	0.1	317000	8.114E+08	1.0000	5.5011	327432	5.5151	1.977E-04
70	0.5	487000	8.114E+08	0.3010	5.6875	502505	5.7011	1.853E-04
70	1	569000	8.114E+08	0.0000	5.7551	594603	5.7742	3.654E-04
70	5	821000	8.114E+08	-0.6990	5.9143	846539	5.9276	1.770E-04
70	10	933000	8.114E+08	-1.0000	5.9699	970223	5.9869	2.887E-04
70	25	1140000	8.114E+08	-1.3979	6.0569	1145754	6.0591	4.781E-06
100	0.1	63900	2.100E+07	3.2347	4.8055	61287	4.7874	3.287E-04
100	0.5	110000	2.100E+07	2.5357	5.0414	107857	5.0328	7.298E-05
100	1	143000	2.100E+07	2.2347	5.1553	136261	5.1344	4.395E-04
100	5	252000	2.100E+07	1.5357	5.4014	227822	5.3576	1.919E-03
100	10	329000	2.100E+07	1.2347	5.5172	280319	5.4477	4.836E-03
100	25	455000	2.100E+07	0.8368	5.6580	363566	5.5606	9.492E-03
130	0.1	16300	1.202E+06	4.9841	4.2122	14076	4.1485	4.057E-03
130	0.5	23500	1.202E+06	4.2851	4.3711	25339	4.4038	1.070E-03
130	1	30300	1.202E+06	3.9841	4.4814	32695	4.5145	1.091E-03
130	5	51700	1.202E+06	3.2851	4.7135	58782	4.7692	3.109E-03
130	10	67400	1.202E+06	2.9841	4.8287	75289	4.8767	2.311E-03
130	25	96800	1.202E+06	2.5861	4.9859	103650	5.0156	8.818E-04

Equation Coefficients					
delta	alpha	beta	gamma	C	Reference Viscosity
2.2278	4.4351	-1.3839	0.3317	1.4082	8.114E+08

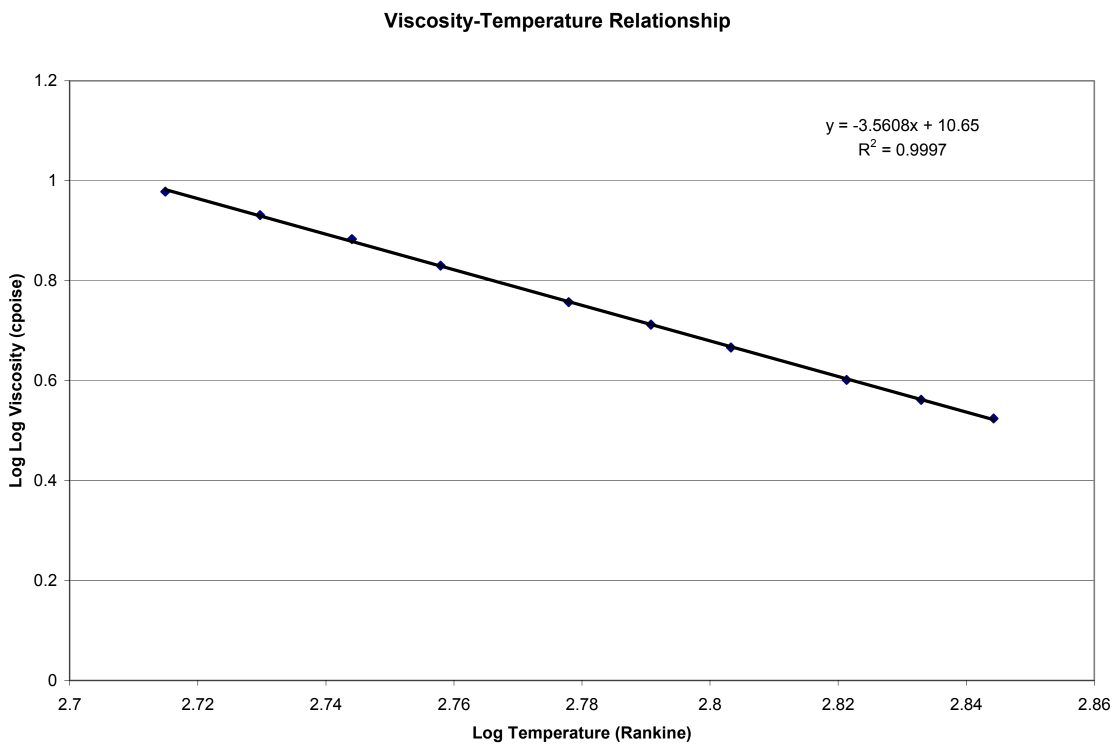
reduced	log E
-10	4197545.4
-9	4050273.4
-8	3855258.8
-7	3601970.2
-6	3281539.5
-4	2434700
-3	1936020.4
-2	1431889.9
-1	970222.99
0	594602.85
2	162700.91
3	74318.31
4	32257.27
5	13891.352
6	6207.4615
8	1586.3371
9	937.32479
10	614.29854



Binder Data

VTS =	-3.5608
A =	10.6495

Temperature (F)	G* (psi)	δ	Temperature (Rankine))	Viscosity (cpoise)	Log Temperature (Rankine)	Log log Viscosity (cpoise)
59	8700000	49.83	518.7	1.07E+11	2.7149	9.78E-01
77	1700000	59.98	536.7	1.37E+11	2.7297	9.31E-01
95	300000	67.64	554.7	1.78E+11	2.7441	8.83E-01
113	48000	74.06	572.7	2.42E+11	2.7579	8.30E-01
140	4900	81.75	599.7	3.82E+11	2.7779	7.57E-01
158	1400	85.34	617.7	5.16E+11	2.7908	7.12E-01
176	430	87.62	635.7	7.17E+11	2.8033	6.66E-01
203	98	89.44	662.7	1.19E+12	2.8213	6.01E-01
221	44	89.48	680.7	1.66E+12	2.8330	5.62E-01
239	22	89.6	698.7	2.33E+12	2.8443	5.24E-01


Viscosity-Temperature Relationship
y = -3.5608x + 10.65
R2 = 0.9997
1.2
1
0.8
0.6
0.4
0.2
0
2.7
2.72
2.74
2.76
2.78
2.8
2.82
2.84
2.86
Log Log Viscosity (cpoise)
Log Temperature (Rankine)