EVALUATION OF DYNAMIC MODULUS VALUES OF OKLAHOMA MIXES

By

SUMESH KC

Bachelor in Engineering/Civil Engineering

Institute of Engineering

Pulchowk, Lalitpur

2004

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December 2007

EVALUATION OF DYNAMIC MODULUS VALUES OF OKLAHOMA MIXES

Thesis Approved:

Dr. Stephen A. Cross
Thesis Adviser

Dr. Hyungseok (David) Jeong
Committee Member

Dr. Rifat Bulut
Committee Member

Dr. A. Gordon Emslie
Dean of the Graduate College

TABLE OF CONTENTS

Chapter Page

II. LITERATURE REVIEW

III.TEST PLAN

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

GENERAL PROBLEM STATEMENT

In 1996, the National Cooperative Highway Research Program (NCHRP) and the Federal Highway Administration (FHWA) decided to start working on development of a new mechanistic-empirical design procedure. They designed a project called NCHRP Project 1-37 A, development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures. The contract was awarded to the ERES Consultants Division of Applied Research Associates, Inc in February 1998 (1). Delivery of the final product was delayed; however, all work is now complete and agencies are working to develop the material input parameters necessary for use in the 2002 Design Guide or the Mechanistic-Empirical Pavement Design Guide (M-EPDG) as it is now called.

One of the major differences between the M-EPDG and the previous Design Guides is material characterization. In the 1972 version of the design guide asphalt mixtures were assigned an ‘a’ coefficient which, along with the thickness of the layer, was used to calculate the structures number of a pavement. In later versions, mixtures were assigned an ‘a’ coefficient based on resilient modulus. The test was rarely performed and ‘a’ coefficients were typically assigned for a mix type by an agency.

The M-EPDG uses the elastic properties of dynamic modulus and Poisson's ratio as two of the materials characterization parameters for asphalt mixtures. The procedure is contained in American Association of State Highway and Transportation Officials (AASHTO) specification number TP62-03. The Test is performed at different temperatures, stress levels and loading frequencies (1,2).

The M-EPDG uses a hierarchical approach with three levels of materials characterization. The first level of material characterization provides the highest design reliability. Each succeeding level is a drop in design reliability. The first or highest level entails measured dynamic modulus and Poisson's ratio for each asphalt mix used in the design. The second and third levels of material characterization entail the use of default master curves. The default master curves are developed from predictive equations developed by the NCHRP 1-37 A research team lead by Dr. Matthew W. Witczak. The predictive equations are based on mixture properties of bitumen viscosity, air void content, effective bitumen content and aggregate gradation. A level 2 analysis entails thorough mixture characterization of each asphalt mix whereas a level 3 design uses default or typical mixture characterization values (1, 3, 4, and 5).

RESEARCH OBJECTIVES

The primary objective of this study was to evaluate the dynamic modulus of Oklahoma hot mix asphalt (HMA) mixtures and to determine if mix type, aggregate source and binder grade had a significant effect on dynamic modulus values at 95% confidence level.

The secondary objective was to determine shift factor and develop a master curve for each mix to demonstrate the effect of loading rate and temperature on the mix.

SCOPE

Cold feed belt samples of S3 and S4 mixtures were sampled throughout the state. Mixtures were selected to include the major aggregate types in Oklahoma and to cover each region of the state. Replicate samples were tested for Dynamic Modulus |E*| at optimum asphalt content with three grades of binders; PG 64-22, PG 70-28 and PG 76-28, the commonly used binder grades in Oklahoma.

CHAPTER II

LITERATURE REVIEW

BACKGROUND

The American Association of State Highway and Transportation Officials (AASHTO) was formed in December 12, 1914. They have produced various editions of the AASHTO Guide for Design of Pavement Structures. The original 1972 interim Design Guides had numerous shortcomings and limitations in various areas. These areas included traffic loading, climatic effect, surface materials, truck characterization and design life (1). Before the 1986 AASHTO Design Guide, designs of pavements were based on empirical performance equations. Most of these came from the AASHO Road Test conducted near Ottawa, Illinois in the late 1950's (1). These empirical equations also failed to account for load changes, changes in materials and design features and also the effect of climate on performance. The necessity of a new design procedure which could address all the short coming was always felt.

The AASHTO Guide for Design of Pavement Structures was introduced in 1986 and it showed the need for and benefits of a mechanistically based pavement design procedure. However, after only 10 years of use, the AASHTO Joint Task Force on Pavements, in cooperation with the National Corporation of Highway Research Program (NCHRP) and

Federal Highway Administration (FHWA), sponsored a "Workshop on Pavement Design" in March 1996 at Irvine, California (1). Based on the conclusions developed at the March 1996 meeting, NCHRP Project 1-37A, development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures was developed and awarded to ERES Consultants Division of Applied Research Associates, Inc. in February 1998. The project was responsible for development of a new mechanistic approach to pavement design which could address all the shortcoming of the previous design guides (1).

According to M-EPDG (1), the design guide was developed to provide the highway community with a state-of-the-practice tool for design of new and rehabilitated pavement structures. The mechanistic-empirical (M-E) format of the Design Guide provides a framework for future continuous improvement to keep up with changes in trucking, materials, construction, design concepts, computers and so on. In addition, guidelines for implementation and staff training have been prepared to facilitate use of the new design procedure as well as strategies to maximize acceptance by the transportation community. The final product is design software and a user guide.

GENERAL INPUT REQUIREMENTS

The M-EPDG consists of a comprehensive pavement design procedure that uses mechanistic-empirical technologies (1,3,4,5,6 and 7). It employs common design parameters for traffic, subgrade, environment, and reliability for all pavement types as well as some new parameters necessary for the design of pavements. Software was developed for the designer to be user friendly and it contains a help section to help new

users . M-EPDG software is temporarily available on the web for trial use which can be downloaded from www.trb.org/mepdg (1). The software is a computational software package and contains documentation based on the Design Guide procedure.
According to M-EPDG (1), the input parameters for the M-EPDG are grouped into five areas: project information, design information, traffic loadings, climatic data and structural data. The structural data is separated into two sections, one on structural layers and one on thermal cracking. The MEPDG uses the elastic properties of dynamic modulus and Poisson's ratio as the materials characterization parameters for asphalt mixtures. Asphalt mixtures are considered to be linearly-viscoelastic materials (2,9,10). Dynamic modulus is used as an input to compute stress, strain, rutting and cracking damage in flexible pavement (10). The dynamic modulus of a mix is affected by the mix characteristics, rate of loading, and local environmental conditions (11).

MEPDG incorporates a hierarchical approach for specifying all pavement design inputs. The hierarchical approach is based on the philosophy that the level of engineering effort exerted in determining design inputs should be consistent with the relative importance, size and cost of the design project (12). The guide has 3 different levels of analysis, depending on the importance of the pavement structure in question. Dynamic modulus testing is required for level 1 analysis. The level 2 and level 3 pavement analyses requires no laboratory test data. The Witczak predictive modulus equation is used with typical temperature-viscosity relationships established for all binder grades to calculate dynamic modulus values (1,3 and 4).

VISCO-ELASTIC MATERIALS

According to Meyers et al. (13), viscoelastic materials are those materials that exhibit both viscous and elastic characteristics when undergoing plastic deformation. Viscous materials resist shear flow and strain linearly with time when a stress is applied. Elastic materials regain their original state after the load is removed. Viscoelastic materials have elements of both of these properties and exhibit time dependent strain. So, a viscoelastic substance will have an elastic component and a viscous component (14 and 15). The viscosity of a viscoelastic substance gives the substance a strain rate dependent on time. A viscoelastic substance loses energy when a load is applied and then removed (13). Linear viscoelasticity is usually applicable only for small deformations . In linear viscoelastic materials, dynamic modulus is independent of stress or strain amplitude (13).

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 $|E^*|$ (6 and 7). 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. According to Charles W. Schwartz (8), when a continuous uniaxial sinusoidal (haversine) compressive stress is applied to an unconfined or confined viscoelastic cylindrical test specimen, the stress-to-strain relationship for linear viscoelastic is defined by a complex number called the complex modulus E^*. The term ‘complex’ modulus is based on the fact that E^* is a complex number consisting of both real and imaginary component:

$|E^*| = E_1 + iE_2$

in which i=√-1, E_1 is the storage modulus, and E_2 is the loss modulus, The dynamic modulus E* is defined as the magnitude of |E*|:

$|E^*|=(E_1^2+E_2^2)^{1/2}$

According to Nam H. Tran and Kevin D. Hall (6), the absolute value of the complex modulus |E*| is defined as the dynamic modulus. The complex modulus |E*| is a fundamental measure of the stiffness of a linearly viscoleastic material. The complex modulus is defined as the ratio of the amplitude of the sinusoidal stress $\delta = \delta_o \sin(\omega t)$ at any given time, t, and the angular load frequency, ω, and the amplitude of the sinusoidal strain $\varepsilon = \varepsilon_o \sin(\omega t - \phi)$, at the same time and frequency, that results in a steady state response:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_\circ e^{i\omega t}}{\varepsilon_\circ^{\,i(\omega t-\phi)}} = \frac{\sigma_\circ \sin \omega t}{\varepsilon_\circ \sin(\omega t - \phi)}$$

Where, σ_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 (7)

$$|E^*| = \frac{\sigma_\circ}{\varepsilon_\circ}$$

σ_o : Peak Stress

ε_o : Recoverable Peak Strain

The dynamic modulus of asphalt concrete is strongly dependent upon temperature (T) and loading rate, defined either in terms of frequency (f) or load time (t) (7). The combined effects of temperature and loading rate can be represented using time-temperature superposition concepts in the form of a ‘master’ curve relating |E*| to a ‘reduced frequency F_r defined as:

$$F_r = \frac{f}{aT}$$

In which f is the actual loading frequency and aT is a temperature shift factor. The |E*| vs F_r master curve and aT vs T temperature shift relation fully describes the loading rate and temperature dependence of asphalt concrete under small strain (<100 $\mu\varepsilon$) linear viscoelastic conditions (17).

WITCZAK DYNAMIC MODULUS (E*) PREDICTION MODEL

According to the M-EPDG (1), the predictive equation developed by Witczak et al. is one of the most comprehensive mixture dynamic modulus models available today, with the capability to predict the dynamic modulus of dense-graded HMA mixtures over a range of temperatures, rates of loading, and aging conditions from information that is readily available from conventional binder tests and the volumetric properties of the HMA mixture.

Witczak’s predictive equation describes the relationship between dynamic modulus and mixture properties. The model is a purely empirical regression model developed from a large database of over 2700 laboratory test measurements of |E*| developed over a 30 year period (6).

The input parameters of the Witczak predictive models are gradation of the mix, air void content, loading frequency, bitumen viscosity and effective bitumen content. The equation for predicting the dynamic modulus |E*| for HMA as developed by Witczak for implementation in the NCHRP 1-37 A Pavement Design Guide is as follows (4):

$$\log|E^*|=3.750063+0.029232.\rho_{200}-0.001767.\left(\rho_{200}\right)^2-0.002841.\rho_4-0.058097.v_a -0.802208.\left(\frac{v_{beff}}{v_{beff+v_a}}\right)+\frac{3.871977-0.0021.\rho_4+0.003958.\rho_{38}-0.000017.\left(\rho_{38}\right)^2+0.005470.\rho_{34}}{1+e^{\left(-0.603313-0.313351.\log(f)-0.393532.\log(\eta)\right)}}$$

E*= dynamic modulus (psi)

η =bitumen viscosity (10^6 poise)

f =loading frequency (Hz)

v_a =air void

v_{beff} = effective bitumen content (% by volume)

ρ_{34}=cumulative % retained on the 19-mm sieve

ρ_{38}=cumulative % retained on the 19-mm sieve

ρ_4=cumulative % retained on the 19-mm sieve

ρ_{200}=cumulative % retained on the 19-mm sieve (6).

MASTER CURVES

According to the M-EPDG (1), a master curve allows varying dynamic moduli values to be used as temperature and loading rates change. Levels 2 and 3 materials characterization uses the prediction equation to create master curves where as Level 1 uses actual mix and binder properties. To develop a master curve, a standard reference temperature is selected and then data at various temperatures are shifted with respect to time until the curves merge into a single smooth function (1 and 7).

The temperature dependency of the material is described by the amount of shifting at each temperature required to form the master curve. So, both the master curve and the shift factors are needed to demonstrate the rate and temperature effects. The dynamic modulus master curve can be represented by the sigmoidal function described by equation:

$$\text{Log } |E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}}$$

Where,

E^*= Dynamic modulus

t_r= time of loading at the reference temperature

δ,α=fitting parameters, for a given set of data, δ represents the minimum value of E^* and $\delta+\alpha$ represents the maximum value of $|E^*|$.

β,γ= parameters describing the shape of the sigmoidal function.

The fitting parameters δ and α depend on aggregate gradation, binder content and air void content . The fitting parameters β and γ depend on the characteristics of the asphalt binder and the magnitude of δ and α (7).

The sigmoidal function describes the time dependency of the modulus at the reference temperature. The shift factors describe the temperature dependency of the modulus. The general equation of the shift factors is:

$$T_r = \frac{t}{aT}$$

$$\text{Log}(T_r) = \log(t) - \log(a(T))$$

Where,
T_r= time of loading at the reference temperature

T = time of loading at a given temperature of interest

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

t= temperature of interest.

By use of the above equation, the time of loading at the reference temperature can be calculated for any time of loading at any temperature. Then the appropriate modulus can be calculated from the Log E* equation using the time of loading at the reference temperature (7).

EFFECT OF MIXTURE VARIABLES ON DYNAMIC MODULUS

M-EPDG considers dynamic modulus as one of the most important material properties in the design of pavements. Many state Department of Transportations (DOT) have carried out research to determine the sensitivity of this modulus to different mix designs. In 2004, Mark King, Mostafa Momen and Y. Richard Kim (3) studied the effect of mixture variables on dynamic modulus for different North Carolina mixes. They prepared mixes that varied with aggregate source and gradation, binder source, binder PG grade and asphalt content. Masters curves for each mix were prepared based on the measured dynamic modulus values provided by North Carolina DOT. The results were compared with the other mixes. The result of the study showed that binder source, binder PG grade and asphalt content had an affect on dynamic modulus. However, aggregate source and gradation, within the same NCDOT Superpave classification; did not seem to have a significant effect on dynamic modulus.

Similar research was carried out by Tran and Hall (4) to evaluate the sensitivity of dynamic modulus values of Arkansas mixes. The result showed that aggregate size had a significant effect. However, the aggregate size they compared were 25.0 mm and 12.5 mm but they did not test for 19.0 mm mix. The results also showed that specimens compacted at 4.5% air void would give significantly different dynamic modulus values then specimens compacted at 7% air voids. Results also showed a significant difference in the modulus value when the asphalt contents varied by 0.5%. Predicted dynamic modulus values using the Witzack predictive equation and measured dynamic modulus values for the Arkansas mixes were not significantly different. This showed that the Witzacks predictive equation could be used to estimate dynamic modulus values for the Arkansas mixes.

Shah, McDaniel and Gallivan (9) evaluated HMA mixes for E* from several states. Their results showed that Wisconsin mixes made with different PG binder grades,58-28 and 70-28, would give significantly different dynamic modulus values. For Minnesota mixes, Superpave mixtures produced significantly different dynamic modulus values than Marshall mixtures. Dynamic modulus values for the conventional mixtures were lower than the values for the stone mastic asphalt (SMA) mixtures.

CHAPTER III

TEST PLAN

INTRODUCTION

The primary objective of this study was to evaluate the dynamic modulus of Oklahoma hot mix asphalt (HMA) mixtures and to determine if mix type, aggregate source and binder grade had a significant effect on dynamic modulus values at 95% confidence level. The secondary objective was to determine shift factor and develop master curves for each mix to demonstrate the effect of loading rate and temperature on the mixes.

MATERIALS

Twelve cold feed belt samples of 19mm (3/4 in) and 12.5 mm (1/2 in) nominal maximum size (NMS) mixtures were sampled throughout the state. ODOT identifies the above mentioned mixes as S3 and S4 mixes, respectively. There were eight S3 mixes and four S4 mixes. The mixes were selected to contain the predominate aggregate types used Oklahoma; limestone, gravel, sandstone, granite and rhyolite. Table 1 shows the mixes sampled, where they were placed, the predominant aggregate in the mix and the region of the state where the quarry is located. The mix design for each mix are in ***Appendix A*.**

TABLE 1. Test materials

Given Name	Mix	Recycle	Mix Design No.	Quarry Region	Predominate Aggregate	Quarry	Region Placed
Evans	S-4	No	05059	NE	Limestone	Bellco	NE
J & R Sand	S-4	No	04006	NW	Gravel (basalt)	Holly	NW
Cummins Enid-1	S-4	No	04063	SW	Sandstone Limestone	Cyril Richard Spur	NW
Cummins Enid-2	S-4	No	05018	SW SW	Granite Limestone	Snyder Richard Spur	NW
NH (160)	S-4	No	04179	SW SW	Limestone Granite	Coopertown Snyder	NW
Tiger TSI	S-4	No	05066	SE	Limestone	Hartshorne	SE
Bellco Kemp	S-4	No	00600	NE	Limestone	Ottawa	NE
Arkhola	S-4	No	05022	NE	Limestone Sandstone	Cherokee Wagnor	NE
Sawyer	S-3	No	03051	SE	Sandstone	Sawyer	SE
Norman	S-3	No	04071	C	Rhyolite	Davis	C
Durant	S-3	No	05002	C	Granite	Mill Creek	SE
Clinton	S-3	No	05090	SW	Limestone	Cooperton	SW

ASPHALT CEMENT

The three grades of asphalt cement used in the study were PG 64-22 OK, PG 70-28 OK and PG 76-28 OK. These are the three standard performance grades used in Oklahoma. In general, PG 64-22 OK is used in roadways with less than 5,000 average daily traffic (ADT) and with all mixes more than 125mm (5 in) below the surface of the pavements and in shoulders and temporary detours. PG 70-28 OK is used with all mixes in the top 125 mm (5 in) of the pavement in roadways with more than 5,000 ADT. PG 76-28 OK is used with all mixes in the top 125mm (5 in) for the roadways with more than 10,000 ADT and also in roadways with slow, standing or turning traffic such as intersections with traffic of more than 5000 ADT.

Valero provided the PG 70-28 asphalt and SemMaterials provided the PG 64-22, 76-28 and some of the PG 70-28 asphalt.

DYNAMIC MODULUS TEST SYSTEM

Dynamic modulus testing was performed in accordance with AASHTO TP 62-03. A dynamic modulus test system consists of a testing machine, environmental chamber and measuring system. The setup for the dynamic modulus testing that we used in the Oklahoma State University asphalt lab is shown in figure 1.

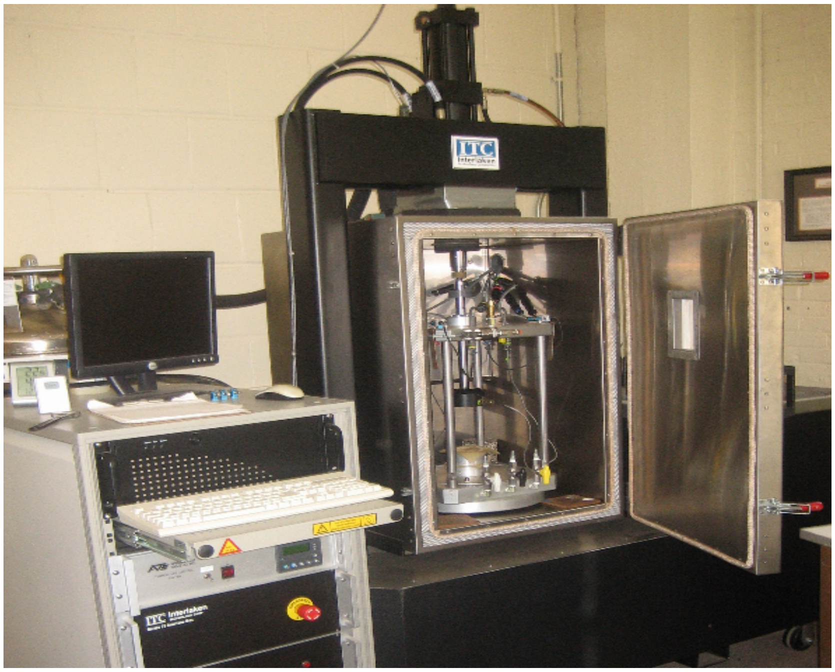

Figure 1. Dynamic Modulus Machine

SAMPLE REQUIREMENTS

AASHTO TP 62-03 requires that samples for dynamic modulus testing be 100mm (4 inches) in diameter and 150mm (6 inches) in height at a target air void content. Recommended target air void contents for HMA samples are 4-7%. The test sample is produced from the coring and sawing of 175 mm (7 inch) high and 150 mm (6 inch) diameter gyratory compacted samples. There is no single equation or conversion factor to relate 100mm high, 150mm diameter superpave gyratory compactor (SGC) compacted samples to a cored dynamic modulus |E*| sample with a given target air void content. It is based on the properties determined from trial samples. Replicate samples are required according to AASHTO TP 62. The AASHTO TP 62 requirements for dynamic modulus test samples are provided in the table below.

TABLE 2. Criteria for Acceptance of Dynamic Modulus Test Specimen

Criterion Items	**Requirements**
Size	Average diameter between 100mm and 104 mm Average height between 147.5 mm and 152.5 mm
Gyratory Specimens	Prepare 175 mm high specimens to required air void content (AASHTO T312)
Coring	Core the nominal 100 mm diameter test specimens from the centre of the gyratory specimen. Check the test specimen is cylindrical with sides that are smooth parallel and free from steps, ridges and grooves
Diameter	The standard deviation should not be greater than 2.5mm
End Preparation	The specimen ends shall have a chut surface waviness height within a tolerance of ±0.05 mm across diameter

	The specimen end shall not depart from perpendicular to the asis of the specimen by more than 1 degree
Air Void Content	The test specimen should be within ±1.0 percent of the target air voids
Replicates	For three LVDT's two replicates with a estimated limit of accuracy of 13.1 percent
Sample Storage	Wrap specimens in polyethylene and store in environmentally protected storage between 5 and 26.7°C (40 and 80°F) and be stored no more than two weeks prior to testing (15)

BATCHING

Trial samples were compacted to verify mix properties and establish optimum asphalt content. For the initial trial, the job mix formula (JMF) gradation provided by the contractor was used to calculate the batch weight. A 4000 gm sample was prepared and compacted to the mix design number of gyrations and the void content was determined. If the void properties were within specification limits, the optimum asphalt content was determined. If not, the gradation was adjusted and more samples were tested until the mix met the requirement. The target air void content was 7±0.5%. Next, based on the height and void content of the mix verification sample, the weight of the 175mm height sample at the target void content was estimated. A target VTM of 7±0.5% was required to produce a sample with 4.5% VTM, the desired VTM of the test sample. This sample would be cored and cut to 100mm (4 in) diameter and 150mm (6in) height test sample to get the target air void of 4.5%.

MIXING

The Superpave volumetric mix design procedure was followed during mixing. The test procedures are found in AASHTO T312, *Preparation of Compacted Specimens of Modified and Unmodified Hot Mix Asphalt by Means of the SHRP Gyratory Compactor*, and AASHTO R30. Batched samples were kept in a 163°C (325°F) oven for at least of 4 hours. The asphalt cement was heated to the mixing temperature 163°C . The time required for asphalt heating varied depending on the amount of asphalt. While aggregates and asphalt were being heated, all mixing implements such as spatulas, mixing bowls and other tools were also kept in the oven. A bucket mixer was used for mixing. The hot mixing bowl was placed on a scale and the scale was tarred to zero. Heated aggregate was poured into the mixing bowl and the scale was tarred again. Then, the required amount of asphalt was poured into the bowl to achieve the desired batch weight. The mixing bowl was now removed from the scale and the sample mixed in the bucket mixer until the aggregate was thoroughly coated.

CURING

The mix was then placed in a flat, shallow pan and the pan was kept in an oven at 150°C for 2 hours for curing in accordance with AASHTO R30 '*The Short and Long-Term Aging of Bituminous Mixes*'.

COMPACTION

A Superpave gyratory compactor was used for the compaction of the specimens. The compaction pressure, compaction angle and speed of gyration were set to the required values in accordance with AASHTO T312. Since we were shooting for a 175 mm height, the compaction mode was set to ‘compaction to height’ and the 175mm height was set. One hour before compaction, the compaction molds and caps were placed in the oven at the compaction temperature as described in AASHO T312. For compaction, the mold was removed from the oven and a paper disk was placed on top of the base plate. The short term oven aged mixture, at the compaction temperature, was placed inside the mold and a second paper disk and top plate was placed on top of the sample. The mold was placed into the compactor. It took around 30 to 50 gyrations to reach the desired height. After compaction, the paper disks were removed, the sample was extruded from the mold and the sample allowed to cool at room temperature. Figure 2, shows the superpave gyratory compactor that was used to compact our sample.

Figure 2. Superpave Gyratory Compactor

CORING AND SAWING

The compacted samples were cored and sawed to obtain a test specimen of 150 mm tall and 100 mm in diameter with around 4% ±0.5 voids. The samples were cored using a diamond studded core barrel to obtain a diameter of 100 mm (4in) as shown in figure 3.

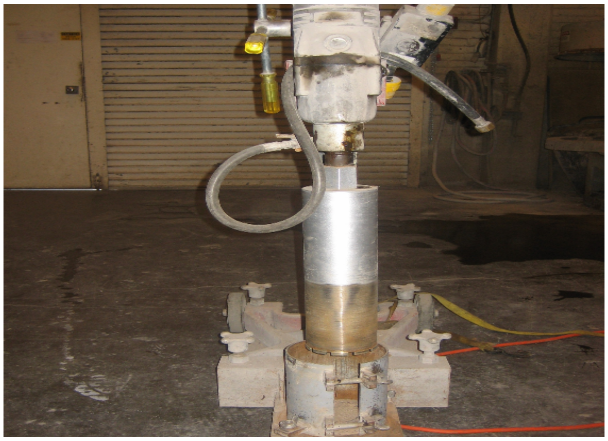

Figure 3. Core drill used to core samples

The cored samples were sawed to obtain a height of 150 mm (6 in). using the saw machine as shown in figure 4.

Figure 4. Saw used for preparing test samples

The cored and sawed samples were washed to eliminate all loose debris. Immediately after washing, the samples were tested for bulk specific gravity in general accordance with AASHTO T 166.

The samples were checked according to the requirements of AASHTO TP 62. Samples which met all criteria were fixed with six steel studs to hold three LVDT's. The LVDT's had a gauge length of 4 inches. Epoxy was used to fix the studs. The samples were then placed in a 4.4°C refrigerator over night before the start of testing. Testing was in accordance with AASHTO TP 62. The test temperatures and frequencies used are shown in table 3.

TABLE 3. Equilibrium Times

Specimen Temperature, °C, (°F)	**Times from Room Temperature (hrs)**	**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

DYNAMIC MODULUS TESTING

Table 3 shows the heating and cooling times required to bring the samples to constant temperatures for the different test temperatures. Tests are performed starting from the lowest temperature and proceeding to the highest frequency (2). Table 4 contains the typical dynamic stress range applied in the actuator during the test. We selected the mid value of the range specified for our testing. The samples were tested at six frequencies. Load cycles along with their respective frequencies are shown in table 5.

TABLE 4. Typical Dynamic Stress Levels

Temperature, °C (°F)	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

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

CHAPTER IV

TEST RESULTS

The objective of this study was to evaluate the dynamic modulus lE*l values of ODOT mixes. The dynamic modulus was determined in according to AASHTO TP 62-03. Test temperatures were 4.4°C, 21.1°C, 37.8°C and 54.4°C. AASHTO TP 62-03 protocol requires testing at -10°C also. Testing was not performed at this temperature because of limitation of the available test setup. The M-EPDG does not require the modulus value at -10°C even though AASHTO TP 62 has a provision for the test at this temperature. Samples were tested at 4.5±0.8% VTM at optimum asphalt content with PG 64-22, PG 70-28 and PG 76-28 binders, replicate sample were tested. The E* values obtained for our mixes are shown in tables 7 to 19.

TABLE 6. Average VTMs of the tested replicate samples

SN	Mix type	Material	Va		
			64-22	**70-28**	**76-28**
1	S3	**Durant**	4.6	4.3	4.7
2	S3	**Sawyer**	3.8	3.7	3.7
3	S3	**Norman**	4.8	4.7	4.5
4	S3	**Clinton**	4.6	4.6	4.7
5	S4	**Bellco**	4.3	4	4.1
6	S4	**Cummins Enid-1**	5.5	5.6	5.5
7	S4	**J & R Sand**	4.1	4.2	3.8
8	S4	**Arkhola**	3.7	3.7	3.7
9	S4	**Cummins Enid-2**	5.3	4.8	4.8
10	S4	**NH(160)**	4.6	4.4	4.2
11	S4	**Evans**	4.3	4.3	4.6
12	S4	**Tiger TSI**	4.3	3.8	3.9

TABLE 7. E* value for S3 Norman

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	2556453	2770396	3123827	2648975	2417993	3133616
4.4	10	2379105	2566174	2448317	2334160	2268584	2823842
4.4	5	2128068	2362993	2027012	2087827	2055676	2533468
4.4	1	1599476	1926446	1375385	1560913	1577522	1924607
4.4	0.5	1441412	1751400	1161094	1362697	1406984	1692432
4.4	0.1	1076560	1370219	797844	980669	1063815	1228745
21.1	25	1293963	1845535	1058616	1239363	1369514	1427478
21.1	10	1087251	1379150	809007	967696	1040211	1075382
21.1	5	900938	1118803	664334	803369	853141	886740
21.1	1	529179	695490	425015	510941	525201	562476
21.1	0.5	416074	572644	354891	428183	427382	464507
21.1	0.1	239310	367701	242461	290335	275781	303664
37.8	25	397356	544864	375414	489659	408695	475050
37.8	10	292189	439806	295590	378486	322718	384967
37.8	5	234363	351728	246963	301843	264024	310654
37.8	1	124422	210277	163944	184529	160274	194045
37.8	0.5	97307	169260	142254	155653	133054	161018
37.8	0.1	65414	109250	116164	114957	95717	116735
54.4	25	172007	223289	524141	552491	186942	250881
54.4	10	106822	139891	210328	326361	155156	226295
54.4	5	89709	110913	183188	280295	120261	203931
54.4	1	62254	60301	80966	100437	54458	99278
54.4	0.5	55862	49358	67003	84832	46465	86095
54.4	0.1	47358	36155	51854	69387	36649	67975

TABLE 8. E* values for Sawyer S3I

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3877717	3766886	2973969	3418469	2876660	3344881
4.4	10	3751634	3446160	2624668	2864794	2605012	2956796
4.4	5	3389695	3179687	2316389	2500801	2340485	2583944
4.4	1	2675424	2621920	1699882	1842311	1809127	1857820
4.4	0.5	2429978	2400295	1494549	1623591	1608331	1619704
4.4	0.1	1895896	1920967	1087640	1185339	1207483	1152565
21.1	25	1929598	2257987	1596778	2181202	1498156	1535471
21.1	10	1578626	1764157	1164139	1409886	1204145	1197142
21.1	5	1324708	1486626	935116	1103504	1015018	978254
21.1	1	878824	1026676	566119	651332	658591	612175
21.1	0.5	734024	886836	463626	528115	539928	495207
21.1	0.1	490217	617067	307247	342318	349523	317997
37.8	25	760906	812159	402469	467856	603299	497788
37.8	10	638780	673877	319868	360896	475690	399750
37.8	5	503143	555194	265756	287984	376377	317500
37.8	1	288980	340556	158283	168740	225700	190398
37.8	0.5	226744	270548	132774	137659	183285	155388
37.8	0.1	138887	170395	101625	97323	126100	108866
54.4	25	279986	330494	200085	239331	179576	174882
54.4	10	200722	297224	186830	211524	151691	152633
54.4	5	180455	262859	166521	201707	129443	127354
54.4	1	74006	140267	55722	68316	80683	67032
54.4	0.5	58233	118379	47069	56918	70218	56076
54.4	0.1	39310	89962	37274	43168	58431	43219

TABLE 9. E* values for S3 Durant

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4278188	4002868	3489649	3282251	2808352	2229945
4.4	10	3836247	3377414	2854568	3013130	2495188	2055476
4.4	5	3413623	2913365	2456283	2661470	2224449	1820538
4.4	1	2580828	2099839	1707523	1940144	1669621	1328114
4.4	0.5	2281282	1830627	1460026	1704817	1469959	1159494
4.4	0.1	1682691	1292757	995081	1248321	1067717	837372
21.1	25	2610018	1641199	1285725	1545133	987892	1855368
21.1	10	2153669	1322811	958295	1251553	816833	1469738
21.1	5	1789276	1076765	747312	1015184	679260	1179398
21.1	1	1061237	641291	440552	625629	429401	624130
21.1	0.5	818886	510241	360084	514638	355173	453099
21.1	0.1	435121	312570	244080	341737	245062	270192
37.8	25	617163	513454	330635	556026	346731	289976
37.8	10	520951	382390	283315	453808	298948	239837
37.8	5	404388	294908	232014	358310	239216	196589
37.8	1	232693	175074	161891	230044	153337	132985
37.8	0.5	183881	139247	142121	190468	128086	113754
37.8	0.1	115968	92260	107409	135515	93791	86264
54.4	25	150463	114640	112925	153285	106389	116169
54.4	10	110828	77688	111490	118790	102936	111243
54.4	5	96428	66625	100252	103429	89168	96451
54.4	1	63721	52105	53097	70587	45915	45854
54.4	0.5	59070	45925	49357	65751	41463	40978
54.4	0.1	57992	37605	42033	56042	34197	33477

TABLE 10. E* values for S3 Clinton

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4848955	3705964	6537171	4748885	6734403	6143536
4.4	10	4065518	3238279	5063716	3998300	4802792	4047837
4.4	5	3525872	2921718	4093256	3454688	3980980	3219237
4.4	1	2585110	2221318	2690917	2453948	2597756	2064692
4.4	0.5	2307508	1968997	2251933	2122721	2171787	1719005
4.4	0.1	1594536	1401375	1478792	1441440	1449296	1145843
21.1	25	1299499	2382697	3723928	1715033	3305082	2520893
21.1	10	1030395	1665177	1890789	1337454	1754451	1477457
21.1	5	846672	1371143	1418702	1108768	1336738	1145332
21.1	1	531031	877955	811763	674155	805987	692263
21.1	0.5	432118	721386	632145	540090	639874	549397
21.1	0.1	272988	457175	385866	339284	404997	342545
37.8	25	534787	1018052	533546	604208	590406	567109
37.8	10	398605	588103	428326	476903	454380	448926
37.8	5	310394	435354	350293	384671	366742	354240
37.8	1	186653	235268	202480	233723	209229	209061
37.8	0.5	150734	184314	167622	194272	172302	173217
37.8	0.1	102034	118345	124780	141882	122738	123971
54.4	25	187445	184669	220047	271749	233740	306568
54.4	10	140199	140672	206680	192153	227776	284630
54.4	5	137178	114728	186659	183254	211499	256358
54.4	1	81254	69517	103588	102558	104824	105078
54.4	0.5	75179	60067	93466	91445	89428	88763
54.4	0.1	75478	48960	77269	76907	71304	66924

TABLE 11. E* values for S4 Bellco Kemp

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4940512	3993712	3231059	4108197	5983457	5983457
4.4	10	4626734	3850768	2884007	3520676	4789674	4789674
4.4	5	4182096	3522248	2533854	3081314	4083966	4083966
4.4	1	3262162	2711460	1855923	2249078	2862981	2862981
4.4	0.5	2940448	2408753	1628134	1953825	2493502	2493502
4.4	0.1	2211539	1762536	1192142	1392086	1729994	1729994
21.1	25	2461682	1852325	1526640	1916874	2057249	2070942
21.1	10	1695522	1417244	1157556	1434576	1618466	1566802
21.1	5	1373622	1187905	932915.9	1164742	1334811	1287477
21.1	1	873477	758055	578726	724747	831439	819397
21.1	0.5	705080	612004	478261	597040	669189	664744
21.1	0.1	424514	381229	318451	388015	418310	420116
37.8	25	690218	664221	458020	527323	763499	833225
37.8	10	518400	529101	357852	428911	596469	643286
37.8	5	399464	417766	289326	346653	468744	478393
37.8	1	230428	225730	177061	213163	255450	262515
37.8	0.5	181849	179268	147322	176766	208075	211490
37.8	0.1	116486	109208	107444	127931	144383	140917
54.4	25	242166	289055	257749	306352	320389	344218
54.4	10	209447	174365	205917	297226	230293	213956
54.4	5	175525	133430	186066	247402	187160	166258
54.4	1	131768	54887	101750	93909	86091	76588
54.4	0.5	116115	42974	89583	83338	70582	61126
54.4	0.1	97356	31277	71702	64630	53750	44938

TABLE 12. E* values for S4 Evans

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3861564	3894726	3303881	3393967	4035228	3348826
4.4	10	3667350	3631582	2948999	3071019	3643605	3080829
4.4	5	3421330	3367434	2646098	2728685	3268998	2803622
4.4	1	2865360	2779921	1979854	2007088	2545046	2179695
4.4	0.5	2617471	2551861	1744321	1742812	2271811	1950765
4.4	0.1	2068808	2030022	1267338	1251238	1677600	1476517
21.1	25	1604037	2089641	1903341	1771351	1991813	2168361
21.1	10	1451507	1639247	1506065	1372199	1544920	1688144
21.1	5	1274551	1398952	1234744	1119576	1259931	1392458
21.1	1	856148	933188	788623	700744	793907	866131
21.1	0.5	714107	775405	652160	571220	649889	698993
21.1	0.1	469593	498143	427600	370949	413592	435279
37.8	25	789415	731712	680098	473462	642830	642830
37.8	10	646207	576509	581105	400698	561989	561989
37.8	5	511929	446185	473155	329324	447864	447864
37.8	1	297322	251838	261467	197962	268446	268446
37.8	0.5	233776	196544	210809	162196	217122	217122
37.8	0.1	142841	122545	141644	113923	147130	147130
54.4	25	325790	316956	322980	256333	262427	297258
54.4	10	254042	222744	268863	228993	209040	245312
54.4	5	216962	181181	225058	207634	177377	200606
54.4	1	94139	86914	104879	81187	87063	108909
54.4	0.5	73612	71068	106689	70866	71483	91621
54.4	0.1	48607	52350	88783	55340	52508	73986

TABLE 13. E* values for Arkhola S4

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4446691	3797947	7168405	5008715	4174114	3564347
4.4	10	3843738	3483187	4910970	4407323	3578069	3152522
4.4	5	3383512	3187871	3904133	3814788	3080786	2835089
4.4	1	2540852	2538399	2611637	2614378	2245465	2214255
4.4	0.5	2213803	2285863	2199716	2208395	1935166	1958059
4.4	0.1	1540862	1740414	1467650	1475854	1347330	1441795
21.1	25	2072460	2714857	2268833	1884724	2395780	2340409
21.1	10	1562036	1841353	1391277	1275013	1476769	1609959
21.1	5	1290903	1498525	1065276	1019802	1146907	1285796
21.1	1	836799	957139	633043	634733	689225	817709
21.1	0.5	683608	776756	503771	510173	540235	653963
21.1	0.1	424104	481394	320664	323131	334581	414463
37.8	25	699076	808887	604065	679481	704464	834281
37.8	10	566742	646036	484333	497908	608992	683615
37.8	5	441549	502755	384787	388036	481179	534223
37.8	1	247443	278611	221519	220460	242992	279095
37.8	0.5	196733	220737	184360	179870	196350	225049
37.8	0.1	129366	144238	133251	123257	133951	152616
54.4	25	335520	276381	247824	225212	268611	456447
54.4	10	247847	222401	228874	217995	228466	405871
54.4	5	199799	151105	182508	150542	174675	236840
54.4	1	102054	85659	105184	85875	87296	109930
54.4	0.5	80683	73231	93288	73655	74207	91414
54.4	0.1	61615	58581	78322	56074	56123	63233

TABLE 14. E* values for NH (160)

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3044826	2666477	3134577	3129360	4862909	2781852
4.4	10	2745960	2457112	2325852	2691254	4131962	2414651
4.4	5	2460361	2268390	1935582	2260909	3500962	2091574
4.4	1	1901129	1827593	1288259	1520912	2461698	1482828
4.4	0.5	1706096	1646452	1074178	1280373	2131674	1267333
4.4	0.1	1284126	1246866	700173	865266	1509436	858524
21.1	25	1334036	1367368	1120122	1238754	1692233	1045249
21.1	10	1074262	1082353	767534	834267	1262059	803264
21.1	5	896969	896186	594055	660003	1013623	651887
21.1	1	575617	561171	358149	394802	618791	390402
21.1	0.5	479244	456439	293024	322356	499249	314091
21.1	0.1	312193	299858	191634	211744	315375	199817
37.8	25	481005	399207	277693	348715	499803	283434
37.8	10	371686	308217	219803	280523	407655	223293
37.8	5	292661	237218	177845	232862	323913	178967
37.8	1	172627	136686	117672	151397	199820	116196
37.8	0.5	137768	108388	99574	125795	164428	97842
37.8	0.1	90677	71976	77257	95218	116714	74286
54.4	25	145429	182191	118323	113709	167474	107214
54.4	10	129507	119203	90038	103992	123367	89834
54.4	5	102930	105580	86393	97905	106135	84714
54.4	1	45090	52419	40519	47422	55924	46090
54.4	0.5	37370	45344	35989	41220	47531	40484
54.4	0.1	27976	37924	30484	34900	37172	32675

TABLE 15. E* values for J+R Sand

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3403052	3621988	3510174	3711950	4172370	2497402
4.4	10	3191326	3434191	3336120	3185982	3428234	2257024
4.4	5	2907241	3099791	2806446	2704566	2960076	2035835
4.4	1	2303234	2359763	1982352	1895856	2183832	1575095
4.4	0.5	2077749	2113143	1693115	1620757	1947394	1408532
4.4	0.1	1586928	1514325	1139107	1107842	1478689	1076120
21.1	25	1521031	3621988	1080691	2073489	1884801	1607441
21.1	10	1186494	3434191	881184	1458941	1420543	1189333
21.1	5	965697	3099791	704111	1146609	1149052	941290
21.1	1	585334	2359763	417011	694553	710007	556524
21.1	0.5	470968	2113143	337969	554352	581369	453503
21.1	0.1	284110	1514325	222743	347500	379783	299047
37.8	25	510907	562913	289463	592797	860408	553745
37.8	10	398260	412505	241691	469558	607379	387954
37.8	5	310660	308838	198098	370152	471709	299960
37.8	1	179682	174544	131725	209627	288135	183667
37.8	0.5	145643	138650	114048	169257	238025	157492
37.8	0.1	95754	88201	88764	117474	166154	107782

TABLE 16. E* values for Cummins Enid-2

Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	2652739	4254551	2016223	1887827	3249896	3163827
4.4	10	2507177	3759094	1705455	1580290	2715058	2653723
4.4	5	2278188	3281490	1470158	1346957	2323374	2292019
4.4	1	1826111	2395750	1022010	926664	1669968	1687599
4.4	0.5	1630001	2090240	869547	785908	1457671	1471086
4.4	0.1	1194223	1482044	597175	544180	1062524	1067124
21.1	25	1717318	1348099	839797	868845	1163413	1474514
21.1	10	1147789	1095468	602458	579396	937911	1064870
21.1	5	931614	916164	481476	446053	781975	865708
21.1	1	600389	585588	305684	275776	513064	547105
21.1	0.5	495618	474045	254716	229552	431857	453572
21.1	0.1	321087	295959	179726	162676	296574	300377
37.8	25	509894	651368	332608	246072	578805	636904
37.8	10	370729	481216	266246	197950	401251	402141
37.8	5	290783	362638	214014	168819	317191	311517
37.8	1	175934	206940	145075	124762	198674	194332
37.8	0.5	140548	162605	120953	109323	160553	155241
37.8	0.1	95450	104506	91222	90143	112392	108612
54.4	25	234441	359966	275326	135087	290336	216134
54.4	10	128548	182927	201427	89979	281784	186628
54.4	5	93124	158398	167724	75481	238582	165033
54.4	1	57828	78227	98287	51438	102363	92564
54.4	0.5	50972	69998	79697	46548	82510	77884
54.4	0.1	42089	65770	68037	41006	60347	57688

TABLE 17. E* values for Cummins Enid-1

Temp	**Freq**	**PG 64-22**		**PG 70-28**		**PG 76-28**	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4783639	3780246	2157942	2115407	2321894	3042868
4.4	10	4372680	3512598	1871187	1829648	1973042	2630084
4.4	5	3854941	3161204	1653435	1594198	1679640	2268765
4.4	1	2835062	2456622	1229506	1158358	1190800	1615715
4.4	0.5	2487409	2218217	1082315	1005071	1029844	1392885
4.4	0.1	1694467	1713689	813059	720529	735866	990732
21.1	25	3009159	1944976	1226808	956648	846490	1044470
21.1	10	1980138	1564983	926557	714585	643020	813544
21.1	5	1521412	1318939	752594	570546	526841	667591
21.1	1	877632	858796	475392	366686	339112	426365
21.1	0.5	696190	711957	399151	308994	283639	356471
21.1	0.1	421149	472022	276233	217783	199847	249142
37.8	25	499966	974560	403162	367750	343663	432010
37.8	10	390154	799443	351539	353823	291706	364585
37.8	5	299134	578006	286994	286562	240858	301369
37.8	1	176958	332280	189215	197424	154061	193056
37.8	0.5	142965	255194	159769	164685	128957	162253
37.8	0.1	101573	156092	122180	125736	96205	121377
54.4	25	151747	205333	121540	150690	138943	193511
54.4	10	155878	176514	125107	131703	124754	153949
54.4	5	114186	142613	101888	122263	111755	136617
54.4	1	73397	82110	72427	88935	71949	76435
54.4	0.5	64809	68987	65712	78777	65940	67129
54.4	0.1	49729	50947	55985	67371	55736	53216

TABLE 18. E* values for Tiger TSI S4

Temp	**Freq**	**PG 64-22**		**PG 70-28**		**PG 76-28**	
		Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4442424	3746540	3595700	5016456	4397105	4184389
4.4	10	4049586	3367650	3146992	4376151	3755259	3781504
4.4	5	3562183	3045181	2778824	3723385	3240354	3401216
4.4	1	2626489	2378695	2099374	2631853	2361043	2597990
4.4	0.5	2317288	2139448	1837181	2257156	2053814	2300977
4.4	0.1	1645693	1642486	1317686	1544908	1430649	1694989
21.1	25	3619753	1946608	1585649	2157980	2663927	2210024
21.1	10	2086511	1547785	1222150	1571269	1808643	1654715
21.1	5	1625591	1300816	1004193	1264723	1364762	1350109
21.1	1	975273	855502	636544	788000	786123	840004
21.1	0.5	769131	706973	517081	632288	618455	677503
21.1	0.1	449597	448946	329783	389716	364572	423443
37.8	25	737086	748250	467525	547374	554608	626533
37.8	10	505026	607691	394760	435182	445896	483538
37.8	5	383926	472768	306630	344430	350546	380653
37.8	1	211849	255821	181102	206875	203363	219131
37.8	0.5	163214	197389	147301	169177	167289	177460
37.8	0.1	107165	120640	103733	117896	121692	122340
54.4	25	341487	213979	189456	199726	231199	231954
54.4	10	274098	165983	155483	167040	213672	196044
54.4	5	232438	137112	112830	148541	187337	171961
54.4	1	94925	77120	58402	66660	109412	118761
54.4	0.5	75876	65236	48865	55149	95814	107570
54.4	0.1	54336	50580	38027	42535	79309	97337

CHAPTER V

COMPARISION AND ANALYSIS

The objective of our study was to develop a master curve for each Oklahoma mix to demonstrate the effect of loading rate and temperature on the mix and to evaluate the dynamic modulus of Oklahoma hot mix asphalt (HMA) mixtures to determine if mix type, aggregate source and binder grade had a significant effect on dynamic modulus values at a 95% confidence level.

SHIFT FACTORS AND MASTER CURVES

According to the M-EPDG (1), a master curve allows varying dynamic modulus values to be used as temperature and loading rate change. Levels 2 and 3 of the M-EPDG use the prediction equation to create master curves where as Level 1 uses dynamic modulus values. To create a master curve, a standard reference temperature is selected and then the data at various temperatures are shifted with respect to time until the curves merge into a single smooth function (1, 2, and 3).

The temperature dependency of the material is described by the amount of shifting at each temperature required to form the master curve. So, both the master curve and the shift factors are needed to demonstrate the rate and temperature effects. Table 30, 31 and

32 demonstrate the shift factors that were used to shift the E* values to the reference temperature, 21.1°C (70°F).

TABLE 19. Shift factors for the Oklahoma mixes with PG 64-22

Mix Type	Mix name	PG	Shift Factors		
			log[a(40)]	log[a(100)]	log[a(130)]
S3	Sawyer	64-22	2.2	-1.7	-3.1
S3	Norman	64-22	1.9	-1.7	-3.1
S3	Durant	64-22	1.7	-1.8	-3.9
S3	Clinton	64-22	2	-1.5	-3.1
S4	Evans	64-22	2.6	-1.7	-2.9
S4	J & R Sand	64-22	1	-3	-4.9
S4	Cummins Enid-1	64-22	1.9	-1.7	-3.4
S4	Cummins Enid-2	64-22	2.2	-1.5	-2.7
S4	NH(160)	64-22	2.3	-1.8	-3.2
S4	Tiger TSI	64-22	1.7	-1.7	-2.9
S4	Bellco Kemp	64-22	2.3	-1.6	-2.9
S4	Arkhola	64-22	1.8	-1.6	-2.9

TABLE 20. Shift factors for the Oklahoma mixes with PG 70-28.

Mix Type	Mix name	PG	Shift Factors		
			log[a(40)]	log[a(100)]	log[a(130)]
S3	Sawyer	70-28	1.7	-1.9	-3.2
S3	Norman	70-28	1.9	-1.4	-1.9
S3	Durant	70-28	2	-1.7	-3.7
S3	Clinton	70-28	1.7	-1.7	-2.9
S4	Evans	70-28	1.7	-1.7	-2.8
S4	J & R Sand	70-28	1.9	-1.7	-3.2
S4	Cummins Enid-1	70-28	1.8	-1.5	-3.4
S4	Cummins Enid-2	70-28	1.9	-1.4	-2.3
S4	NH(160)	70-28	1.9	-1.7	-3.3
S4	Tiger TSI	70-28	2	-1.8	-3.3
S4	Bellco Kemp	70-28	2	-1.8	-2.6
S4	Arkhola	70-28	2	-1.4	-2.7

TABLE 21. Shift factors for the Oklahoma mixes with PG 76-28

Mix Type	Mix name	PG	Shift Factors		
			log[a(40)]	log[a(100)]	log[a(130)]
S3	Sawyer	76-28	1.9	-1.6	-3.2
S3	Norman	76-28	2.1	-1.7	-2.8
S3	Durant	76-28	1.8	-2	-3.7
S3	Clinton	76-28	1.5	-1.7	-2.7
S4	Evans	76-28	2	-1.7	-3
S4	J & R Sand	76-28	1.9	-1.4	-2.9
S4	Cummins Enid-1	76-28	2.3	-1.4	-2.8
S4	Cummins Enid-2	76-28	2	-1.4	-2.4
S4	NH(160)	76-28	2.2	-1.7	-3.4
S4	Tiger TSI	76-28	1.7	-1.8	-2.9
S4	Bellco Kemp	76-28	2.1	-1.5	-2.8
S4	Arkhola	76-28	1.7	-1.3	-2.4

After shift factors were determined, master curves were build to demonstrate the rate and temperature effect E* on the Oklahoma mixes. Figures 4 to 15 illustrate the masters curves for our mixes.

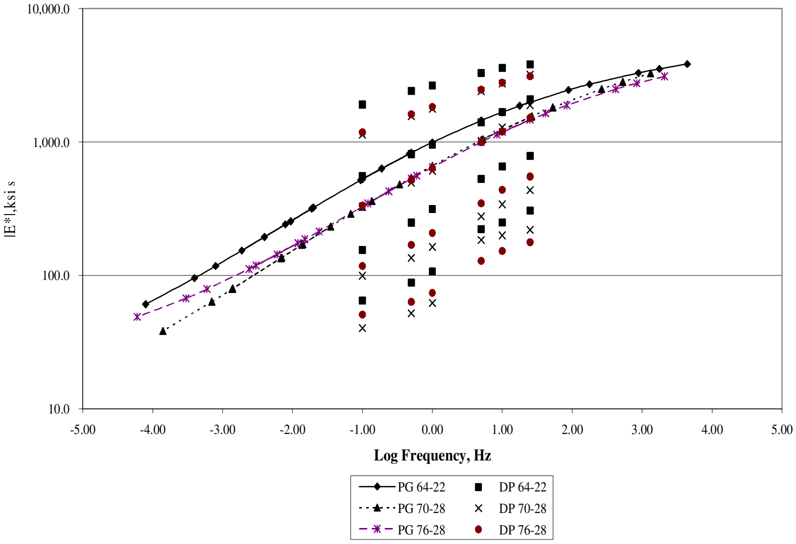

Figure 4. Master curve for Sawyer S3I

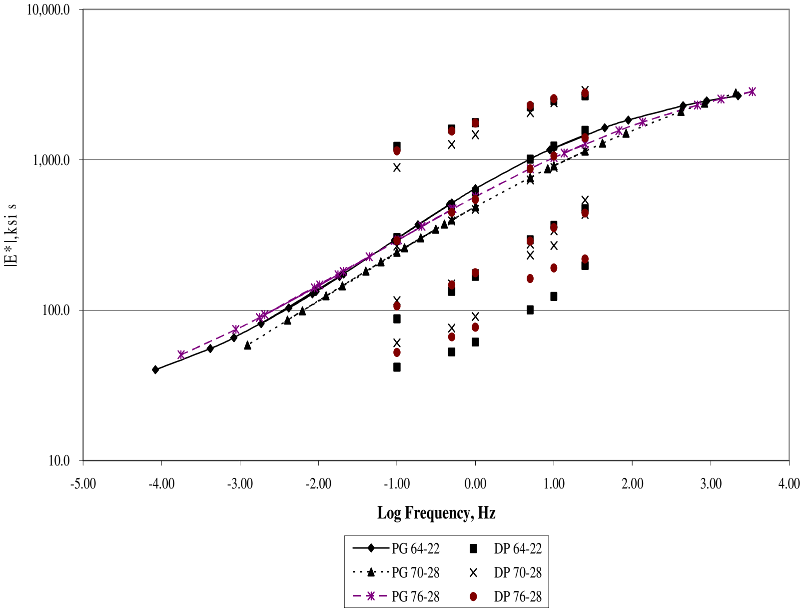

Figure 5. Master curve for Norman

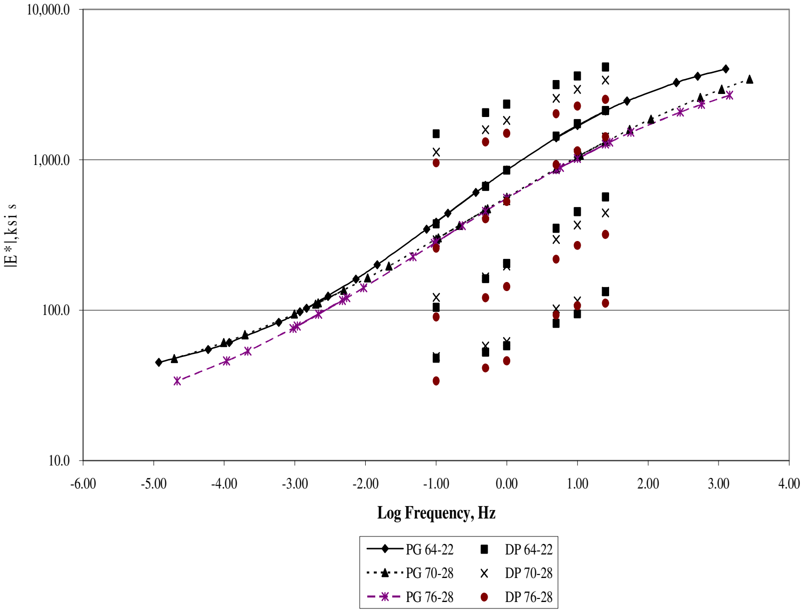

Figure 6. Master curve for Durant

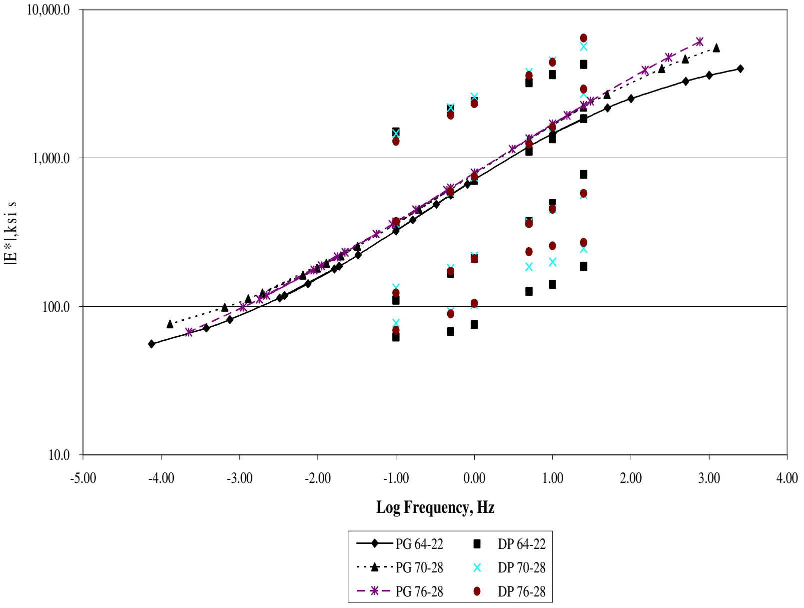

Figure 7. Master curve for Clinton

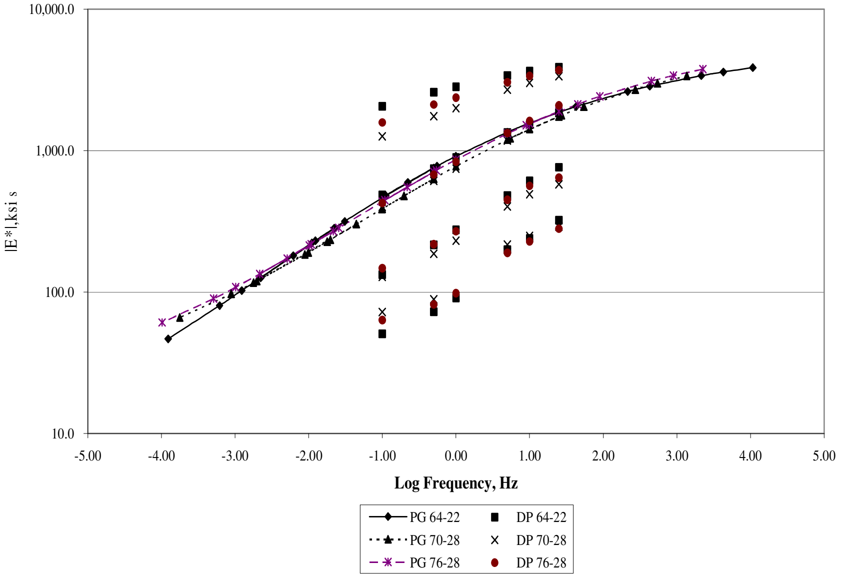

Figure 8. Master curve for S4 Evans

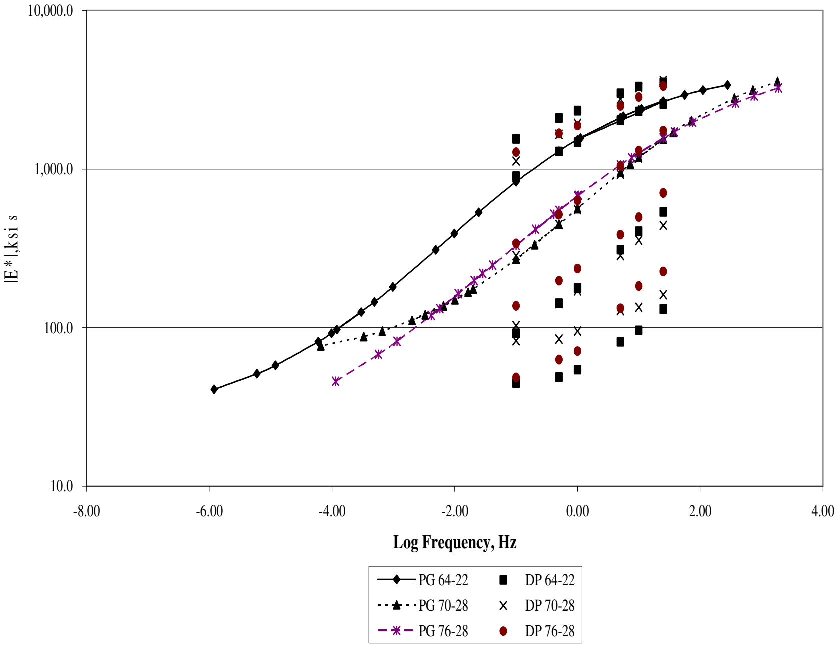

Figure 9. Master curve for J and R Sand

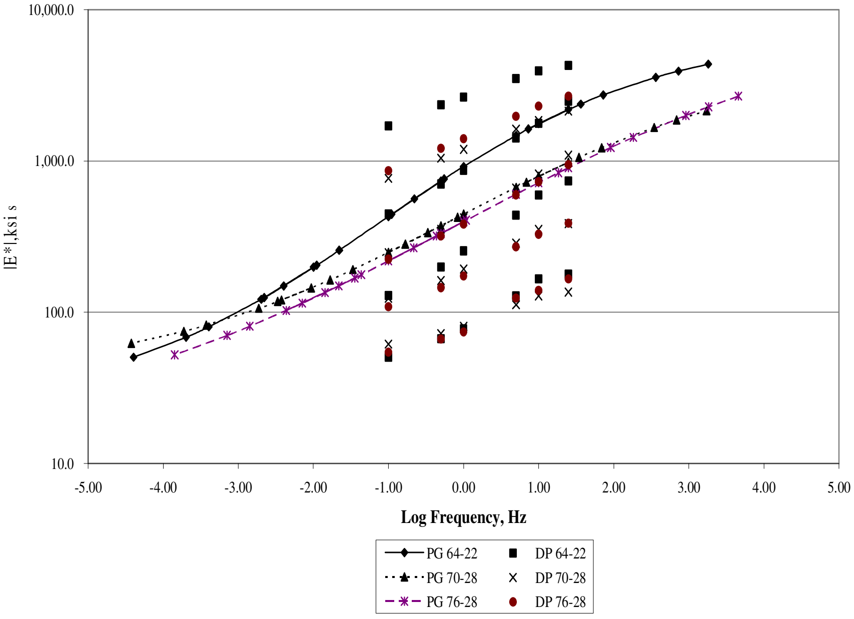

Figure 10. Master curve for Cummins Enid-1

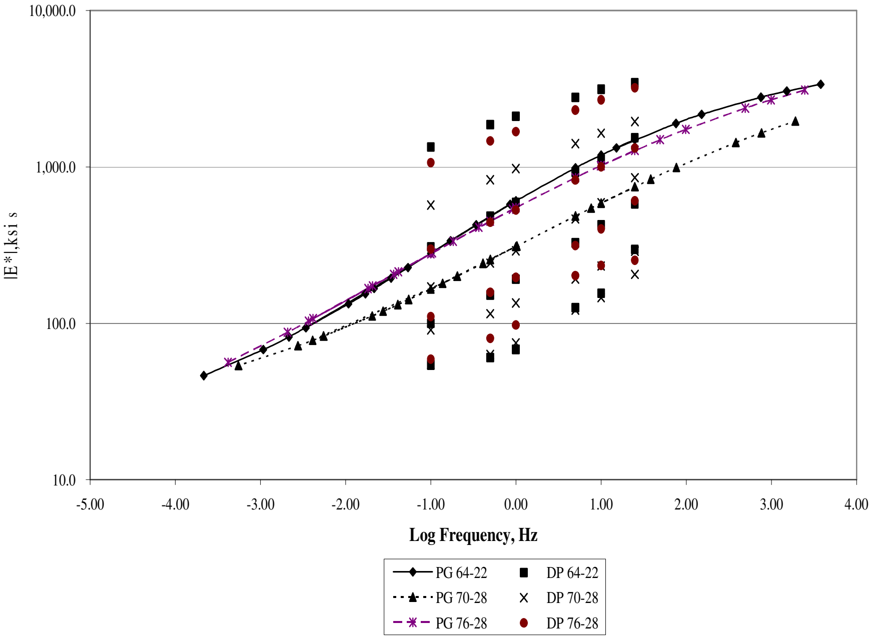

Figure 11. Master curve for Cummins Enid-2

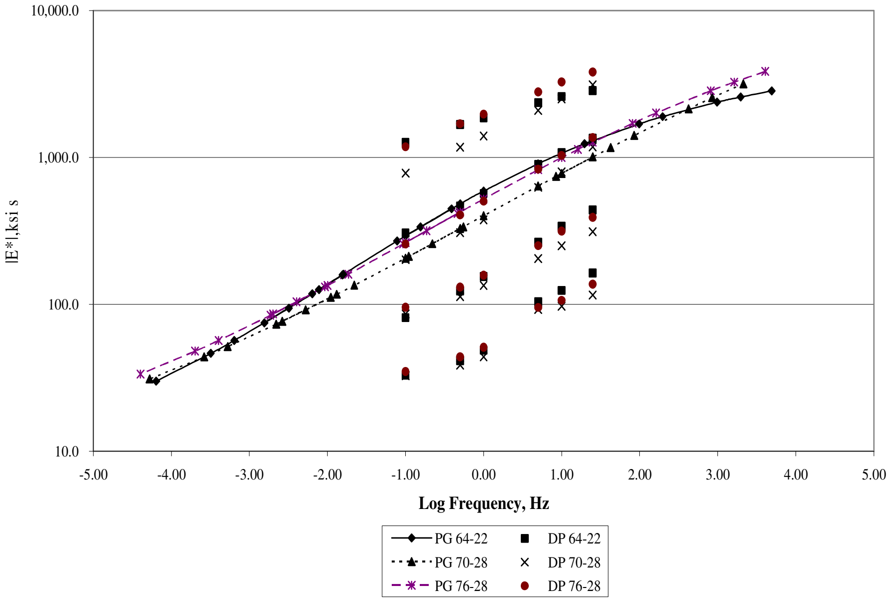

Figure 12. Master curve for NH(160)

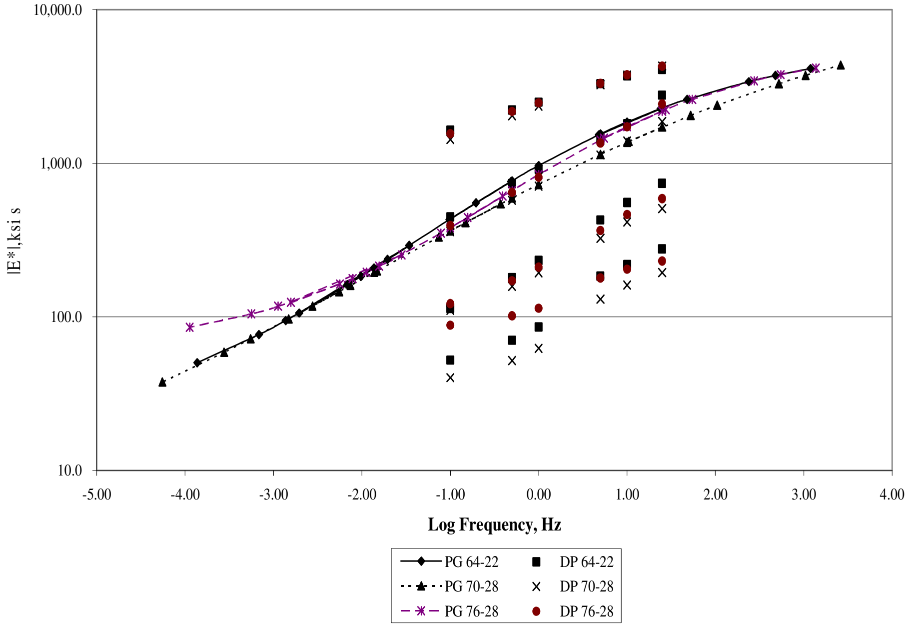

Figure 13. Master curve for Tiger TSI

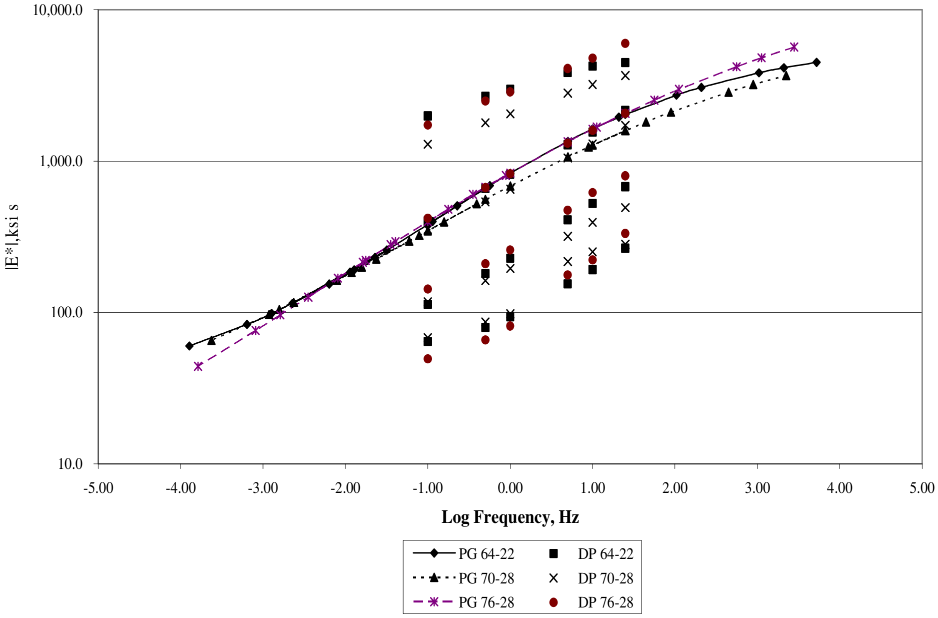

Figure 14. Master curve for Bellco Kemp

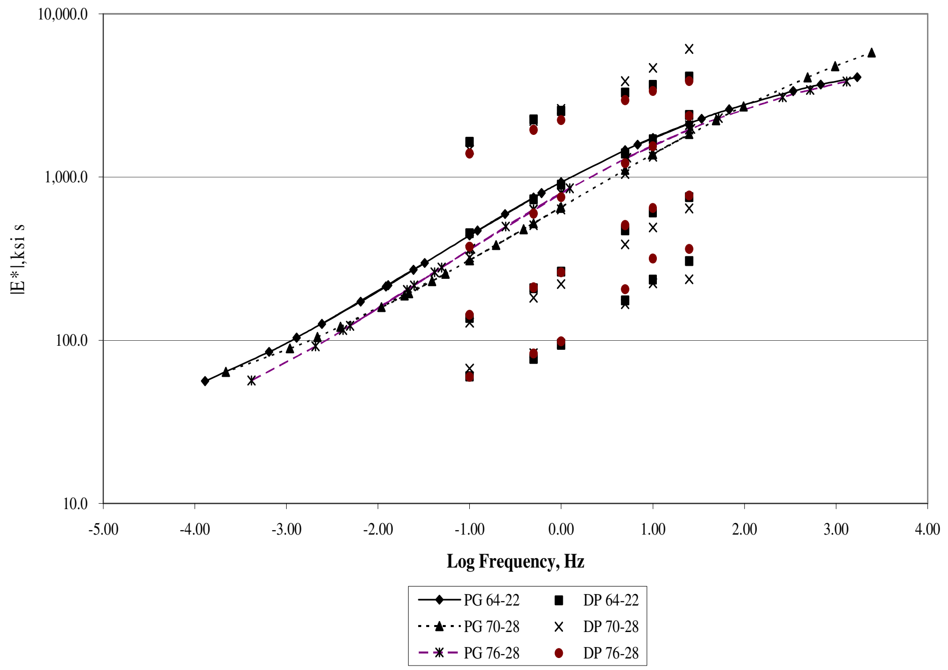

Figure 15. Master curve for Arkhola

Development of master curves are not necessary for using the M-EPDG, the software calculates the master curve for the user. For our testing, only one binder source for each PG grade was used. Addition research is needed on the effect of binder source within each PG grade on dynamic modulus values.

The other objectives of our study were to evaluate E* values to determine if mix type, aggregate source and binder grade had a significant effect on dynamic modulus values at a 95% confidence level. Statistical Analysis System (SAS) software was used to carry out analysis of variance (ANOVA) procedures.

TEST TEMPERATURE, PG BINDER GRADE, MIX TYPE

Analysis of Variance

A three way ANOVA was performed on all the measured dynamic modulus values. The three independent mix variables were test temperature, PG binder grade and mix type. The E* testing was performed at four test temperatures, five frequencies, 3 PG binder grades and two mix types. AASHTO TP62 requires dynamic modulus testing at different frequencies because frequency has a significant effect on E*. Therefore, the analysis was performed at one frequency, 5 Hz. The levels of the three main effects are shown in Table 22. Testing was performed at four temperatures, using three PG binder grades with 2 mix types.

TABLE 22. Independent Mix Variables

Class	Levels	Values
Temp	4	4.4°C, 21.1°C, 37.8°C, 54.4°C
PG	3	64-22, 70-28, 76-28
Mix	2	S3, S4

Table 23 shows the results of the ANOVA. The ANOVA results indicated that temperature and PG grade had a significant effect on measured dynamic modulus values but the mix types did not have significant effect. The interaction between temperature and PG grade had a significant effect. However, the interaction between temperature and mix type and the three way interaction among temperature, PG grade and mix type did not show a significant difference in the dynamic modulus values.

TABLE 23: SAS output of three way ANOVA

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Temp	3	3.2207716E14	1.0735905E14	719.09	<.0001
PG	2	2.9211643E12	1.4605821E12	9.78	<.0001
Mix	1	103858809603	103858809603	0.78	0.4050
Temp*PG	6	2.3415726E12	390262092260	2.61	0.0177
Temp*Mix	3	127504647115	42501549038	0.28	0.8365
Temp*PG*mix	6	301808779819	50301463303	0.34	0.9170
Error	264	3.9415017E13	149299306590		
Total	287	3.6764606E14			

Duncan's Multiple Range Test

Duncan's multiple range tests were performed on independent mix variables to check for the statistical difference in the mean dynamic modulus values obtained. Table 21 shows the result of Duncan's multiple range test to evaluate the effect of PG binder grade on E*.

TABLE 24. Evaluation of Effect of PG on E*

Duncan grouping	Mean	N	PG
A	1238985	96	64-22
B	1084458	96	76-28
B	995185	96	70-28

As shown in table 24, E* values measured for PG binder grades 70-28 and 76-28 were not significantly different from each other. However, both of these values were significantly different from the values for PG binder grade 64-22. The analysis was performed using data at all four test temperatures.

Table 25 shows the result of Duncan's multiple range test to evaluate the effect of mix type on E*. The results show that the mix type had no significant effect on measured dynamic modulus values.

TABLE 25. Evaluation of Effect of Mix type on E*

Duncan grouping	Mean	N	Mix
A	1119637	192	S4
A	1079354	96	S3

The results of Duncan's multiple range test on temperature are shown in table 26. Temperature had a significant effect on the measured dynamic modulus values.

TABLE 26. Evaluation of Effect of Temperature on E*

Duncan grouping	Mean	N	Temp
A	2834841	72	4.4
B	1089783	72	21.1
C	347661	72	37.8
D	152553	72	54.4

The test procedure requires testing at different test temperatures. There was a significant interaction between test temperature and PG grade. To evaluate the effect of the interaction, Duncan's multiple range test was performed on PG grade by test temperatures. The results are shown in tables 27-30.

TABLE 27. Results of Duncan's Multiple Range Test for E* at 4.4°C to evaluate the effect of PG

Temp	Duncan grouping	Mean	N	PG
	A	3117437	24	64-22
4.4°C	A & B	2779542	24	76-28
	B	2607544	24	70-28

TABLE 28. Results of Duncan's Multiple Range Test for measured E* at 21.1°C to evaluate the effect of PG

Temp	Duncan grouping	Mean	N	PG
21.1°C	A	1308857	24	64-22
	B	1045587	24	76-28
	B	914904	24	70-28

TABLE 29. Results of Duncan's Multiple Range Test for measured E* at 37.8°C to evaluate the effect of PG

Temp	Duncan grouping	Mean	N	PG
37.8°C	A	389406	24	64-22
	A & B	352512	24	76-28
	B	301063	24	70-28

TABLE 30. Results of Duncan's Multiple Range Test for measured E* at 54.4°C to evaluate the effect of PG

Temp	Duncan grouping	Mean	N	PG
54.4°C	A	160191	24	76-28
	A	157229	24	70-28
	A	140239	24	64-22

As shown in table 27, there is a significant difference in the mean E* at 4.4° C between mixes with PG binder grade 64-22 and 70-28. Mean E* of the mix with PG binder grade 76-28 is in between the mean E* with earlier two binder grades and is not significantly different from the other two.

As shown in table 28, there is no significant difference in mean E* at 21.1° C between the mixes with PG binder grades 70-28 and 76-28. However; there is a significant difference in mean E* between the mixes with PG binder grade 64-22 and the other two mixes.

As shown in Table 29, there is a significant difference in mean E* at 37.8° C between mixes with PG binder grade 64-22 and 70-28. Mean E* of the mix with PG binder grade 76-28 is in between the mean E* of the mixes with earlier two binder grades and is not significantly different from the other two.

As shown in Table 30, there is no significant different in mean E* at 54.4°C. However, the means did follow the expected trend with the stiffer binders producing stiffer mixtures.

The results above show that mixes with PG 64-22 would give different dynamic modulus values at the lower temperature range but give similar dynamic modulus values as PG 70-28 and PG 76-28 at the higher temperature ranges. Mixes with PG 70-28 or PG 76-28 would not give statistically different E* values in the temperature ranges tested.

AGGREGATE TYPE, QUARRY REGION AND AREA PLACED

The impact of aggregate type, quarry regions and areas placed on E* values were one of the major objectives of our study. To determine the effect of predominate aggregate type, quarry region and area placed, an ANOVA was performed on the main effects only for the data at 5 Hz. Five Hz was chosen because it is one of the medium frequencies in our study and previous analysis showed a consistent effect of frequency on E*. The analysis was performed by PG binder grade because PG binder grade was shown to have a significant effect on E*. The results of the ANOVA are shown in table 31.

TABLE 31. ANOVA on Aggregate Type, Quarry Region and area placed, by PG grade

Source	Degrees Freedom	Sum Squares	mean Squares	F value	Prob.>Fcr
			PG 64-22		
Aggregate	3	1.0880E+12	3.6267E+11	0.23	0.8784
Quarry	3	8.0486E+11	2.6829E+11	0.17	0.9185
Placed	2	6.3625E+11	3.1813E+11	0.20	0.8209
Error	87	1.3993E+14	1.6084E+12		
Total	95	1.42E+14			
			PG 70-28		
Aggregate	3	2.9008E+12	9.6693E+11	0.83	0.4786
Quarry	3	1.0945E+12	3.6483E+11	0.31	0.8146
Placed	2	1.7375E+12	8.6875E+11	0.75	0.4755
Error	87	1.0082E+14	1.1589E+12		
Total	95	1.07E+14			
			PG 76-28		
Aggregate	3	3.5764E+12	1.1921E+12	0.93	0.4281
Quarry	3	4.4939E+11	1.4980E+11	0.12	0.9497
Placed	2	5.8262E+11	2.9131E+11	0.23	0.7965
Error	87	1.1111E+14	1.2771E+12		
Total	95	1.16E+14			

As shown in table 31, aggregate type, quarry region and region placed had no significant effect on E* values. This means that it is not necessary to use different dynamic modulus values for mixes with different aggregate type, quarry, region and region placed in Oklahoma.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Testing at -10°C was not possible because of moisture accumulation and frost build up at this temperature. The MEPDG does not require testing at this temperature.
2. Drierite, a moisture absorbing substance, was kept inside the chamber while testing at lower temperature to help prevent moisture build up.
3. Tuning setting had to be changed during the tests at higher temperatures because of the sensitivity of the LVDT at lesser load and higher temperature.
4. Test temperature had a major effect on the dynamic modulus values, which were as predicted.
5. E* values for mixes with PG 64-22 binder were significantly different than mixes made with PG 70-28 or PG 76-28 binder. However, E* for mixes with PG 70-28 and PG 76-28 were not significantly different.
6. Mix type S3 was not significantly different than mix type S4.
7. Aggregate type, quarry region and location placed had no significant effect on the measured dynamic modulus values of the mix.

RECOMMENDATIONS:

Evaluation of dynamic modulus values of Oklahoma mixes showed that the E* values were significantly different for the mixes with different PG binder grades and at different test temperatures. Previous work has shown that frequency has a significant effect on E*. No significant difference was found in E* values for the different mix types, aggregate type, quarry or region placed. Table 32 shows the recommended dynamic modulus values for Oklahoma mixes. These values are the average of all measured values which were not significantly different.

TABLE 32. Recommended dynamic modulus values

Temperture (°C)	Frequency (Hz)	E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	3797461	3613043	3810555
4.4	10	3465053	3041399	3201268
4.4	5	3117437	2607544	2779542
4.4	1	2413290	1847672	2023594
4.4	0.5	2160656	1590176	1767155
4.4	0.1	1608085	1108807	1269197
21.1	25	2061910	1615263	1798207
21.1	10	1574505	1145160	1297430
21.1	5	1308857	914904	1045587
21.1	1	845481	561613	643980
21.1	0.5	697203	457662	519637
21.1	0.1	445432	298820	332253
37.8	25	652393	460642	565421
37.8	10	502609	373295	445706
37.8	5	389406	301063	352512
37.8	1	222859	185423	208434
37.8	0.5	175971	154334	171035
37.8	0.1	112886	113197	120327
54.4	25	230215	229868	230545
54.4	10	169562	181068	195058
54.4	5	140239	157229	160191
54.4	1	76194	80102	82281
54.4	0.5	64816	70595	70434
54.4	0.1	52132	58851	55303

More research is needed to evaluated the effect of different PG binder sources on the dynamic modulus values.

REFERENCES

1. *Mechanistic Empirical Pavement Design Guide*. 1-37A NCHRP. http://www.trb.org/mepdg/. Accessed January-August, 2007.

2. "Determining Dynamic Modulus of Hot-Mix Asphalt Concrete mixtures, AASHTO Designation: TP 62." *Standard Specifications for Transportation Materials and Methods of Sampling and Testing"*, Twenty-fifth Edition, Part II A, Tests, American Association of State Highway and Transportation Officials, Washington D.C., 2003, pp. 2-13.

3. M. King, M. Momen, and Y.R. Kim," Typical Dynamic Moduli Values of Hot Mix Asphalt in North Carolina and Their Prediction*," Compendium of Papers, 84th Annual Meeting of the Transportation Research Board*. CD-ROM. Transportation Research Board, national Research Council, Washington. D.C., January 2005.

4. Tran, Nam H. and Hall, Kevin D. ,"Evaluating the Predictive Equation in Determining Dynamic Moduli of Typical Asphalt Mixtures Used in Arkansas', *Association of Asphalt paving Technologist(AAPT), Volume 74E, Electronic Journal*, 2005

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, vol. 71*,2002.

6. Tran, Nam H. and Hall, Kevin D. ,'Investigation of the Simple Performance Test for Measuring Hot Mix Asphalt Dynamic Modulus", University of Arkansas, Fayetteville, Arkansas, August 2003.

7. Bari, Javed and Witczak M., " Evaluation of the Effect of Lime Modification on the Dynamic Modulus Stiffness of HMA: Use with the New RR 1929 M-E Pavement Design Guide", *Transportation Research Board: Journal of the Transportation Research Board*, *No. 1929,*National Research Council, Washington, D.C., 2005,pp 10-19.

8. Schwartz, Charles W., 'Evaluation of the Witczak Dynamic Modulus Predictive Model', *Compendium of Papers, 84th Annual Meeting of the Transportation Research Board*. CD-ROM. Transportation Research Board, National Research Council, Washington. D.C., January 2005.

9. Shah, A., McDaniel, R. and Gallivan, V., ‘Evaluation of Mixtures Using Dynamic Modulus Tester: Results and Practical Considerations’ *Association of Asphalt paving Technologist (AAPT), Volume 74E, Electronic Journal*, 2005.

10. Birgisson, B., Sholar, G. and Roque, R. ‘Evaluation of Predicted Dynamic Modulus for Florida Mixtures’, *Transportation Research Board: Journal of the Transportation Research Board*, *No. 1929,* National Research Council, Washington, D.C., 2005.

11. Sotil, A., Kaloush, K. E., and Witczak M. W. ,”Reduced Confined Dynamic Modulus Testing Protocol for Asphalt Mixtures”, *Transportation Research Board: Journal of the Transportation Research Board, No. 1891,* National Research Council, Washington, D.C., January 2004, pp 153-162

12. Cross, S. A., and Jakatimath Y.,”*Evaluation of Cold In-Place Recycling For Rehabilitation of Transverse Cracking on US 412*”, Final Report, Report No. FHWA-OK-07-(05), Oklahoma Department of Transportation, Oklahoma City, Oklahoma, December 2007.

13. Meyer, M.A. and Chawla, K.K.: "*Mechanical Behavior of Materials*," New Jersey, 1999, pp 98-103.

14. McCrum, Buckley, and Bucknell: "*Principles of Polymer Engineering*," 2003, pp 117-176.

15. Silbey and Alberty: “*Physical Chemistry, 4th edition”*. John Wiley & Sons, Inc,2001

16. Dougan, C.E., Stephens, J. E., and Mahoney J. , “*E*-Dynamic Modulus, Test Protocol, Problems and Solutions*”, Report CT-SPR-0003084-F-03-3, University of Connecticut, Storrs, April 2003

17. “Hot Mix Asphalt Materials, Mixtures Design and Construction”, 2nd Edition, Roberts et al, NAPA Education Foundation, Lanham, MD 1996

18. Garcia, G., and Thompson M. R., “*HMA Dynamic Modulus Predictive Models: A Review*”, Research Report FHWA-ICT-07-005, Illinois Center of Transportation, January 2007.

19. Witczack M.W, Kaloush K, Pellinen T., El-Basyouny M., Quintus H.V., “*Simple. Performance Test for Superpave Mix Design*”, NCHRP Report 465, 2002, pp.6.

20. Tran, N.H., and Hall, K.D. “Evaluation of Testing Protocols for Dynamic Modulus of Hot-Mix Asphalt,” *Transportation Research Record 1970*, Transportation Research Board, National Research Council, Washington, DC, 2006; pp. 126—132.

21. Francken,L., and Vanelstraete, A., " Complex moduli of bituminous materials: A rational method for the interpretation of test results", *Mechanical Test for Bituminous Materials*, Edited by Di Benedetto & Francken, 1997.

22. "Mixture Conditioning of hot-mix Asphalt, AASHTO Designation:R30-02" *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Twenty-fifth Edition, Part I B, Specifications, American Association of State Highway and Transportation Officials, Washington, D.C.,2005.

APPENDIX

TABLE A1. S3 Durant mix formula

Mix Type	S3		
Mix ID	Durant		
Design Number		3073-CCC-05002	
Material	**% in Blend**		
#57 Rock	29		Martin-Marietta@Mill Creek,OK(3502)
1/4" Chips	28		Martin-Marietta@Mill Creek,OK(3502)
Manufactured Sand	24		TXI@Mill Creek,OK(3504)
Asphalt Sand	10		Martin-Marietta@Mill Creek,OK(3502)
Sand	9		Tate Sand Co.@Durant,OK
Gradation			
Sieve Size	**% Passing(field)**		**%Passing (lab)**
1"	100		100
3/4"	97		97
1/2"	85		85
3/8"	79		79
No.4	61		61
No.8	41		41
No.16	32		32
No.30	25		25
No.50	19		19
No.100	8		8
No.200	4.1		4.1
% AC	4.2	4.2	4.2
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.703	2.703	2.703
Gmm	2.503	2.504	2.504
Gsb	2.682	2.682	2.682
VTM(%)	4.0		
VMA(%)	13.2		
VFA(%)	70		
DP	1		

TABLE A2. S3 Clenton mix formula

Mix Type	S3			
Mix ID	Clenton S3			
Design Number		3073-OAEST-05090		
Material		**% in Blend**		
3/4" Chips		24		Dolese@ Cooperton,OK(3801)
5/8"		10		Dolese@ Cooperton,OK(3801)
Shot		21		Dolese@ Cooperton,OK(3801)
Screenings		30		Dolese@ Cooperton,OK(3801)
Sand		15		McLemore Pit,Elk City,OK
Gradation				
Sieve Size	**% Passing(field)**		**% Passing (lab)**	
1"	100		100	
3/4"	100		100	
1/2"	90		85	
3/8"	73		69	
No.4	48		47	
No.8	37		32	
No.16	28		23	
No.30	23		19	
No.50	12		8	
No.100	7		5	
No.200	4.8		4	
% AC	4.1	4.1	4.1	
PG	64-22	70-28	76-28	
Gb	1.026	1.0274	1.0288	
Gse	2.734	2.734	2.734	
Gmm	2.559	2.560	2.560	
Gsb	2.703	2.703	2.703	
VTM(%)	4			
VMA(%)	13			
VFA(%)	69			
DP	1.6			

TABLE A3. Sawyer S3I Mix Formula

Mix Type	S3 INS	
Mix ID	Sawyer	
Design Number		3073-CCC-03051

Material	**% in Blend**	
Pile #7	30	Martin-marietta @sawyer,OK(1206)
D-Rock	21	Martin-marietta @sawyer,OK(1206)
Man Sand	8	Martin-marietta @sawyer,OK(1206)
Screenings	33	Martin-marietta @sawyer,OK(1206)
Sand	8	Martin-marietta @Grant,OK

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	95	95
1/2"	74	74
3/8"	69	69
No.4	54	54
No.8	44	44
No.16	38	38
No.30	28	28
No.50	15	15
No.100	10	10
No.200	5.7	5.7

% AC	5.1	5.1	5.1
PG Grade	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.590	2.590	2.590
Gmm	2.403	2.404	2.404
Gsb	2.537	2.537	2.537

VTM(%)	4.0
VMA(%)	13.7
VFA(%)	71
DP	1.3

TABLE A4. S3 Norman Mix Formula

Mix Type	S3
Mix ID	Norman
Design Number	3074-OAEST-04071

Material	**% in Blend**	
5/8" Chips	27	Hanson Aggregates @ Davis, OK (5008)
Washed Screenings	30	Martin Marietta @ Davis OK (5005)
Stone Sand	28	Martin Marietta @ Davis OK (5005)
Sand	15	GMI Meridian Pit

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	85
1/2"	99	84
3/8"	89	74
No.4	67	52
No.8	45	31
No.16	30	16
No.30	21	9
No.50	12	5
No.100	6	3
No.200	3.1	2.7

% AC	4.6	4.6	4.6
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.671	2.671	2.671
Gmm	2.488	2.488	2.488
Gsb	2.654	2.654	2.654

VTM(%)	4.0
VMA(%)	14.4
VFA(%)	72.2
DP	0.6

TABLE A5. S4 Bellco Kemp Mix Formula

Mix Type S4
Mix ID Bellco
Design Number S4PV0170600600

Material	**% in Blend**	
3/4 Chips	19	Kemp Stone @ Fairland,OK (5807)
Mine Chat	27	Bingham Sand & Gravel @Miami, OK (5807)
Screenings	40	Kemp Stone @ Fairland,OK (5807)
Drag Sand	9	Bingham Sand & Gravel @Miami, OK (5807)
Sand	5	Muskogee Sand @Muskogee,OK

Gradation **Sieve Size**	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	94	94
3/8"	87	89
No.4	61	62
No.8	38	40
No.16	28	28
No.30	20	20
No.50	15	12
No.100	9	7
No.200	6.7	5.2

% AC	4.95	4.95	4.95
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.626	2.626	2.626
Gmm	2.438	2.438	2.439
Gsb	2.609	2.609	2.609

VTM(%)	4.0
VMA(%)	14.7
VFA(%)	69
DP	1.1

TABLE A6.S4 Evans Mix Formula

Mix Type	S4
Mix ID	Evans
Design Number	3074-OAEST-05059

Material	**% in Blend**	
3/4" Chips	13	Bellco Materials @ Pawhuska,OK (5703)
Mine Chat	32	3-Way Materials @Baxter Springs,KS(8011)
Screenings	40	Bellco Materials @ Pawhuska,OK (5703)
Sand	15	Sober Sand @ Ponca City,OK

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	96	96
3/8"	90	90
No.4	78	78
No.8	53	53
No.16	35	35
No.30	25	25
No.50	16	16
No.100	10	10
No.200	7.6	7.6

% AC	5	5	5
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.649	2.649	2.649
Gmm	2.503	2.504	2.504
Gsb	2.631	2.631	2.631

VTM(%)	4.0
VMA(%)	14.9
VFA(%)	73.2
DP	1.6

TABLE A7. Arkhola S4 Mix Design

Mix Type	S4
Mix ID	Arkhola Glover
Design Number	3074-ARKH-05022

Material	**% in Blend**	
#67 Rock	23	Arkhola S&G @Okay,OK(7302)
3/8" Chips	36	Arkhola S&G @Zeb,OK (1102)
Washed Screenings	24	Arkhola S&G @Zeb,OK (1102)
Screenings	17	Arkhola S&G @Okay,OK(7302)
AntiStrip Add.(Perma-Tac Plus)		Akzo-Nobel @Waco, TX

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	92	92
3/8"	82	86
No.4	56	55
No.8	34	34
No.16	21	21
No.30	14	14
No.50	11	8
No.100	8	6
No.200	5.7	4.1

% AC	5.35	5.35	5.35
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.637	2.637	2.637
Gmm	2.433	2.433	2.433
Gsb	2.586	2.586	2.586

VTM(%)	4.0
VMA(%)	14.5
VFA(%)	72.4
DP	0.9

TABLE A8. NH (160) Mix Formula

Mix Type	S4
Mix ID	NH (160)
Design Number	3074-BCC-04179

Material	**% in Blend**	
5/8" Chips	23	Dolese @ Cooperaton, OK (3801)
Screenings	32	Martin-Marietta @ Snyder, OK (3802)
Manufactured Sand	15	Martin-Marietta @ Snyder, OK (3802)
Screenings	15	Dolese @ Cooperaton, OK (3801)
Sand	15	Kline Sand @ Woodward,OK

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	99	99
3/8"	89	89
No.4	74	74
No.8	54	54
No.16	41	41
No.30	31	31
No.50	20	20
No.100	9	9
No.200	5.6	5.6

% AC	5.35	5.35	5.35
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.666	2.666	2.666
Gmm	2.456	2.456	2.457
Gsb	2.642	2.642	2.642

VTM(%)	4.0
VMA(%)	15.5
VFA(%)	74.2
DP	1.1

TABLE A9. J+R Sand Mix Formula

Mix Type	S4
Mix ID	J & R Sand
Design Number	3074-JRS-04006

Material	**% in Blend**	
3/4" Chips	25	Eastern Colorado Aggregates @ Holly,CO (8104)
Screenings	60	Eastern Colorado Aggregates @ Holly,CO (8104)
Sand	15	J & R Sand Co., Inc

Gradation **Sieve Size**	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	91	91
3/8"	84	84
No.4	73	73
No.8	53	53
No.16	38	38
No.30	26	26
No.50	17	17
No.100	11	11
No.200	6.1	6.1

% AC	5.5	5.5	5.5
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.639	2.639	2.639
Gmm	2.429	2.429	2.430
Gsb	2.59	2.59	2.59

VTM(%)	4.0
VMA(%)	14.8
VFA(%)	73
DP	1.3

TABLE A10. Cummins Enid-2 Mix Formula

Mix Type	S4		
Mix ID	Cummins Enid-2		
Design Number	3074-CCC-05018		

Material	**% in Blend**	
5/8" Chips	22	Martin-Marietta @ Snyder, OK (3802)
3/8" Chips	30	Dolese @ Richard Spur, OK (1601)
Stone sand	23	Dolese @ Cyril,OK (0801)
Screenings	16	Dolese @ Richard Spur, OK (1601)
Sand	9	Kerns @ Watonga,OK

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	98	98
3/8"	89	89
No.4	54	54
No.8	35	35
No.16	25	25
No.30	20	20
No.50	16	16
No.100	9	9
No.200	4.2	4.2

% AC	4.8	4.8	4.8
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.661	2.661	2.661
Gmm	2.472	2.472	2.473
Gsb	2.651	2.651	2.651

VTM(%)	4.0
VMA(%)	14.5
VFA(%)	72.5
DP	0.9

TABLE A11. Cummins Enid-1 Mix Formula

Mix Type S4
Mix ID Cummins Enid-1
Design Number 3074-CCC-04063

Material	**% in Blend**	
5/8" Chips	35	Dolese @ Cyril,OK (0801)
3/8" Chips	8	Dolese @ Richard Spur, OK (1601)
Stone sand	30	Dolese @ Cyril,OK (0801)
Screenings	19	Dolese @ Richard Spur, OK (1601)
Sand	8	Kerns @ Watonga,OK

Gradation **Sieve Size**	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	99	99
3/8"	89	89
No.4	59	59
No.8	46	46
No.16	26	26
No.30	20	20
No.50	15	15
No.100	7	7
No.200	3.4	3.4

% AC	4.7	4.7	4.7
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.672	2.672	2.672
Gmm	2.485	2.485	2.485
Gsb	2.636	2.636	2.636

VTM(%)	4.0
VMA(%)	14
VFA(%)	72.1
DP	0.8

TABLE 12A. Tiger TSI S4 Mix Formula

Mix Type	S4
Mix ID	Tiger Ind. Trans. Sys.,Inc
Design Number	3074-OAEST-05066

Material	**% in Blend**	
3/4" chips	12	Dolese @ Hartshorne,OK (6101)
5/8" Chips	22	Dolese @ Hartshorne,OK (6101)
Screenings	51	Tiger I.T. System @ Enterprise,OK (3101)
Sand	15	Pryor Sand @ Whtefield,OK
AntiStrip Add. (perma-Tac Plus)		Akzo-Nobel @Waco,TX

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	93	97
3/8"	82	86
No.4	61	64
No.8	48	49
No.16	35	41
No.30	27	32
No.50	18	20
No.100	13	11
No.200	6.9	6

% AC	5	5	5
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.627	2.627	2.627
Gmm	2.437	2.437	2.438
Gsb	2.571	2.571	2.571
VTM(%)	4.0		
VMA(%)	13.6		
VFA(%)	70.6		
DP	1.4		

VITA

SUMESH KC

Candidate for the Degree of

Master of Science/Civil Engineering

Thesis: Evaluation of Dynamic Values of Oklahoma Mixes

Major Field: Civil Engineering

Biographical:

Personal Data:
Sumesh KC

Education:
Bachelor in Engineering/Civil Engineering, Institute of Engineering, Pulchowk, Lalitpur, Nepal, October, 2004

Completed the requirements for the Master of Science in civil engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2007.

Experience:
Worked as a Research Assistant in Asphalt lab, Civil and Environmental Engineering Department, Oklahoma State University, Stillwater, from August 2004 to December 2007

Professional Memberships:
Member, Nepal Engineering Council

Name: Sumesh KC Date of Degree: December, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EVALUATION OF DYNAMIC MODULUS VALUES OF OKLAHOMA MIXES

Pages in Study:65 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study:
Cold feed belt samples of S3 and S4 mixtures were sampled throughout the state. Mixtures were selected to include the major aggregate types in Oklahoma and to cover each region of the state. Replicate samples were tested for Dynamic Modulus |E*| at optimum asphalt content with PG 64-22, PG 70-28 and PG 76-28, the commonly used binder grades in Oklahoma.

Findings and Conclusions:
Tests were performed in accordance with AASHTO TP 62-03. Samples were tested at 4.5±0.8% VTM. Binder grade was found to have a significant effect on dynamic modulus. Mix type did not have a significant effect on dynamic modulus. Quarry region and aggregate type did not have a significant effect on the dynamic modulus values of the mixes.

Default dynamic modulus values were recommended for use in the M-EPDG for Oklahoma HMA mixtures.

ADVISER'S APPROVAL: Dr. Stephen A Cross