Determination of Dynamic Modulus Master Curves

for Oklahoma HMA Mixtures

Final Report

by

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					*Approximate Conversions from SI Units*				
Symbol	**When you know**	**Multiply by**	**To Find**	**Symbol**	**Symbol**	**When you know**	**Multiply by**	**To Find**	**Symbol**
		LENGTH					**LENGTH**		
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yds
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.00155	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectacres	ha	ha	hectacres	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallon	3.785	liters	L	L	liters	0.2642	gallon	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Fahrenheit	9/5(°C)+32	degrees Celsius	°F
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

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The Mechanistic-Empirical Pavement Design Guide (M-EPDG) uses a hierarchical approach with three levels of material characterization for asphalt materials. The first level provides the highest design reliability and each succeeding level is a drop in design reliability. Dynamic modulus is one of the required material characteristics. The first or highest level of reliability entails measured dynamic modulus. The second and third levels of entail the use of predictive equations.

The objective of this research was to gather the data necessary to develop a procedure where ODOT could approach a high level of reliability for HMA dynamic modulus master curves without performing detailed dynamic modulus testing for each mix in a pavement system. ODOT HMA mixtures were evaluated to determine which material and mix characteristics affect dynamic modulus and the resulting master curve. Based on the results of the analysis, the need for typical master curves based on asphalt binder grade, aggregate type and/or nominal aggregate size were determined.

Twenty-one mixes were sampled for testing. Mixtures were sampled to represent the different mixes and aggregates used in Oklahoma. Each mix was prepared with PG 64-22, PG 70-28 and PG 76-28 at optimum asphalt content and tested for dynamic modulus in accordance with AASHTO TP 62-03.

The use of RAP and PG binder grade had a significant effect on measured dynamic modulus. ODOT mix designation (nominal aggregate size), aggregate type, and region placed did not have a significant effect on measured dynamic modulus. Recommendations of typical dynamic modulus values for Oklahoma HMA mixtures are made.

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TABLE OF CONTENTS

page

page

LIST OF FIGURES

page

LIST OF TABLES

page

page

page

CHAPTER 1

STATEMENT OF WORK

PROBLEM STATEMENT

The objective of the National Cooperative Highway Research Program (NCHRP) project 1-37A was to develop a new mechanistic-empirical design procedure. The final product was originally called the *AASHTO 2002 Design Guide for Design of New and Rehabilitated Pavement Structures*. Delivery of the final product was delayed; however, the work is complete and agencies are beginning to develop the material input parameters necessary for use in the Design Guide.

With the development of the *2002 Design Guide for New and Rehabilitated Pavement Structures,* or the Mechanistic-Empirical Pavement Design Guide (M-EPDG) as it is now called, there is a new emphasis on mechanistic-empirical thickness design procedures. Material input parameters for these procedures are typically either resilient modulus or dynamic modulus, and Poisson's ratio.

One of the major differences between the new M-EPDG and the current 1993 AASHTO Design Guide (1) is materials characterization. In the 1972 version of the AASHTO Design Guide, asphalt mixtures were assigned an "a" coefficient to characterize their structural support. In subsequent versions, asphalt mixtures were assigned an "a" coefficient based on resilient modulus. The resilient modulus test was usually performed in accordance with ASTM D 4123 at three test temperatures and three stress levels. The resilient modulus at 68^{o}F was generally recommended for use in determining the "a" coefficient. However, the test was rarely performed and "a" coefficients were typically assigned to different mix types by DOTs.

The M-EPDG (2) uses dynamic modulus and Poisson's ratio as the material characterization parameters for asphalt mixtures. The procedure is contained in AASHTO TP 62-03. The test is performed at different temperatures, stress levels and loading frequencies and a master curve is developed that describes the relationship between mix stiffness, mix temperature and time rate of loading. This master curve is combined with a binder aging model and is used as the basis for selecting mixture modulus values over the service life of the pavement.

The M-EPDG uses a hierarchical approach with three levels of materials characterization. The first level provides the highest design reliability and 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 stabilized mixture used in the pavement structure. The second and third levels of material characterization entail the use of master curves from predictive equations developed by the NCHRP 1-37A research team (2).

OBJECTIVES

The objectives of this research project were to gather the data necessary to develop a procedure where ODOT could approach a high level of reliability for HMA master curves without performing detailed dynamic modulus testing for each mix in a pavement system. This would result in improved pavement performance by providing HMA master curves with near level 1 reliability while using level 2 or level 3 material characterization costs.

The improved reliability and reduced cost would be accomplished by evaluating ODOT HMA mixtures and determining which material and mix characteristics affect dynamic modulus and the resulting master curve. By evaluating the dynamic modulus of ODOT mixtures, the material and or mix characteristics that affect dynamic modulus, and the resulting master curve, would be identified. Based on the results of the analysis, the need for typical master curves based on asphalt binder grade, aggregate type and/or nominal aggregate size would be determined.

WORK PLAN

To accomplish the objectives of this study the following work plan was proposed.

Task 1: Literature Review: The available literature would be reviewed to gain insight on current work regarding evaluation of dynamic modulus of HMA mixtures. Development of the test procedure is extensively covered in the draft final report of the M-EPDG and would not be the emphasis of the literature review. The emphasis of the literature review would be on recent work to gain insight as to the most efficient way to perform dynamic modulus testing.

Task 2: Equipment Purchase and Setup: A universal testing machine, test head fixtures, LVDTs and an environmental chamber are required for performing dynamic modulus. The same equipment would be capable of performing the proposed simple performance test. However, the equipment being designed for the simple performance test would not be sufficient for complete dynamic modulus testing. A universal testing machine capable of performing both dynamic modulus and the simple performance test would be purchased for this project.

Dynamic modulus sample preparation requires three additional pieces of equipment, a Superpave Gyratory Compactor (SGC), a core drill and a saw that can prepare the 100 mm diameter by 150 mm high test samples from the 150 mm diameter by 175 mm tall SGC compacted test samples. Oklahoma State University (OSU) has a core drill and saw that can trim the SGC compacted samples to the required test sample size, reducing equipment costs.

OSU has a Troxler SGC which cannot compact a sample to the required 175 mm height for dynamic modulus testing. Therefore, it is proposed that OSU swap its Troxler SGC for the ODOT Central Materials Laboratory Pine SGC for the duration of the proposed study. At the completion of the study the SGC compactors would be returned to each agency. OSU would be responsible for transporting the SGC compactors.

Task 3: Mixture Sampling: Once the equipment is purchased and set up, mixture sampling would commence. Field produced HMA mixtures from current ODOT projects would be sampled for dynamic modulus testing. Using field produced mixtures would allow the evaluation of “real” mixtures and remove the mix design element from the research project, saving time and money. ODOT S-2, S-3 and S-4 mixtures would be sampled. Mixtures would be selected to include the four predominant aggregate types used for HMA mixes in Oklahoma, limestone, granite, sandstone and gravel.

The aggregates, asphalt cement and mix designs would be obtained from these projects and the materials returned to the OSU asphalt laboratory. The mixtures would be reproduced in the lab at the N_{design} compactive effort used in the field. Mixtures would be evaluated with PG76-28, PG70-28 and PG64-22 asphalt cements, the three grades used in Oklahoma by ODOT. The proposed test matrix is shown in table 1.

Table 1. Proposed Test Matrix

Predominate Aggregate	S-2 Mix	S-3 Mix	S-4 Mix
Limestone	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28
Sandstone	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28
Granite	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28
Sand & Gravel	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28	PG 64-22 PG 70-28 PG 76-28

Task 4: Dynamic Modulus Testing: The mixtures sampled in Task 3 would be tested for dynamic modulus in accordance with AASHTO TP 62-03.

Task 5: Data Analysis: The test data obtained in Task 4 would be evaluated to determine dynamic modulus. The mixtures would be sorted into subsets and the data analyzed using ANOVA techniques to determine if and where significant differences exist between subsets. Recommended subsets include PG asphalt grade, mix designation (nominal aggregate size), aggregate type and region of the state. The objective of this task would be to determine how many subsets and where they should be divided for default dynamic modulus values.

Task 6: Evaluation of Predictive Equations: The default dynamic modulus values determined in Task 5 would be compared to the results determined from mix parameters using the predictive equations in the M-EPDG.

Task 7: Final Report: A final report would be prepared summarizing the significant findings from the study. Recommendations for default dynamic modulus values for ODOT mixtures for use in the M-EPDG would be provided.

BENEFITS

Benefits of implementation of the mechanistic-empirical procedures of the M-EPDG are numerous and are adequately spelled out on the web page of the 2002 Design Guide at www.2002designguide.com (3). The specific benefits of completing the proposed research program are as follows:

1. Test equipment, test procedures and trained personnel would be available to ODOT for determination of dynamic modulus of HMA mixtures.
2. Default dynamic modulus master curves would be developed for ODOT HMA mixtures.
3. By utilizing the master curves developed from this study, near level 1 reliability would be available for level 2 and level 3 material characterization costs, resulting in cost savings to ODOT in reduced materials testing and improved reliability in pavement performance.

CHAPTER 2

BACKGROUND

NEED FOR THE M-EPDG

The various editions of the *AASHTO Guide for Design of Pavement Structures* have served well for several decades; nevertheless, many serious limitations exist for their continued use as the nation's primary pavement design procedures. Listed below are some of the major deficiencies of the existing design guide (2):

- Traffic loading deficiencies
- Rehabilitation deficiencies
- Climatic effects deficiencies
- Subgrade deficiencies
- Surface materials deficiencies
- Base course deficiencies
- Truck characterization deficiencies
- Construction and drainage deficiencies
- Design life deficiencies
- Performance deficiencies
- Reliability deficiencies

GENERAL INPUT REQUIREMENTS

The guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (referred to hereinafter as M-EPDG) was developed to provide the highway community with a state-of-the-practice tool for design of new and rehabilitated pavement structures. The M-EPDG is a result of a large study sponsored by AASHTO in cooperation with the Federal Highway Administration and was conducted through the National Cooperative Highway Research Program (NCHRP) [NCHRP-1-37A]. The final product is design software and a user guide. The M-EPDG is based on comprehensive pavement design procedures that use existing mechanistic-empirical technologies. M-EPDG software is temporarily available for trial use on the web. The software can be downloaded from www.trb.org/mepdg. The software is described as a user oriented computational software package and contains documentation based on M-EPDG procedures (2). The M-EPDG employs common design parameters for traffic, subgrade, environment, and reliability for all pavement types (2).

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 (2). The focus of this study is on the input data required in the *Layers* section for HMA mixtures.

Layers

The input requirement for asphalt layers uses a hierarchical approach with three levels of materials characterization. The first level provides the highest design reliability and each succeeding level is a drop in design reliability. Within each level there are three input screens, *Asphalt Mix, Asphalt Binder* and *Asphalt General*. Any level of reliability may be used with any layer in the pavement system. However, the same level of reliability is required for each input screen within a pavement layer (2).

Asphalt Mix Screen

The *Asphalt Mix* screen allows three levels of reliability; however, the required inputs are the same for reliability levels 2 and 3. For level 1 reliability, dynamic modulus is required at a minimum of three temperatures and three frequencies. One of the temperatures must be greater than 51.7^{o}C (125^{o}F). For level 2 and 3 reliability, the dynamic modulus is calculated using a predictive equation based on mix properties. The required mix properties for the *Asphalt Mix* screen are the aggregate percent retained on the 3/4 inch, 3/8 inch and No. 4 sieves and the percent passing the No. 200 sieve (2).

Asphalt Binder Screen

The *Asphalt Binder* screen allows three levels of reliability; however, the required inputs are the same for reliability levels 1 and 2. For level 1 or 2 reliability, the shear modulus (G*) and phase angle (δ) for the binder are required from the dynamic shear rheometer (DSR) test. The DSR parameters are required at a minimum of three temperatures. For level 3 reliability the grading of the asphalt binder is all that is required. The M-EPDG allows the use of PG graded binders, viscosity (AC) graded binders or penetration graded binders (2).

Asphalt General Screen

The *Asphalt General* screen allows three levels of reliability; however, the required inputs are the same for all three reliability levels. The *Asphalt General* screen is separated into four sections: *General, Poisson's Ratio, As Built Volumetric Properties* and *Thermal Properties*. The *General* section requires the reference temperature for development of master curves for dynamic modulus. The default value is 70^{o}F but other temperatures may be entered. The *Poisson's Ratio* section allows the user to select the default value of 0.35 for asphalt, enter a user defined value or allow the software to calculate Poisson's ratio using a predictive equation. *As Built Volumetric Properties* include volume binder effective (Vbe), air voids and compacted unit weight. Default values are 11.0%, 8.5% and 148 pcf, respectively. Required *Thermal Properties* are thermal conductivity and heat capacity. Either user defined or default values may be entered. Default values are 0.67 BTU/hr-ft-^{o}F for thermal conductivity and 0.23 BTU/lb-^{o}F for heat capacity (2).

MASTER CURVES

To perform a level 1 analysis using the M-EPDG, dynamic modulus at a minimum of three test temperatures and three frequencies are required (2). AASHTO TP 62-03 recommends six frequencies and five test temperatures. The dynamic modulus values at different frequencies are used by the M-EPDG to develop master curves. According to the user manual for the M-EPDG (2), the stiffness of HMA at all levels of temperature and time rate of load is determined from a master curve constructed at a reference temperature (generally taken as 70°F). Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve of dynamic modulus as a function of time formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. The greater the shift factor, the greater the temperature dependency (temperature susceptibility) of the mixture. Figure 1 shows the results of a dynamic modulus test on an HMA sample and how the data at each temperature can be shifted to form a smooth curve. Figure 2 shows the resultant master curve at a reference temperature of 70° F (21.1° C).

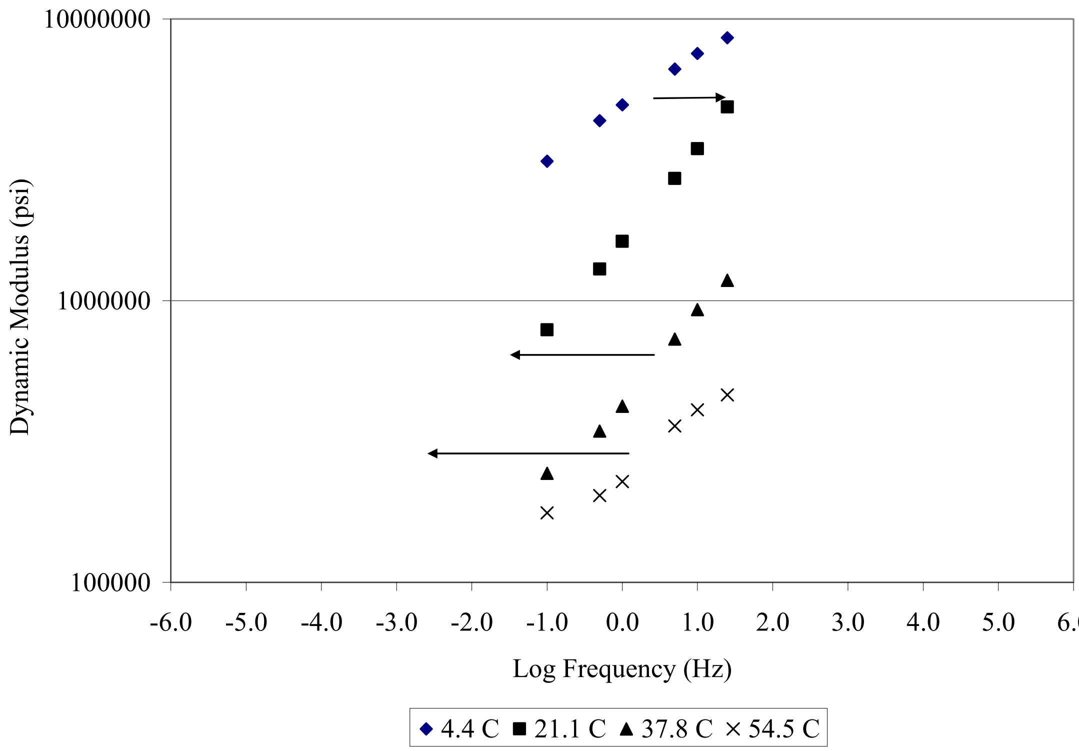

Figure 1 Results of dynamic modulus test on HMA sample.

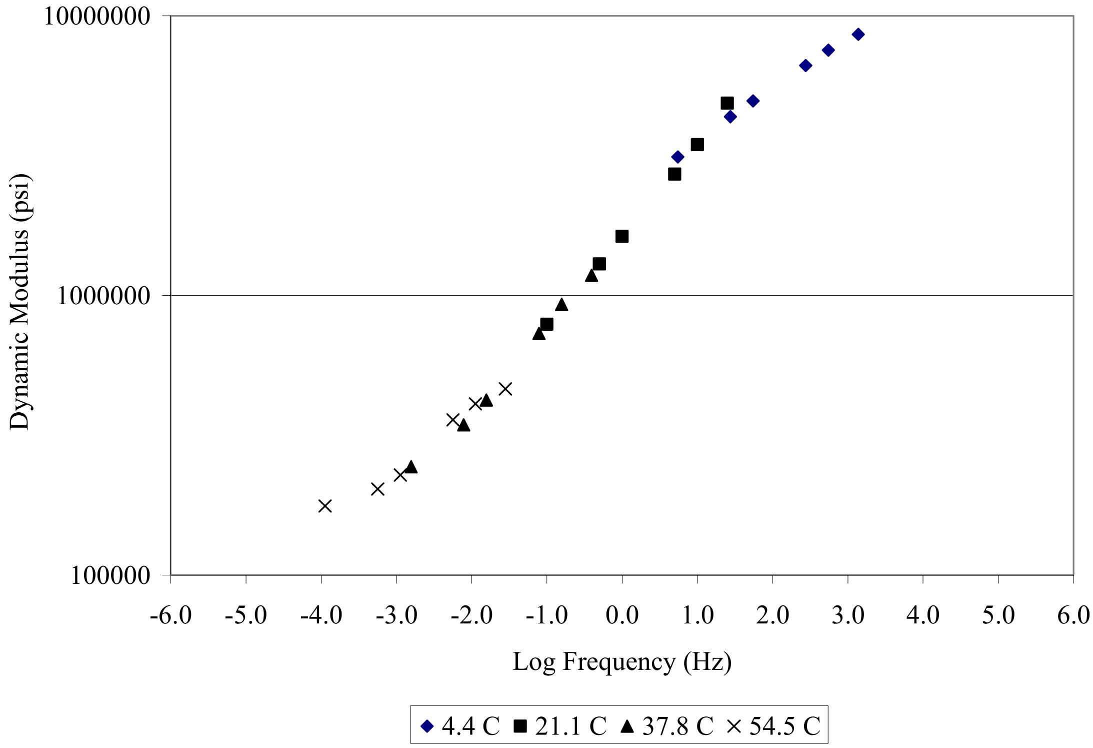

Figure 2 Test data shifted to form master curve.

According to the M-EPDG (2), the master modulus curve can be mathematically modeled by a sigmoidal function described as:

$$\log\left(E^*\right) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}} \qquad [1]$$

Where,

t_r = reduced 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.

The shift factor can be shown in the following form:

$$a(T) = t / t_r \qquad [2]$$

Where,
a(T) = shift factor as a function of temperature
t = time of loading at desired temperature

t_r = reduced time of loading at reference temperature
T = temperature of interest.

For precision, a second order polynomial relationship between logarithm of the shift factor i.e. log a (Ti) and temperature in degrees Fahrenheit is used. The relationship can be expressed as follows:

$$L\log a\left(Ti\right) = aTi^2 + bTi + c \qquad [3]$$

Where,

a(Ti) = shift factor as a function of temperature Ti
Ti = temperature of interest, °F
a, b and c = coefficients of the second order polynomial.

The time-temperature superposition is performed by simultaneously solving for the four coefficients of the sigmoidal function (δ, α, β, and γ) as described in equation [1] and the three coefficients of the second order polynomial (a, b, and c) as described in equation [3]. A nonlinear optimization program for simultaneously solving these seven parameters is used for developing master curves.

E* PREDICTIVE EQUATION

The M-EPDG uses laboratory E* data for Level 1 reliability designs, while it uses E* values from Witczak's E* predictive equation for Levels 2 and 3 reliability designs. There are two other E* predictive equations available, the Hirsch model (4) and the New Revised Witczak E* Predictive Model (5). The current version of the Witczak's E* predictive model that is included in the M-EPDG was based upon 2,750 test points and 205 different HMA mixtures (34 of which are modified). Most of the 205 HMA mixtures were dense-graded using unmodified asphalts. The current version of the E* predictive equation in the M-EPDG, updated in 1999, is (2):

$$\log E^* = 1.249937 + 0.249937 + 0.02932\rho_{200} - 0.001767\left(\rho_4\right)^2 - 0.002841\rho_4 - 0.058097V_a$$
$$-0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017\left(\rho_{38}\right)^2 + 0.005470\rho_{34}}{1+e^{\left(-0.603313-0.313351\log(f)-0.393532\log(\eta)\right)}} \qquad [4]$$

Where,

E* = dynamic modulus, 10^5 psi
η = asphalt viscosity at the age and temperature of interest, 106 Poise (use of RTFO aged viscosity is recommended for short-term oven aged lab blend mix)
f = loading frequency, Hz
Va = air void content, %

V_{beff} = effective asphalt content, % by volume
ρ_{34} = cumulative % retained on 3/4 in (19 mm) sieve
ρ_{38} = cumulative % retained on 3/8 in (9.5 mm) sieve
ρ_{4} = cumulative % retained on #4 (4.76 mm) sieve
ρ_{200} = % passing #200 (0.075 mm) sieve.

The major difference between the current Witczak E* predictive model and the other two models is in how the asphalt viscosity is determined. In the Hirsh model (4) and the new revised Witczak model (5), the asphalt viscosity is determined directly in the model from the binder complex shear modulus (G*) and phase angle (δ), determined in accordance with AASHTO T 315 *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).* In the current E* predictive equation in the M-EPDG, the asphalt viscosity must be calculated in a separate equation.

In the Witczak E* predictive equation [4], the asphalt viscosity (η) can be determined using equation [5] if the binder complex shear modulus (G*) and phase angle (δ), determined in accordance with AASHTO T 315 *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, are known at a minimum of three test temperatures (5).

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \qquad [5]$$

Where,

η = asphalt viscosity, cP
G^* = binder complex shear modulus, Pa
δ = binder phase angle, °.

Once the asphalt viscosity (η) is determined, the ASTM VTS parameters shown in equation [6] are found by linear regression of equation [6] after log-log transformation of the viscosity and log transformation of the temperature data (5).

$$\log\log\eta = A + VTS \log T_R \qquad [6]$$

Where,

η = asphalt viscosity, cP
A, VTS = regression parameters
T_R = temperature, ° Rankine.

If AASHTO T 315 test results are not available, default values for A and VTS, measures of asphalt's temperature susceptibility, are available in the M-EPDG if the grade of the asphalt cement is known. The viscosity is calculated using the default A and VTS values and equation [6]. The viscosity at each test temperature is used with equation [4] to calculate the dynamic modulus (2). The default A and VTS values for the three asphalt binders used in this study are shown in Table 2.

Table 2. Default A and VTS Parameters from M-EPDG

Parameters	PG 64-22	PG 70-28	PG 76-28
A	10.980	9.715	9.200
VTS	-3.680	-3.217	-3.024

Tran and Hall (6) compared measured dynamic modulus values to predicted values using the Witzack predictive equation found in the M-EPDG for Arkansas HMA mixtures. The authors reported that there was no significant difference between measured and predicted dynamic modulus values, indicating that the Witzack predictive equation could be used to estimate dynamic modulus values of Arkansas mixes.

Birgisson et al. (7) compared measured dynamic modulus results from 28 Florida HMA mixtures to the results using the Witczak predictive equation. Results showed a bias in the results and a multiplier was recommended to correlate Florida mixtures to the predictive equation results. Birgisson et al. (7) reported that using binder viscosities from DSR testing were lower than measured values and that using binder viscosities from the Brookfield rotational viscometer resulted in slightly higher predicted modulus values compared to measured values.

EFFECT OF MIXTURE VARIABLES ON DYNAMIC MODULUS

The available literature was reviewed to gain insight on current work regarding evaluation of dynamic modulus of HMA mixtures. Development of the test procedure is extensively covered in the draft final report for the M-EPDG and was not the emphasis of the literature review.

King, et al. (8) studied the effects of mixture variables on dynamic modulus for different North Carolina mixes. Mixtures were prepared with different aggregate gradations, aggregate sources, binder sources, binder PG grades and asphalt contents. Master curves for each mix were prepared based on measured dynamic modulus values provided by the North Carolina DOT. The results of the study indicated that binder source, binder PG grade and asphalt content had a significant effect on dynamic modulus. However, aggregate source and gradation, within the same NCDOT mix classification, did not have a significant effect on dynamic modulus.

Tran and Hall (6) evaluated the sensitivity of measured dynamic modulus values of Arkansas HMA mixtures. Mix parameters evaluated included maximum nominal aggregate size (25 mm and 12.5 mm), void content (4.5% and 7.0%), and asphalt content (optimum and optimum ± 0.5%). The results indicated that aggregate size, air void content and asphalt content all had a significant effect on measured dynamic modulus.

Shah, McDaniel and Gallivan (9) summarized the results of dynamic modulus values obtained from 11 HMA mixtures from the North Central Superpave User Producer Group. Mixtures made with PG 58-28 binders were found to be statistically different from mixtures made with PG 70-28 binders. Superpave mixtures produced significantly different dynamic modulus values than Marshall mixtures, and Superpave mixtures had lower dynamic modulus values than stone mastic asphalt (SMA) mixtures.

CHAPTER 3
FIELD PRODUCED HMA MIXTURES

INTRODUCTION

The objectives of this study were to determine the dynamic modulus (E*) of laboratory prepared HMA mixes, compare the laboratory E* values with predicted E* values from the M-EPDG and recommend default E* values for use with the M-EPDG. Twenty-one HMA mixes were tested with three different PG binders. The E* values were compared based on PG binder, nominal aggregate size (ODOT mix designation), use of RAP, predominate aggregate type and region of the state where the mix was produced and placed.

MIXTURES

To meet the above objectives, samples of mixtures produced for ODOT projects were collected over a two-year period. Mixtures were obtained by either contacting contractors directly or by contacting ODOT personnel to obtain mix samples. Mixtures were sampled to include the four predominant aggregate types used in Oklahoma, limestone, sandstone, granite/rhyolite and crushed gravel; and the three main mix designations, S-2, S-3 and S-4. Twenty-five mixtures were sampled by either OSU personnel, contractor personnel or ODOT personnel. Four of the mixtures sampled could not be evaluated for dynamic modulus because either the mix could not be verified or sufficient materials were not provided to allow completion of the required verification and testing.

All mix samples were cold feed belt samples obtained after aggregate blending but prior to entering the drum dryer. If the mixtures contained RAP, the RAP was sampled from the RAP stockpile. Mixtures with RAP were not a part of the scope of this project. However, many of the S-2 and S-3 mixtures provided contained 25% RAP and were tested because of the high percentage of S-3 and S-2 mixtures containing RAP used in the state. Mix design information on each mix sampled was obtained from either the contractor or ODOT. Table 3 shows the mixtures sampled, predominant coarse aggregate, quarry and region of the state, and where in the state the mix was placed. For the purpose of this study, the state was divided into five regions, the northeast (NE), southeast (SE), central (C), southwest (SW) and northwest (NW).

Tables 4 - 6 provide a breakdown of mixtures by quarry region, region placed and predominant aggregate, respectively. There were very few S-2 mixtures produced during the period of this research project. Only two S-2 mixtures were available for sampling and one of these mixtures contained 25% RAP. As shown in table 3, the quarries in Oklahoma are primarily located in the southwest, central and northeast regions of the state. These three regions produced 17 of the 21 mixtures tested. Table 4 shows the region in the state where the mixtures were placed. Five mixtures were placed in the northwest, six in the northeast, one in the southwest, four in the southeast and five in the central part of the state.

Table 3. Summary of Mixtures Sampled and Tested

Mix	Recycle	Mix Design No.	Quarry Region	Predominate Aggregate	Quarry	Region Placed
S-4	No	05059	NE	Limestone	Bellco	NE
S-4	No	04006	NW	Gravel (basalt)	Holly	NW
S-4	No	04063	SW SW	Sandstone Limestone	Cyril Richard Spur	NW
S-4	No	05018	SW SW	Granite Limestone	Snyder Richard Spur	NW
S-4	No	04179	SW SW	Limestone Granite	Coopertown Snyder	NW
S-4	No	05066	SE	Limestone	Hartshorne	SE
S-4	No	00600	NE	Limestone	Ottawa	NE
S-4	No	05022	NE NE	Limestone Sandstone	Cherokee Wagnor	NE
S-3	No	03051	SE	Sandstone	Sawyer	SE
S-3	No	05702	C	Rhyolite	Davis	C
S-3	No	04071	C	Rhyolite	Davis	C
S-3	Yes	04062	SW SW	Limestone Sandstone	Richard Spur Cyril	NW
S-3	Yes	05010	NE	Limestone	Bellco	NE
S-3	No	05002	C	Granite	Mill Creek	SE
S-3	Yes	03043	C	Limestone	Richard Spur	C
S-3	Yes	20610	NE	Limestone	Tulsa	NE
S-3	No	05024	NE	Limestone	Cherokee	NE
S-3	No	05090	SW	Limestone	Cooperton	SW
S-3	Yes	03162	C	Rhyolite	Davis	C
S-2	No	05007	SE	Cherty LS	Stringtown	SE
S-2	Yes	04068	C	Limestone	Davis	C

Table 4. Mixtures Sampled by Quarry Region

	Quarry Region				
Mix	NW	NE	SW	SE	C
S-2	0	0	0	1	1
S-3	0	3	2	1	5
S-4	1	3	3	1	0

Table 5. Mixtures Sampled by Region Placed

	Region Placed				
Mix	NW	NE	SW	SE	C
S-2	0	0	0	1	1
S-3	1	3	1	2	4
S-4	4	3	0	1	0

Table 6. Mixtures Sampled by Aggregate Type

Predominate Aggregate	Mix		
	S-2	S-3	S-4
Limestone (NE)	0	3	3
Limestone	2	3	4
Sandstone	0	2	2
Granite	0	1	2
Rhyolite	0	3	0
Crushed Gravel	0	0	1

Table 6 shows that each major aggregate type is well represented. Sandstone or granite rarely made up all of the aggregate in a mix. Two out of three of the granite mixes, and three out of four of the sandstone mixes, contained an almost equal percentage of limestone. These five mixes are double counted in Table 6 for a total of 26 mixes. There were 15 mixtures using limestone coarse aggregate. Ten of these mixtures were comprised mainly of limestone with three mixes containing an almost equal portion of granite and two containing an almost equal portion of sandstone. Six of the limestone mixtures consisted of the softer limestones from the northeast region of the state. Four mixtures used sandstone as the predominant aggregate with three of those containing some limestone as well. Three mixtures were granite with two of them containing some limestone. Three mixtures were mainly rhyolite. There was one mixture with crushed gravel. Crushed gravel is not a common source of coarse aggregate in Oklahoma.

MIXTURE VERIFICATION

Mixtures Without RAP

The objective of this study was not to exactly reproduce field mixtures, only to produce mixture similar to field produced mixtures. The aggregates from each mix sampled were oven dried at 230^{o} F and then the entire amount was sieved over a 1.5-inch sieve through No. 50 sieve, inclusive, and the material separated into sizes for batching. Next, 4,700 g samples were prepared to the job mix formula (JMF) gradation and to the "as received" gradation. Each sample was mixed to the JMF asphalt content with the same PG grade asphalt as listed in the mix design. Replicate samples were compacted to the mix design N_{design} number of gyrations in accordance with AASHTO T 312. After compaction, the samples were tested for bulk specific gravity in accordance with AASHTO T 166. The samples were then reheated until just soft enough to separate and the maximum theoretical specific gravity (Gmm) was determined in accordance with AASHTO T 209. After Gmm determination, the asphalt content of each sample was determined in accordance with AASHTO T 308 and the recovered aggregate gradation determined in accordance with AASHTO T 30.

A voids analysis was performed on each sample to determine if either gradation met ODOT mix requirements. If the VTM was not 4.0%, the asphalt content was adjusted to produce 4.0% VTM and the new mix properties calculated in accordance with the procedures of AASHTO R 35 (10). If adjusting the asphalt content produced a mixture that would meet ODOT mix requirements from either gradation, then two verification samples were compacted at the new asphalt content. If both gradations met the mix requirements then the "as received" gradation was selected to optimize aggregate supply. If neither gradation met the mix requirements, then the gradation was altered and the process repeated until a satisfactory mix was produced or materials were exhausted.

Mixtures With RAP

Mixtures with RAP were handled in a similar manner as mixtures without RAP. RAP was allowed to air dry prior to being separated by sieving. The RAP percentage was held to the JMF percentage and the gradation of the RAP was held constant to the "as received" RAP gradation. Mixtures with RAP were more difficult to produce, and the gradation of the virgin aggregates often had to be adjusted to produce a mixture that would meet ODOT mix requirements. RAP samples were always stockpile samples. The inherent difficulty in obtaining representative samples from a stockpile probably accounted for the majority of the difficulty experienced with RAP samples.

Appendix A contains the information on the mixes evaluated. The tables show the asphalt content, gradation and mix properties of the samples tested. The first column under gradation lists the belt sample gradation or "as received" gradation of the mix. The column labeled "%Passing Lab" is the gradation utilized to fabricate the test samples.

CHAPTER 4

DYNAMIC MODULUS TEST PROCEDURES

DYNAMIC MODULUS TESTING

Preparation of Dynamic Modulus Test Specimen

Samples for dynamic modulus testing were prepared by mixing the aggregates with three different PG graded asphalt cements. The three different asphalt cements were PG 64-22 OK, PG 70-28 OK and PG 76-28 OK. Test samples were prepared in accordance with the requirements of AASHTO TP 62-03 (11).

Sample Requirements
The AASHTO TP 62 requirements for dynamic modulus test samples are provided in table 7. Dynamic modulus testing requires a 150 mm high by 100 mm diameter sample, of a target air void content, be cored from 175 mm high by 150 mm diameter sample. There is no simple conversion factor for compaction of a 175 mm high, 150 mm diameter SGC compacted sample to a cored dynamic modulus (E*) sample with a given target air void content. The two samples will not have the same VTM due to a density gradient present in SGC compacted samples. A trial and error procedure is required to determine the density or void content of the larger sample required to produce a cored and sawed test sample of the intended void content.

Recommended target air void contents for HMA samples are 4-7%. For this project, the HMA test samples were compacted to a void content of 4.5 ± 1 % VTM. After several trials, it was determined that a 175 mm high by 150 mm diameter sample compacted to 6.0 ± 1% VTM would yield a dynamic modulus test sample of the target 4.5 ± 1% void content.

Batching
A 5,700 to 6,300 gram batch of aggregate, batched to the desired gradation, was required to produce a 175 mm high by 150 mm diameter test specimen with 6.0 ± 1% VTM. When the compacted sample was cored to 100 mm diameter and sawed to the required sample height of 150 mm, the required target void content of 4.5 ± 1% VTM was obtained.

Table 7. Criteria for Acceptance of Dynamic Modulus Test Specimens (11)

Criterion Items	Requirements
Size	Average diameter between 100 mm 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 T 312)
Coring	Core the nominal 100 mm diameter test specimens from the center 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 2.5 mm
End Preparation	The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm across diameter The specimen end shall not depart from perpendicular to the axis 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

Mixing

All samples were mixed in a bucket mixer (figure 3). The asphalt cement was stirred occasionally to prevent localized overheating while being heated to the mixing temperature of 325^{o} F. The aggregates were heated for a minimum of four hours at the mixing temperature of 325^{o} F. Approximately one hour before mixing, the compaction molds, spoons and spatulas were placed in the oven and brought to the mixing temperature. For mixing, the aggregates were placed in the bucket mixer and the desired amount of asphalt cement added. The mixture was mixed until well coated, approximately two minutes.

Figure 3 Bucket mixer used for mixing HMA samples.

Compaction
After mixing, the mixture was placed in a large flat pan and placed in an oven set at the compaction temperature (300^o F) for two hours in accordance with AASHTO R 30. The samples were compacted in a 150 mm diameter mold to a height of 175 mm using a Pine SGC. To produce the required 175 mm high by 150 mm diameter sample with a void content of 6.0 ± 1 %, 5,700 to 6,300 grams of aggregate were required. Thirty to 45 gyrations were typically required to reach a height of 175 mm.

Coring & Sawing
After compaction, the samples were extruded from the compaction molds, labeled and allowed to cool to room temperature. Next, the compacted samples were cored and sawed to obtain a 150 mm tall by 100 mm diameter test sample with 4.5 ± 1 % air voids. The samples were cored using a diamond studded core barrel to obtain the required diameter of 100 mm (figure 4). The cored samples were then sawed to obtain the required 150 mm height (figure 5). The cored and sawed samples were washed to eliminate all loose debris. After cleaning, the samples were tested for bulk specific gravity in accordance with AASHTO T 166. The dry mass was determined by using the CoreDry™ apparatus.

From the bulk specific gravity and the calculated Gmm for each PG graded asphalt cement, the air void content was determined.

Figure 4 Sample being cored to required test diameter.

Figure 5 Sample being sawed to obtain parallel faces.

The HMA test samples were next checked for conformance to the sample requirements of AASHTO TP 62-03. The criterion for acceptance of the samples was listed in the table 7. Samples which met all criteria were fixed with six steel studs to hold three linear variable displacement transducers (LVDTs). The LVDT have a gauge length of 4 inches. Care was taken to precisely position the studs 4 inches apart and 2 inches from the center of the sample. Once the epoxy was dry and the studs were firmly attached to the sample, they were ready for testing. Figure 6 shows a sample prepared for dynamic modulus testing.

Figure 6 Test specimens for dynamic modulus testing.

Testing

Specimens were tested for dynamic modulus according to AASHTO TP 62-03 (7). The procedure is briefly explained in figure 7. The test parameters are provided in table 8.

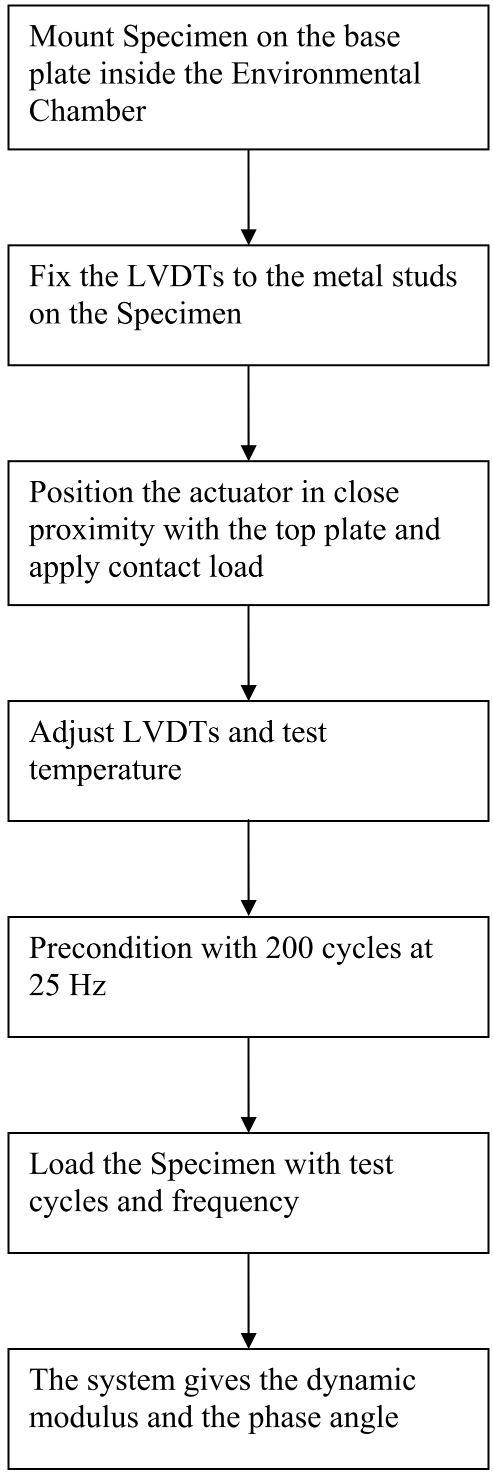

Figure 7 Test procedures for dynamic modulus of HMA samples.

Table 8. Test Parameters for Dynamic Modulus Test (11)

Test Parameters	Values		
Frequencies	25, 10, 5, 1, 0.5, 0.1 Hz		
Temperature	4.4°, 21.1°, 37.8° and 54.4°C (40°, 70°, 100° and 130° F)		
Equilibrium Times	Specimen Temperature,°C (°F)	Time from room temperature, hrs 25°C (77°F)	Time from previous test temperature, hrs
	4.4 (40)	Overnight	4 hrs or overnight
	21.1 (70)	1	3
	37.8 (100)	2	2
	54.4 (130)	3	1
Contact Load	5 percent of the test load		
Axial Strains	Between 50 to 150 microstrain		
Dynamic load range	Depends on the specimen stiffness and ranges between 2 and 400 psi		
Load at Test Frequency *	At 4.4° C (40° F): 100 to 200 psi		
	At 21.1° C (70° F): 50 to 100 psi		
	At 37.8° C (100° F): 20 to 50 psi		
	At 54.4° C (130° F): 5 to 10 psi		
Preconditioning	With 200 cycles at 25Hz		
Cycles	At 25Hz: 200 cycles		
	At 10Hz: 200 cycles		
	At 5Hz: 100 cycles		
	At 1Hz: 20 cycles		
	At 0.5Hz: 15 cycles		
	At 0.1Hz: 15 cycles		

* The load should be adjusted to obtain axial strains between 50 and 150 microstrain.

Figure 8 shows the setup of OSU's dynamic modulus testing machine. The machine has two main components, a control unit and an operating unit. Both units are connected with different power supplies. The control unit (figure 9) is compromised of a computer and temperature control unit. The computer gives commands to the operating unit through software, provided by Interlaken Inc., the manufacturer of the machine. The temperature control unit is used to regulate different test temperatures in the testing chamber (which is located in the operating unit) according to the specifications of the test procedures.

Figure 8 OSU's ITC dynamic modulus testing machine.

Figure 9 Control unit for the ITC dynamic modulus machine.

The operating unit (figure 10) consists of a test chamber, hydraulic pump, actuator and a load cell attached to the actuator. The test chamber has the capacity to maintain a temperature of -10° C (14° F) to 125° C (257° F) with an accuracy of ± 1° F. Two load cells of 10 and 2 kips capacity are available, depending on the testing needs. The deformation of the test sample is recorded in a data file using three LVDT's.

The test is initiated by double clicking on the ITC software icon located on the desk top. A screen comes up asking for units and desired load cell. The 2-kip load cell is used for test temperatures at or above 25^{o}C (77^{o}F) and the 10-kip load cell is used for test temperatures below 25^{o}C (77^{o}F). After checking the load cell, the hydraulic pump is turned on and allowed to warm up for 30 minutes before initiating a test.

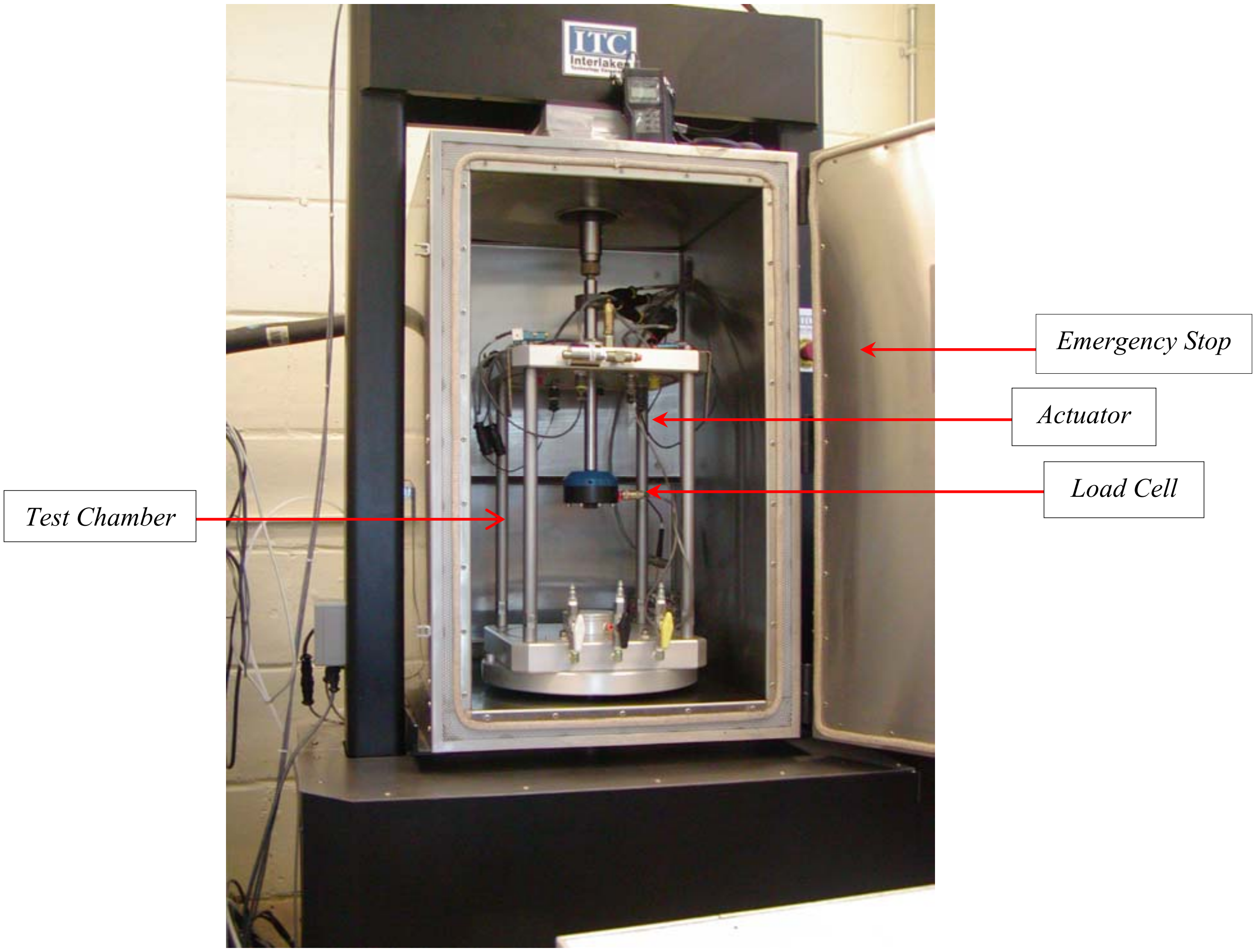

Figure 10 Operating unit for ITC dynamic modulus machine.

A test specimen is placed on a pair of rubber membranes with silicon gel in between them and set on the bottom testing platform located in the operating unit. Three LVDT's are mounted on the steel studs and are adjusted so that they have enough range to record the maximum deformation of the test specimen at all test frequencies at the selected test temperature. Once the test specimen is fixed with all the three LVDT's, a second set of rubber membranes are placed on top of the test specimen and then the top plate is placed on the sample and rubber membranes. The sample is ready for testing (figure 11).

The actuator is manually operated to place the actuator just above the test sample. The software applies the selected confining load (usually 5 psi) during testing. After positioning the actuator, the LVDTs are checked to verify if they are reading and are readjusted if necessary. The test chamber door is closed and the test temperature set using the temperature control panel located in the middle of the control unit shown in figure 12. The sample is allowed to reach equilibrium at the desired test temperature prior to commencing the test.

Figure 11 HMA sample ready for dynamic modulus testing.

Figure 12 Temperature controller.

The software walks the operator through the procedure to perform a test. Basic information for the test specimen and test operators are requested and saved. The initial position of the actuator, which the machine assumes to be the zero position, is input. The desired test temperature is input in degrees centigrade and the output data file is specified. The number of test frequencies and the initial dynamic load and load cycles are input. The load is adjusted by the software during the initial loading to produce the recommended strain measurements.

CHAPTER 5

LABORATORY TEST RESULTS

The main objective of this project was to obtain typical dynamic modulus values for Oklahoma HMA mixture for use in the M-EPDG. Aggregates were obtained from HMA mixtures across the state and the mixtures reproduced using three grades of asphalt cement, PG 64-22, PG 70-28 and PG 76-28. The dynamic modulus was determined on replicate samples in accordance with AASHTO TP 62-03.

AASHTO TP 62-03 (11) requires testing at -10° C (14°F). With OSU's test apparatus, samples could not be easily tested at -10° C (14°F) due to accumulation of frost in the test chamber. When changing from one test sample to another, the environmental chamber door must be opened. When the door was opened, warm moist air mixed with the cold chamber air causing moisture to collect on metal surfaces of the test chamber and test specimen. At -10°C (14°F), significant frost build-up can result making it very difficult and time consuming to perform testing at -10° C (14°F) even though it is listed as a recommended test temperature in AASHTO TP 62-03. The M-EPDG only requires dynamic modulus values at three temperatures for Level 1 analysis, one less than 7°C (45°F), one in-between 7°C and 52°C (45°F - 125°F) and one greater than 52°C (125°F) (2). After only a few attempts, testing at -10°C was discontinued.

At the high test temperature, 54.4°C (130°F), problems were encountered with repeatability of the strain measurements within each test frequency. Several test samples were damaged due to excessive strain. The problem was eventually traced to insufficient sensitivity of the 10-kip load cell at the low loads required at elevated test temperatures. This was corrected by the purchase of a 2-kip load cell. All mixtures tested up to that point were thrown out and new mixtures were sampled and tested. This resulted in significant delays in the completion of this project. Results from the dynamic modulus testing are provided in Appendix B.

CHAPTER 6

ANALYSIS OF TEST RESULTS

LABORATORY DYNAMIC MODULUS

Initial Analysis

The initial analysis looked at the main effects of the experimental design. That is, the effect of recycled material in the mix, mix type (nominal aggregate size), PG grade of the binder, test temperature and test frequency. To determine the effect of these main effects on measured dynamic modulus, an analysis of variance (ANOVA) was performed. Only the main effects were analyzed in this preliminary analysis. The results of the ANOVA are shown in table 9.

Table 9. Results of ANOVA on Main Effects

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
Recycle	1	8.6102E+13	8.6100E+13	249.22	<0.0001
Mix	2	3.5370E+13	1.7685E+13	51.19	<0.0001
PG Grade	2	2.5012E+13	1.2506E+13	36.20	<0.0001
Temp.	3	3.3148E+15	1.1049E+15	3198.16	<0.0001
Freq.	5	5.6341E+14	1.1268E+14	326.15	<0.0001
Error	3010	1.0400E+15	3.4549E+11		
Total	3023	5.0650E+15			

Each main effect had a significant effect on measured dynamic modulus. To determine which level or levels of each main effect had a significant effect on measured dynamic modulus; Duncan's multiple range test was performed. Duncan's multiple range test indicates which means are significantly different at a selected confidence limit. The results of Duncan's multiple range test on the five main effects are shown in tables 10 to 14. Means with the same letter not significantly different at a confidence limit of 95% (alpha = 0.05).

Table 10. Duncan's Multiple Range Test on Recycle

Grouping*	Mean Dynamic Modulus (psi)	n	Recycle
A	1,340,319	1,152	Yes
B	992,848	1,872	No

*Means with the same letter are not significantly different.

Table 11. Duncan's Multiple Range Test on Mix Type

Grouping*	Mean Dynamic Modulus (psi)	n	Mix
A	1,488,258	288	S-2
B	1,156,376	1,584	S-3
C	991,615	1,152	S-4

*Means with the same letter are not significantly different.

Table 12. Duncan's Multiple Range Test on Binder PG Grade

Grouping*	Mean Dynamic Modulus (psi)	n	PG Grade
A	1,225,452	1,008	PG 64-22
B	1,144,898	1,008	PG 76-28
C	1,005,305	1,008	PG 70-28

*Means with the same letter are not significantly different.

Table 13. Duncan's Multiple Range Test on Test Temperature

Grouping*	Mean Dynamic Modulus (psi)	n	Test Temperature (C)
A	2,828,003	756	4.4
B	1,131,025	756	21.1
C	383,787	756	37.8
D	158,057	756	54.4

*Means with the same letter are not significantly different.

Table 14. Duncan's Multiple Range Test on Test Frequency

Grouping*	Mean Dynamic Modulus (psi)	n	Test Frequency (Hz)
A	1,792,178	504	25
B	1,487,307	504	10
C	1,271,400	504	5
D	888,000	504	1.0
E	766,572	504	0.5
F	545,852	504	0.1

*Means with the same letter are not significantly different.

As shown in table 10, the use of recycled material (RAP) had a significant effect on measured dynamic modulus. The use of RAP in a mix stiffens the mix. Evaluation of the effect of RAP on E* was outside the scope of this study; therefore, RAP mixtures were deleted from the data base for all additional analysis. The effect of RAP on S-3 mixtures is analyzed in a separate section of this report.

Table 11 shows that mix designation (nominal aggregate size) had a significant effect on measured E*. The larger the nominal aggregate size, the stiffer or larger the E*. There were only two S-2 mixtures and one of these mixtures contained RAP. Therefore, the S-2 mixtures were removed from further analysis. It should also be noted that half of the S-3 mixtures contained 25% RAP and none of the S-4 mixtures contained RAP. RAP has a significant effect on E*. Subsequent analysis was performed on mixtures without RAP.

Asphalt cement or binder grade had a significant effect on measured E*. At first glance, the ranking of E* by PG grade might not appear as anticipated. As shown in table 12, the PG 64-22 asphalt had a larger average E* than the PG 76-28 or the PG 70-28. The average E* shown in table 12 is for all test temperatures, and even though at high test temperatures a PG 76 is stiffer than a PG 64, a PG -22 is stiffer than a PG -28 at lower test temperatures.

AASHTO TP 62-03 requires dynamic modulus testing at different frequencies and test temperatures because temperature and frequency have a significant effect on dynamic modulus. The results shown in tables 13 and 14 confirm this. Additional analysis indicated that frequency had a consistent effect on dynamic modulus showing an increase in E* with an increase in frequency. Therefore, in order to simplify the analysis, additional ANOVAs were performed using a single frequency. The middle frequency (5 Hz) was selected since all the frequencies showed a similar trend.

The results of the ANOVA shown in table 9 indicated that binder grade, mix type and test temperature all had a significant effect on measured E*. To further study the effects of these factors, a second ANOVA was performed on the E* results without recycled mixtures and at a frequency of 5 Hz. The S-2 mixtures were removed from the analysis as well because there was only one S-2 mix without RAP. The results are shown in table 15.

Table 15. ANOVA on E* at 5 Hz.

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
Mix	1	1.0386E+11	1.0386E+11	0.70	0.4050
PG Grade	2	2.9212E+12	1.4606E+12	9.78	<0.0001
Temp.	3	3.2208E+14	1.0736E+14	719.09	<0.0001
Mix*PG	2	3.5797E+11	1.7899E+11	1.20	0.3032
Mix*Temp.	3	1.2750E+11	4.2502E+10	0.28	0.8365
PG*Temp.	6	2.3416E+12	3.9027E+11	2.61	0.0177
Mix*PG*Temp	6	3.0181E+11	5.0301E+10	0.34	0.9170
Error	264	3.94E+13	1.4930E+11		
Total	287	3.68E+14			

The results of the ANOVA indicate that mix type (S-3 & S-4) did not have a significant effect on measured E* values. Binder grade and test temperature again had a significant effect on average measured E*. The only significant interaction was between PG Grade and test temperature.

Because there were no other significant interactions, Duncan's multiple range test was performed on the three main effects only. Duncan's multiple range test indicates which means are significantly different at a confidence limit of 95% ($\alpha = 0.05$). The results of the Duncan's multiple range tests are shown in tables 16 - 18.

Table 16. Duncan's Multiple Range Test on Mix Type at 5 Hz.

Grouping*	Mean Dynamic Modulus (psi)	n	Mix
A	1,119,637	192	S-4
A	1,079,354	96	S-3

*Means with the same letter are not significantly different.

Table 17. Duncan's Multiple Range Test on Test Temperature at 5 Hz.

Grouping*	Mean Dynamic Modulus (psi)	n	Test Temperature (C)
A	2,834,841	72	4.4
B	1,089,783	72	21.1
C	347,661	72	37.8
D	152,553	72	54.4

*Means with the same letter are not significantly different.

Table 18. Duncan's Multiple Range Test on PG Grade at 5 Hz.

Grouping*	Mean Dynamic Modulus (psi)	n	PG Grade
A	1,238,985	96	PG 64-22
B	1,084,458	96	PG 76-28
B	995,185	96	PG 70-28

*Means with the same letter are not significantly different.

Table 16 shows there is no significant difference in average E* for the S-3 and S-4 mixtures. In the original analysis, mix type had a significant effect on E*. However, in the original analysis recycled mixtures (with RAP) were included and there were no S-4 mixtures with RAP. The presence of RAP increased the average stiffness of the S-3 mixtures to where there was a significant difference between the S-3 and S-4 mixtures.

Removing the recycled S-3 mixtures decreased the average stiffness to a level where the difference in means was not statistically significant.

Table 17 indicates that test temperature has a significant effect on E*, with each test temperature being significantly different. The relationship between average E* and test temperature is shown in figure 13. The best fit equation is for the average values, not all of the data. The R^2 would not be as high if all of the data were used. The figure shows the pronounced effect test temperature has on mixture stiffness. AASHTO TP 62-03 requires testing at different temperatures, as well as different frequencies.

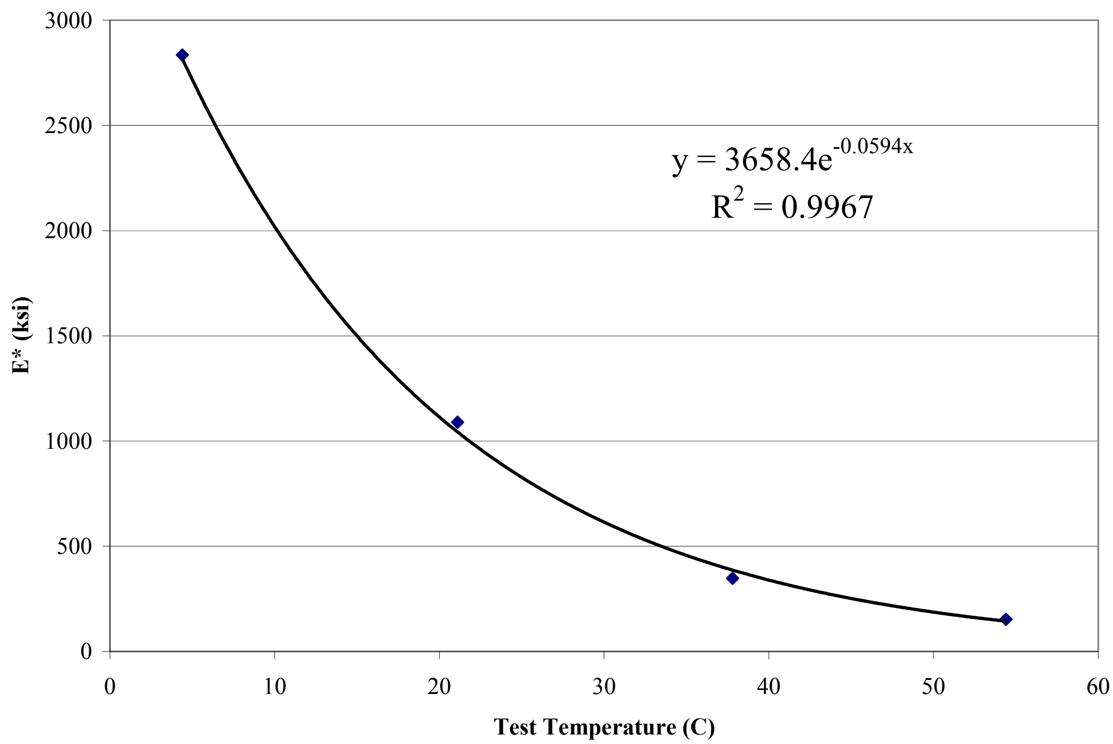

Figure 13 Average E* versus test temperature at 5 Hz.

Binder Grade

Table 18 shows that binder grade has a significant effect on mixture E*. The mixtures with PG 64-22 binder had significantly larger average E* than either the PG 76-28 or the PG 70-28 mixtures. There was no significant difference in E* between the PG 76-28 and the PG 70-28 mixtures. The ANOVA in table 15 indicated an interaction between binder grade and temperature. To fully explore the effect of binder grade on E*, a 1-way ANOVA was performed on binder grade, by test temperature. The results of ANOVA are shown in table 19.

Table 19. ANOVA on PG Grade at 5 Hz., by Test Temperature

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
			4.4 C		
PG Grade	2	3.2300E+12	1.6150E+12	3.55	0.0342
Error	69	3.1431E+13	4.5552E+11		
Total	71	3.4661E+13			
			21.1 C		
PG Grade	2	1.9327E+12	9.6635E+11	8.22	0.0006
Error	69	8.1156E+12	1.1762E+11		
Total	71	1.0048E+13			
			37.8 C		
PG Grade	2	9.4501E+10	4.7251E+10	5.73	0.005
Error	69	5.6861E+11	8.2407E+09		
Total	71	6.6311E+11			
			54.4 C		
PG Grade	2	5.5638E+09	2.7819E+09	1.01	0.3707
Error	69	1.9064E+11	2.7629E+09		
Total	71	1.9621E+11			

The ANOVA on PG Grade by test temperature indicates a significant difference in average mixture E* at 5 Hz for each test temperature except the highest test temperature, 54.4^{o} C. To determine which binder was significantly different at each test temperature, Duncan's multiple range test was performed. The results of Duncan's multiple range test on PG Grade at the four test temperatures are shown in table 20. Means with the same letter are not significantly different at a confidence limit of 95% (alpha = 0.05).

The results from Duncan's multiple range test shown in table 20 indicate that there is no statistical difference in E* values for the two PG -28 binders at the lower three test temperatures. The PG 64-22 binder is significantly stiffer than the PG 70-28 at the same three test temperatures. At the highest test temperature, 54.4^{o} C, there was no significant difference in E* between the three binders. However, the order of the means was as expected with the PG 76-28 being the stiffest, followed by the PG 70-28 and the PG 64-22 binder.

Table 20. Duncan's Multiple Range Test on PG Grade at 5 Hz., by Test Temperature

Grouping*	Mean Dynamic Modulus (psi)	n	PG Grade
	4.4 C		
A	3,117,437	24	PG 64-22
AB	2,779,542	24	PG 76-28
B	2,607,544	24	PG 70-28
	21.1 C		
A	1,308,857	24	PG 64-22
B	1,045,587	24	PG 76-28
B	914,904	24	PG 70-28
	37.8 C		
A	389,406	24	PG 64-22
AB	352,512	24	PG 76-28
B	301,063	24	PG 70-28
	54.4 C		
A	160,191	24	PG 76-28
A	157,229	24	PG 70-28
A	140,239	24	PG 64-22

*Means with the same letter are not significantly different.

Aggregate Type

One of the objectives of this study was to determine the impact of aggregate type on E* and to determine if different default E* values would be required by aggregate type, quarry region or region placed. It was originally believed that mixtures from the northeastern portion of the state, that are produced using softer limestone aggregates, might have a significantly different average E* values than mixtures from the rest of the state. 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. PG binder grade has been shown to have a significant effect on E*; therefore, the analysis was performed by PG binder grade. The results are shown in table 21.

Table 21. ANOVA on Aggregate Type and Region, by PG Grade

Source	Degrees Freedom	Sum Squares	Mean Square	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 21, none of the main effects had a significant effect on measured E* values. This means that aggregate type and region of the state, as measured by quarry region and region placed, did not have a significant effect on measured E* values and that separate master curves are not required. Although the ANOVA indicated no significant difference in E* values, the mean E* values, by aggregate type, are of interest. Therefore, Duncan's multiple range test was performed on aggregate type, by PG binder grade. The results are shown in table 22.

Table 22. Duncan's Multiple Range Test on Aggregate Type and Region

Grouping*	Mean Dynamic Modulus (psi)	n	Aggregate
	PG 64-22		
A	1,367,050	16	Sandstone
A	1,356,811	8	Gravel
A	1,261,458	48	Limestone
A	1,069,387	24	Granite/Rhyolite
	PG 70-28		
A	1,157,621	48	Limestone
A	1,023,243	8	Gravel
A	821,641	16	Sandstone
A	776,657	24	Granite/Rhyolite
	PG 76-28		
A	1,273,642	48	Limestone
A	1,015,373	8	Gravel
A	877,015	24	Granite/Rhyolite
A	862,613	16	Sandstone

*Means with the same letter are not significantly different.

As shown in table 22, there is no significant difference in average E* values for the data at 5 Hz. It is significant to note that granite and rhyolite mixes tend to have the lowest average E* values. However, the differences shown are not statistically significantly different.

MASTER CURVES

To perform a level 1 analysis using the M-EPDG, dynamic modulus at a minimum of three test temperatures and three frequencies are required (2). According to the user manual for the M-EPDG (2), the stiffness of HMA at all levels of temperature and time rate of load is determined from a master curve constructed at a reference temperature (generally taken as 70°F). Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve of the dynamic modulus as a function of time formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. The greater the shift factor, the greater the temperature dependency (temperature susceptibility) of the mixture.

The test data available at the four test temperatures and six frequencies were shifted with respect to time until the curves merged into a single sigmoidal function representing the master curve using a second order polynomial relationship between the logarithm of the shift factors, log a(T_i) and the temperature. As described in Chapter 2, the time-temperature superposition was performed by simultaneously solving for the four coefficients of the sigmoidal function (δ, α, β, and γ) as described in equation [1] and the three coefficients of the second order polynomial (a, b, and c) as described in equation [3]. A Microsoft™ Excel program, developed by Tran (12), was used to conduct the nonlinear optimization for simultaneously solving these seven parameters for developing the master curves. Figures 14–27 show the complete master curves for the S-3 and S-4 mixtures without recycled (RAP) materials.

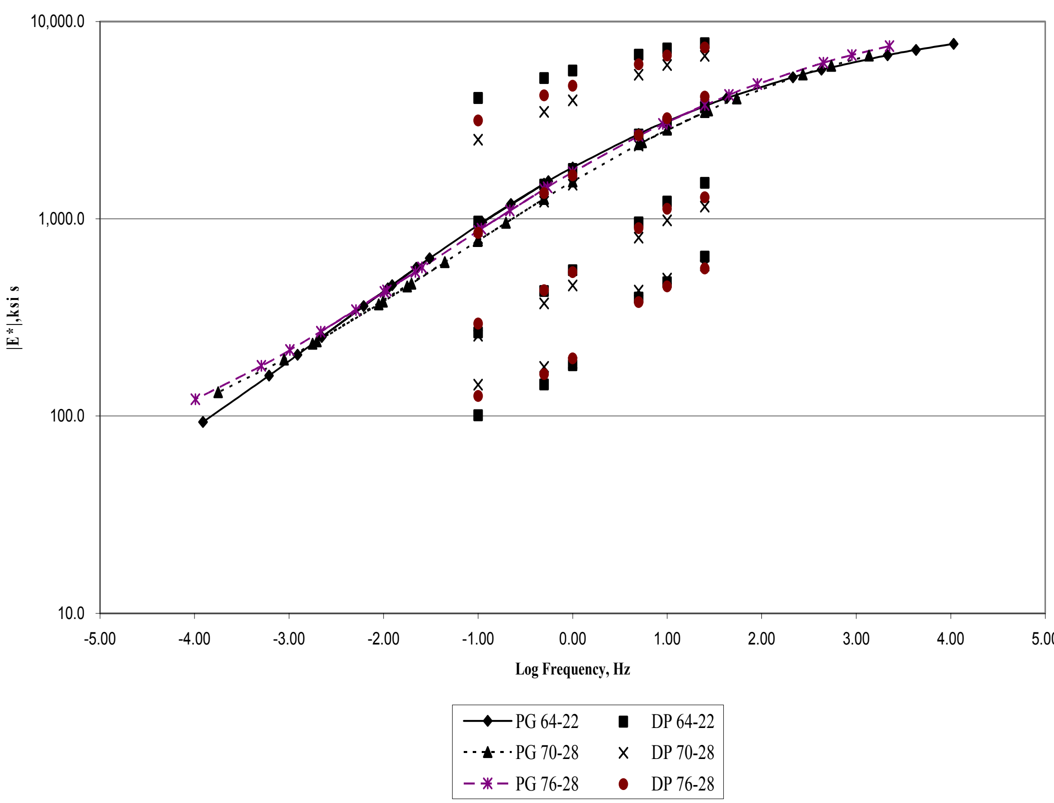

Figure 14 Master curves for Mix Design No. 05059, S-4 mix.

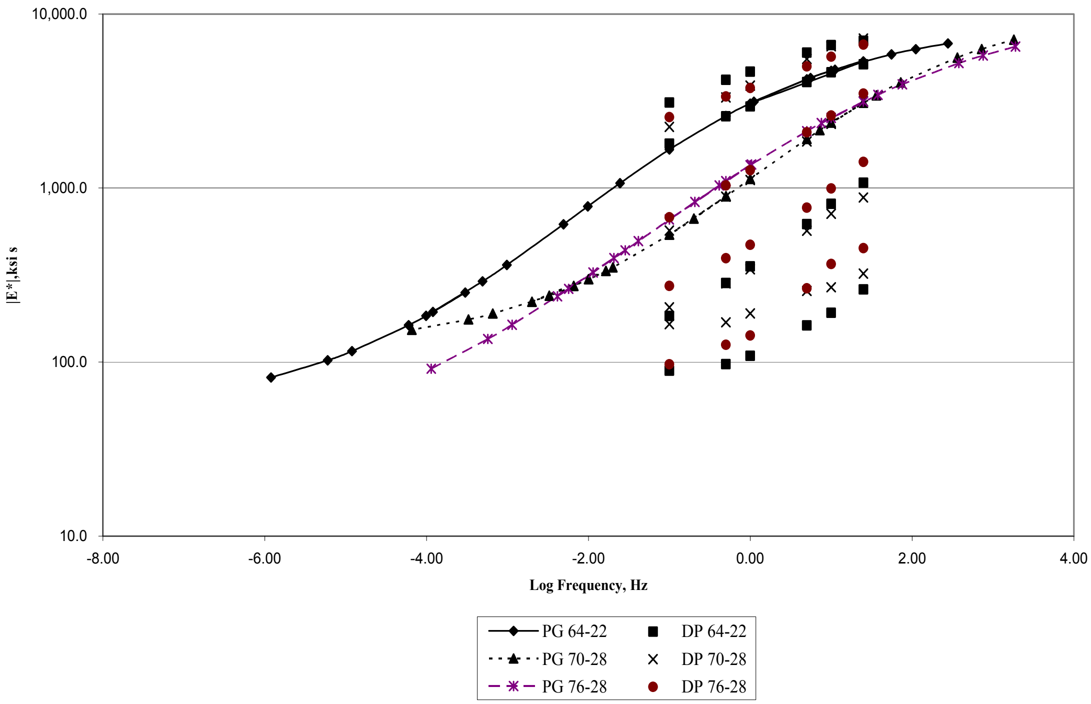

Figure 15 Master curves for Mix design No. 04006, S-4 mix.

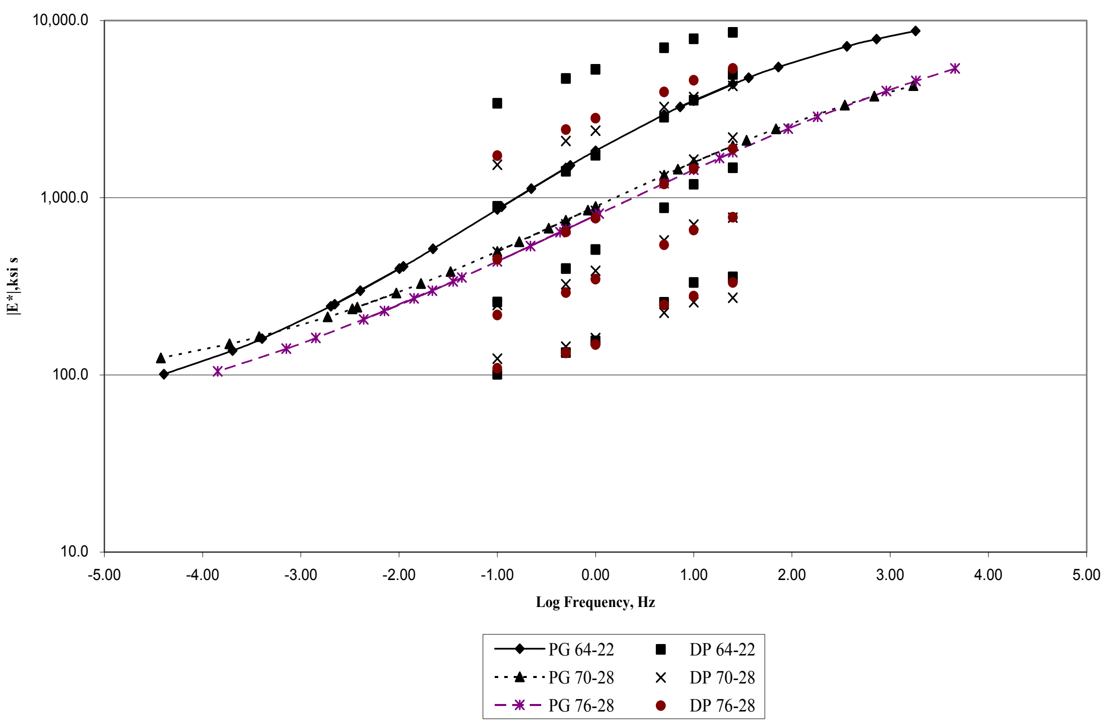

Figure 16 Master curves for Mix Design No. 04063, S-4 mix.

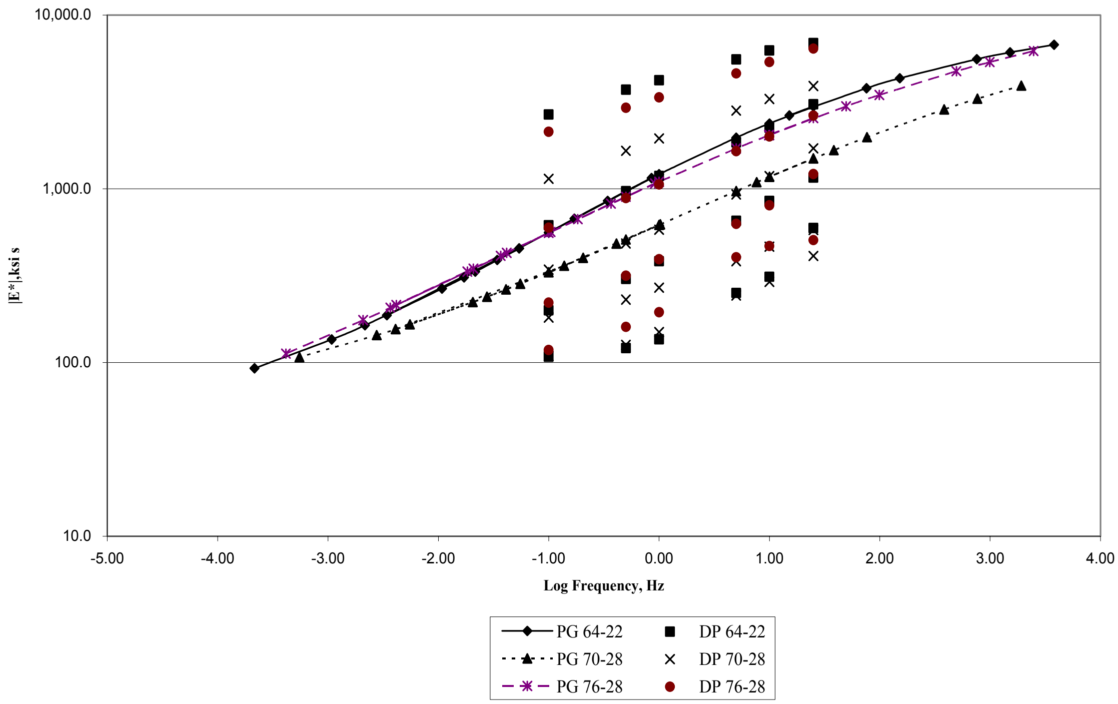

Figure 17 Master curves for Mix Design No. 05018, S-4 mix.

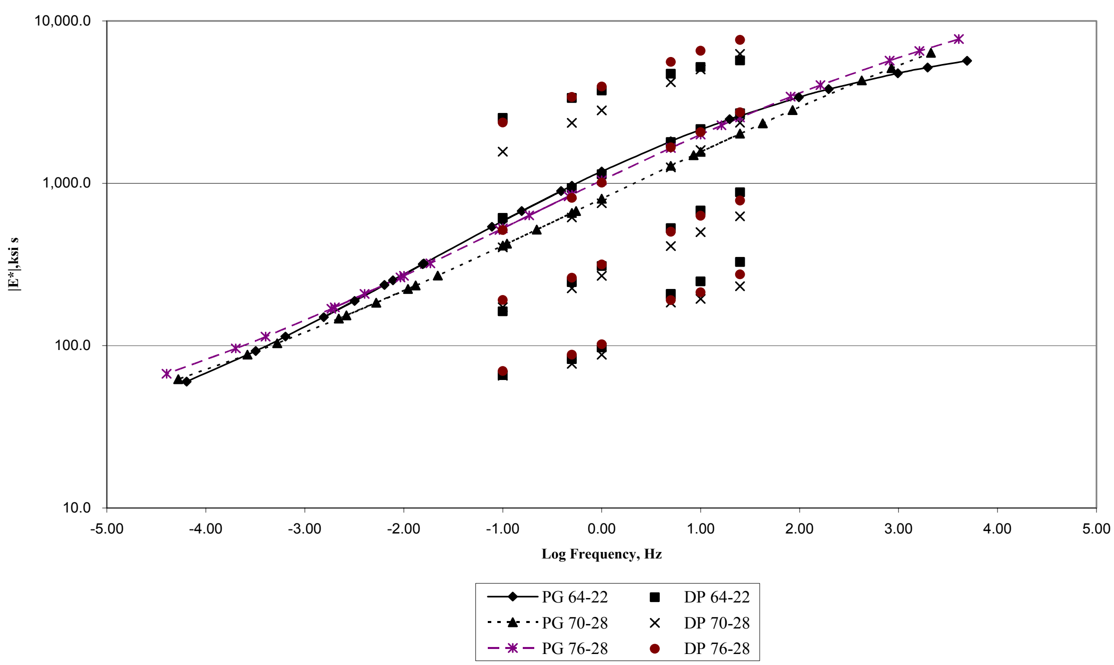

Figure 18 Master curves for Mix Design No. 04179, S-4 mix.

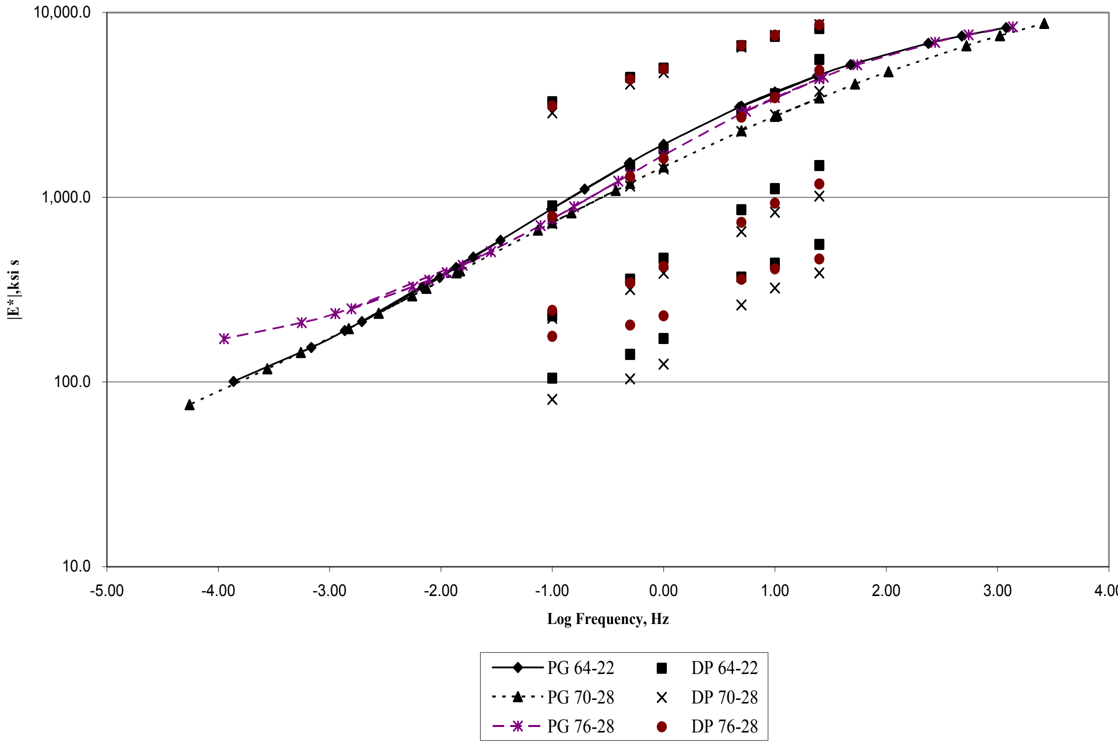

Figure 19 Master curves for Mix Design No. 05066, S-4 mix.

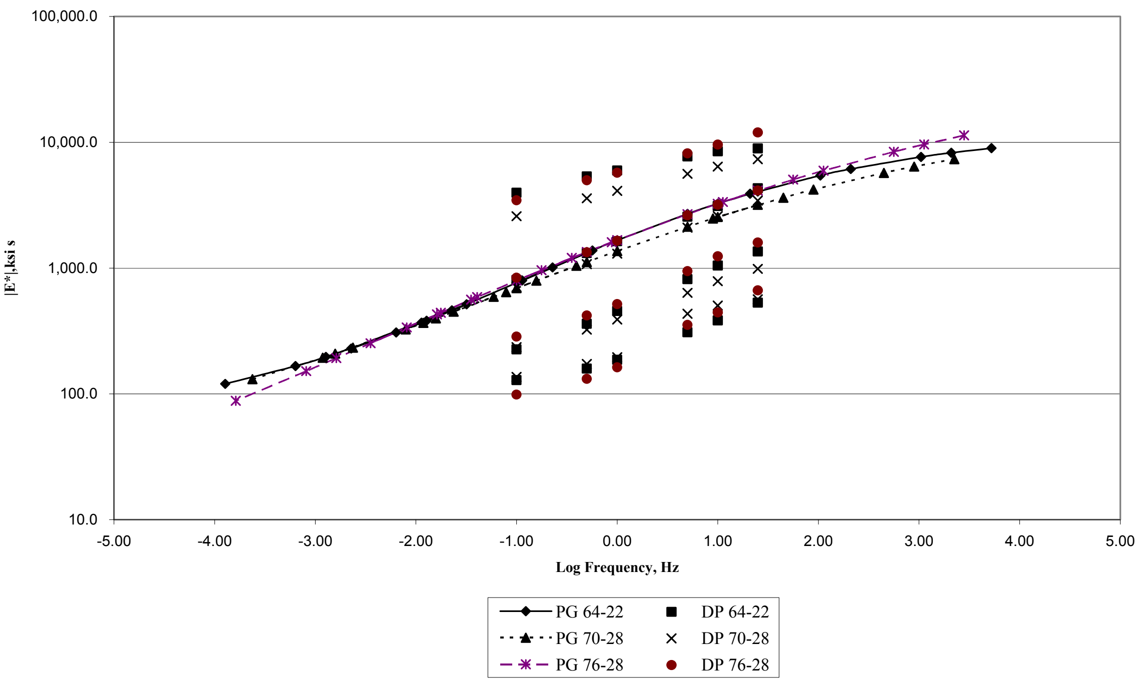

Figure 20 Master curves for Mix Design No. 00600, S-4 mix.

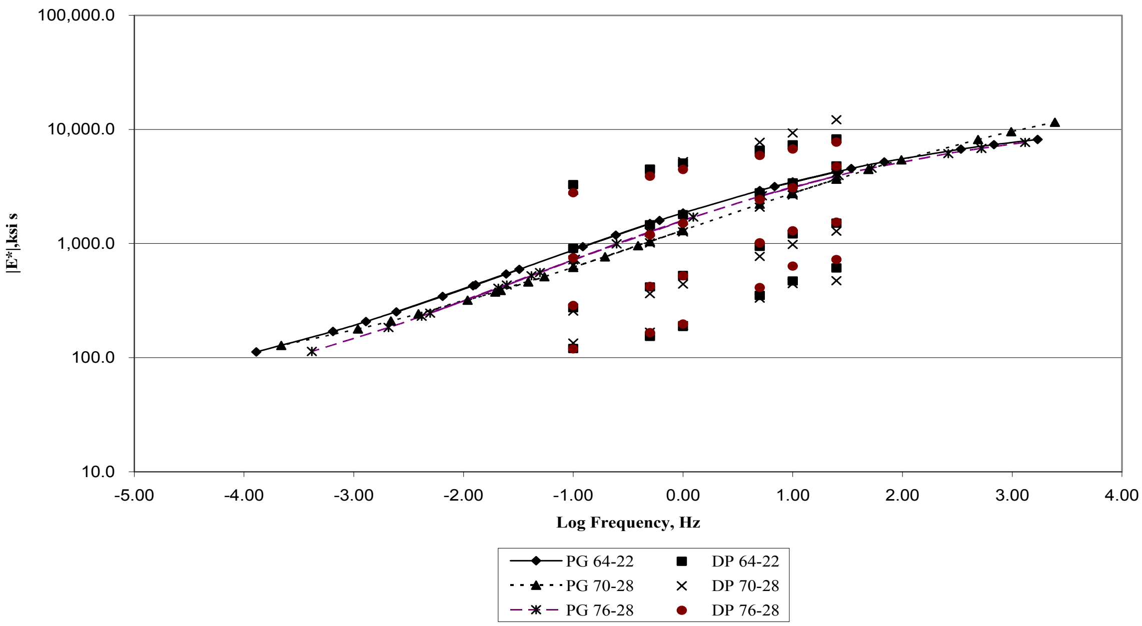

Figure 21 Master curves for Mix Design No. 05022, S-4 mix.

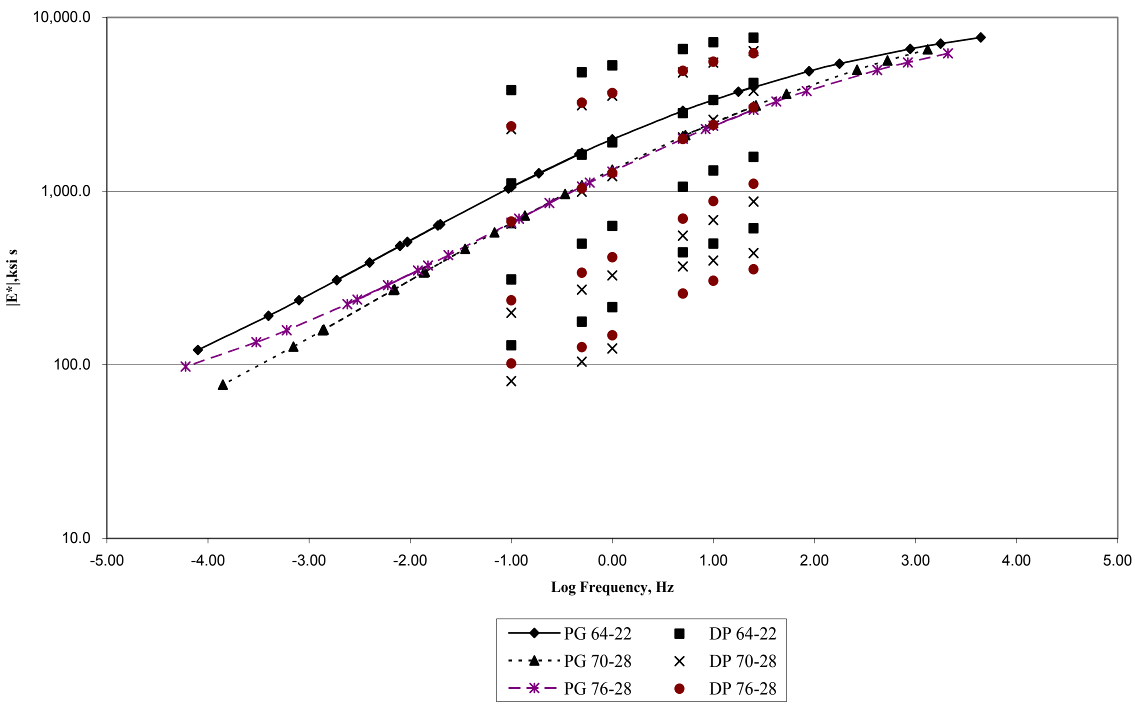

Figure 22 Master curves for Mix Design No. 03051, S-3 mix.

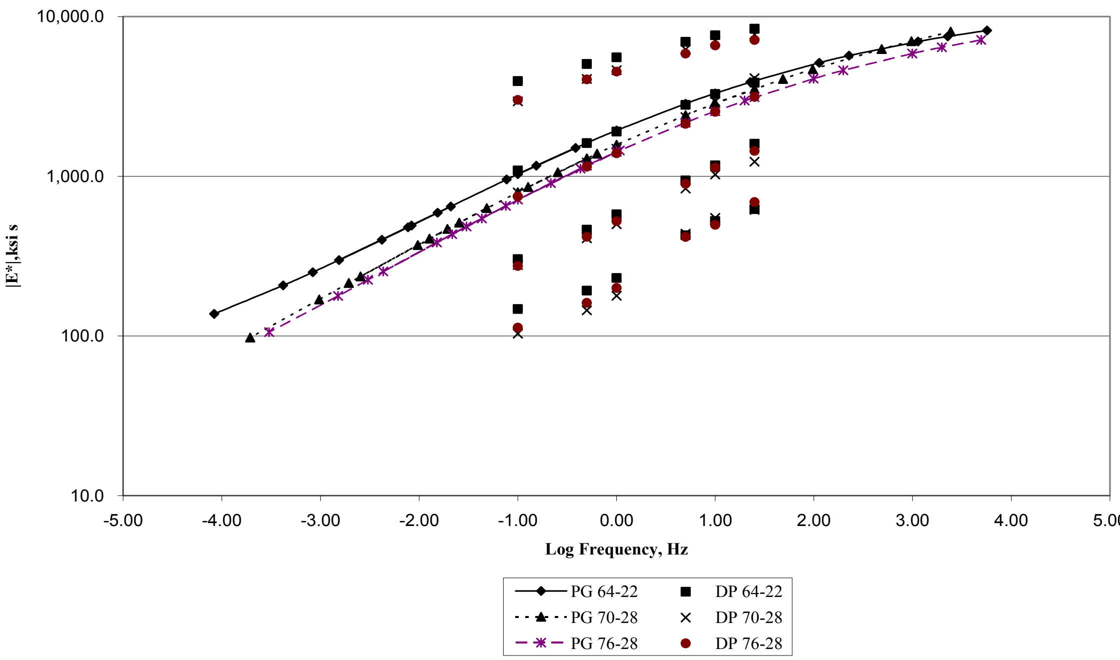

Figure 23 Master curves for Mix Design No. 05702, S-3 mix.

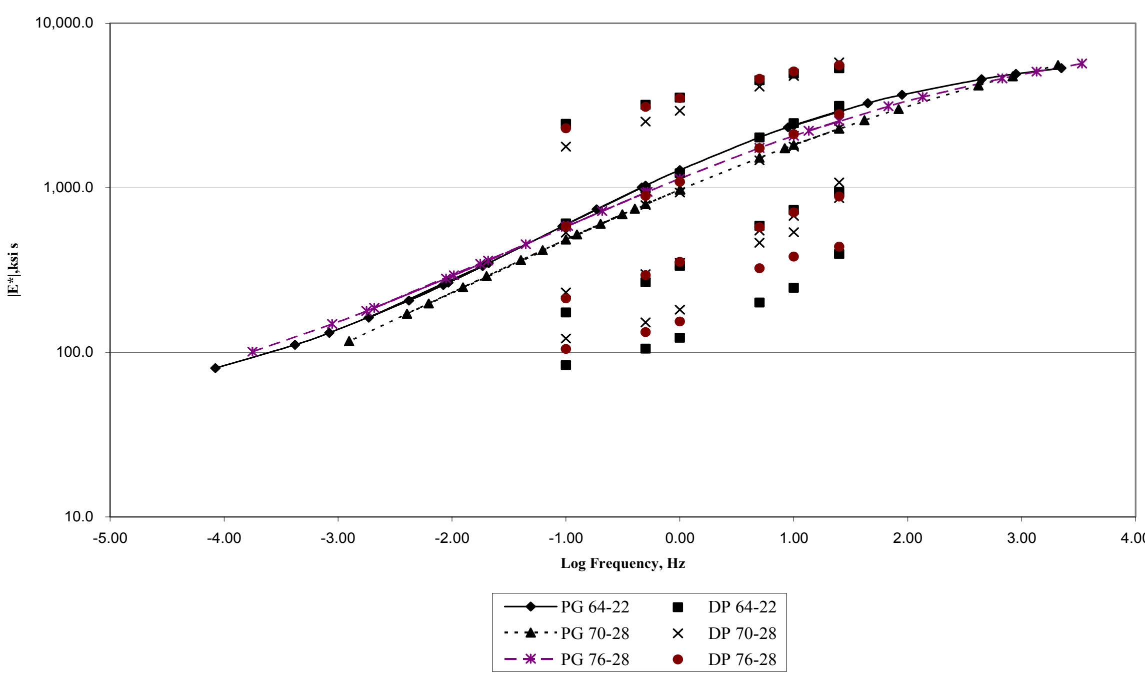

Figure 24 Master curves for Mix Design No. 04071, S-3 mix.

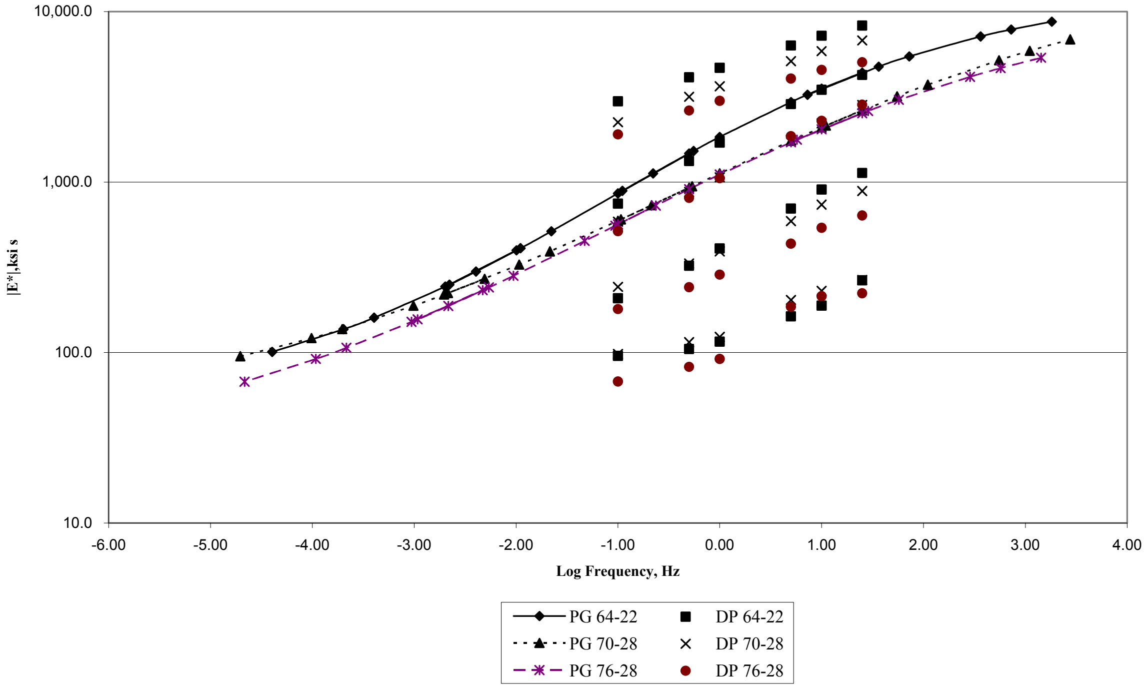

Figure 25 Master curves for Mix Design No. 05002, S-3 mix.

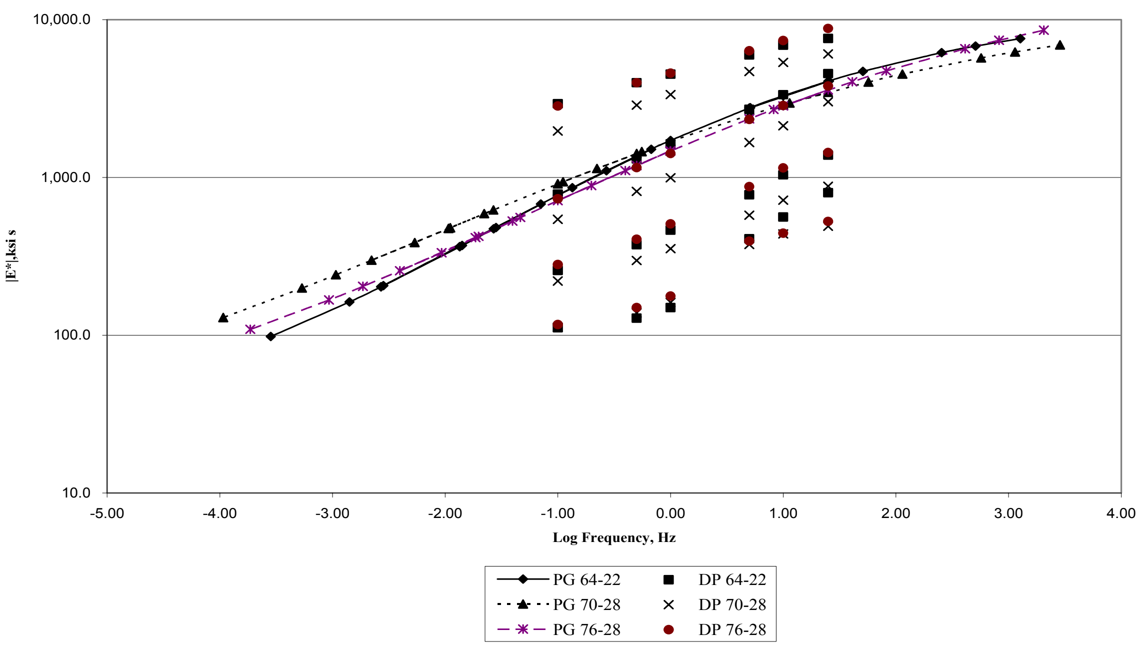

Figure 26 Master curves for Mix Design No. 05024, S-3 mix.

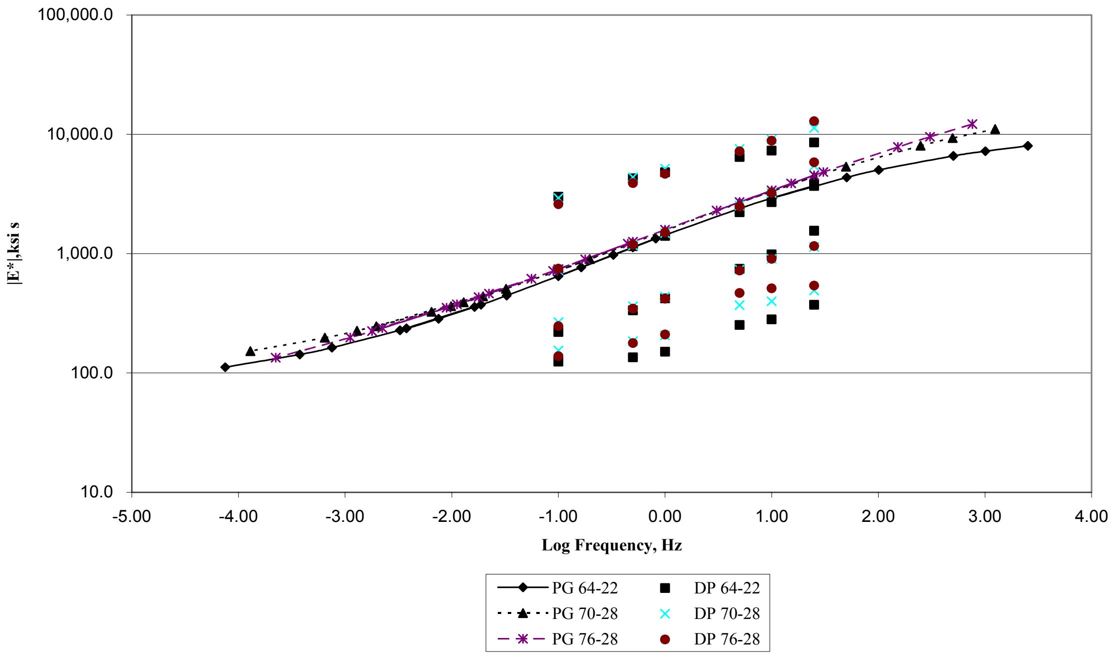

Figure 27 Master curves for Mix Design No. 05090, S-3 mix.

RECYCLED MIXTURES

There were five S-3 mixtures without RAP and six with 25% RAP. All mixes were tested for E* with PG 64-22, PG 70-28 and PG 76-28. However, all recycled mixtures were originally designed using PG 64-22 binder. The main effects of test temperature and PG binder grade were evaluated using ANOVA techniques. Mixes with RAP are designated by adding an R to the PG Grade. For example, an S-3 mix with RAP made with PG 70-28 binder was given the symbol PG 70-28R. As with previous analysis, only the test data at 5 Hz were used. The results of the ANOVA are shown in table 23.

Table 23. ANOVA on Recycled S-3 Mixtures

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
Temp.	3	3.6079E+14	1.2026E+14	553.20	<0.0001
PG Grade	5	1.1852E+13	2.3704E+12	10.90	<0.0001
Temp * PG	15	5.4963E+12	3.6642E+11	1.69	0.0544
Error	240	5.2175E+13	2.1740E+11		
Total	263	4.3031E+14			

The ANOVA indicated that PG Grade and test temperature had a significant effect on measured E*. The interaction between test temperature and binder grade was significant at a confidence limit of 95% (α = 0.05); therefore, the ANOVA was repeated by test temperature. The results are shown in table 24.

Table 24. Duncan's Multiple Range Test on Recycled S-3 Mixtures

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
4.4 C					
PG Grade	5	1.2155E+13	2.4310E+12	3.94	0.0038
Error	60	3.7066E+13	6.1777E+11		
Total	65	4.9221E+13			
21.1 C					
PG Grade	5	3.8345E+12	7.6690E+11	3.73	0.0053
Error	60	1.2345E+13	2.0575E+11		
Total	65	1.6180E+13			
37.8 C					
PG Grade	5	1.1752E+12	2.3504E+11	6.36	<0.0001
Error	60	2.2179E+12	3.6965E+10		
Total	65	3.3931E+12			
54.4 C					
PG Grade	5	1.8331E+11	3.6662E+10	4.02	0.0032
Error	60	5.4664E+11	9.1106E+09		
Total	65	7.2994E+11			

As shown in table 24, the ANOVA on PG Grade by test temperature indicates a significant effect at a confidence limit exceeding 95% (α ≤ 0.05) at each test temperature. To determine which PG binder grade was significantly different at each test temperature, Duncan's multiple range test was performed by test temperature. The results are shown in table 25. Means with the same letter not significantly different at a confidence limit of 95% (alpha = 0.05). The letter R at the end of the binder grade indicates a mix with 25% RAP.

Table 25. Duncan's Multiple Range Test on Recycled S-3 Mixtures, by Temperature

Grouping*	Mean Dynamic Modulus (psi)	n	PG Grade
	4.4 C		
A	3,703,048	12	PG 64-22R
A	3,689,015	12	PG 76-28R
A B	3,292,289	12	PG 70-28R
A B	2980821	10	PG 64-22
B	2,710,398	10	PG 76-28
B	2,628,157	10	PG 70-28
	21.1 C		
A	1,586,523	12	PG 64-22R
A	1,560,456	12	PG 76-28R
A B	1,397,620	12	PG 70-28R
A B C	1261535	10	PG 64-22
B C	1,040,178	10	PG 76-28
C	945,978	10	PG 70-28
	37.8 C		
A	630,927	12	PG 76-28R
A	617,520	12	PG 64-22R
A B	537,853	12	PG 70-28R
A B C	386642	10	PG 64-22
B C	329,961	10	PG 76-28
C	300,387	10	PG 70-28
	54.4 C		
A	284,723	12	PG 76-28R
A B	259,781	12	PG 64-22R
A B	249,544	12	PG 70-28R
B C	178134	10	PG 70-28
C	162,957	10	PG 76-28
C	146,718	10	PG 64-22

*Means with the same letter are not significantly different.

The results from Duncan's multiple range test show the effect that RAP has on measured E*. At the lowest test temperatures, 4.4^{o} C, the S-3 recycled mixtures made with PG -28 binders were not significantly different from the S-3 mixtures made with PG -22 binder.

At the intermediate test temperatures, 21.1 and 37.8^{o} C, mixtures with RAP were not significantly different from PG 64-22 mixtures. At the highest test temperature, 54.4^{o} C, recycled mixtures made with PG 64-22 were not significantly different than S-3 mixtures made with PG 70-28. It appears that 25% RAP in a mixture has the same effect on measured E* as raising the PG grade of binder in a virgin mix approximately one PG grade.

CHAPTER 7

E* PREDICTIVE EQUATION

E* PREDICTIVE EQUATION

One of the objectives of this study was to compare the experimental dynamic modulus data to the predicted values obtained using the procedures described in the M-EPDG. The M-EPDG uses the laboratory E* data for a Level 1 reliability design while it uses E* values from the predictive equation [4], shown in Chapter 3, for input Levels 2 and 3 reliability.

The original intent of this study was to compare predicted E* values using equation [4] with the actual A and VTS parameters of the binders used in this study. However, ODOT was not able to perform the AASHTO T 315 testing and information on binder complex shear modulus (G*) and phase angle (δ) of Oklahoma asphalts were only available at one test temperature. Therefore, binder samples from the asphalts used in this study were sent to a commercial laboratory for the required testing. The A and VTS parameters calculated from the measured binder complex shear modulus (G*) and phase angle (δ) provided by the commercial laboratory were considerably different from default values published in the M-EPDG and resulted in unreasonable E* values when using equation [4]. Therefore, comparisons between measured and calculated E* values had to be made using default binder viscosity values shown in Chapter 2, from the M-EPDG (2).

The predictive equation [4] was used to determine the dynamic modulus for each non recycle sample tested. The volumetric properties used to determine the predicted dynamic modulus for each sample are listed in table 26. The predicted dynamic modulus data for each temperature and frequency evaluated are provided in Appendix C.

ANALYSIS

Mix Type and Binder Grade

The predicted dynamic modulus was calculated for the S-3 and S-4 mixtures without recycle for each binder grade. To determine the effect of mix type and PG binder grade on calculated dynamic modulus, an analysis of variance (ANOVA) was performed. The results of the ANOVA are shown in table 27.

Table 26. Summary of Required Mix Properties for Predictive E* Equation

Design	% Retained			% Pass.	Va (%)			Vbeff (%)		
No.	3/4"	3/8"	No.4	No. 200	64-22	70-28	76-28	64-22	70-28	76-28
S-3 Mixtures										
05002	3	21	39	4.1	4.6	4.3	4.7	7.8	7.8	7.7
03051	5	31	44	5.7	3.8	3.7	3.7	8.5	8.5	8.5
04071	15	26	48	2.7	4.8	4.7	4.5	8.4	8.4	8.4
05024	0	26	59	2.5	4.3	4.4	4.3	9.0	9.0	8.9
05090	0	31	53	4.8	4.6	4.6	4.7	7.3	7.3	7.3
05072	10	24	49	2.7	4.3	4.2	3.9	9.3	9.3	9.2
Average	5.5	26.5	48.7	3.8	4.40	4.29	4.31	8.39	8.37	8.33
Std. Dev.	6.0	3.9	6.9	1.3	0.34	0.38	0.43	0.73	0.75	0.74
S-4 Mixtures										
0600	0	11	38	5.2	4.3	4.0	4.1	9.4	9.4	9.3
04063	0	11	41	3.4	5.5	5.6	5.5	8.4	8.3	8.2
04006	0	16	27	6.1	4.1	4.2	3.8	9.5	9.5	9.5
05022	0	14	45	4.1	3.7	3.7	3.7	9.1	9.2	9.1
05018	0	11	46	4.2	5.3	4.8	4.8	9.3	9.2	9.2
04179	0	11	26	5.6	4.6	4.4	4.2	9.8	10.0	9.9
05059	0	10	22	7.6	4.3	4.3	4.6	9.4	9.4	9.3
05066	0	14	36	6.0	4.3	3.8	3.9	8.3	8.3	8.3
Average	0	12.3	35.1	5.28	4.50	4.35	4.33	9.16	9.16	9.10
Std. Dev.	0	2.1	9.1	1.35	0.62	0.63	0.61	0.55	0.58	0.57

Table 27. ANOVA on Predicted E*

Source	Degrees Freedom	Sum Squares	Mean Square	F Value	Prob. > Fcr
Mix	1	1.7010E+12	1.7010E+12	3.59	0.0583
PG Grade	2	1.1569E+12	5.7845E+11	1.22	0.2951
Mix * PG	2	6.2120E+09	3.1060E+09	0.01	0.9935
Error	1362	6.4496E+14	4.7354E+11		
Total	1367	6.4782E+14			

The ANOVA indicates that neither the main effects of PG binder grade and mix type nor the interaction had a significant effect on calculated dynamic modulus, at a confidence limit of 95 percent ($\alpha = 0.05$). However, mix type did have a significant effect on calculated dynamic modulus at a 94 percent confidence limit ($\alpha = 0.06$). To show which means were significantly different, Duncan's multiple range test was performed. Duncan's multiple range test indicates which means are significantly different at a selected confidence limit. The results are shown in tables 28 and 29. The statistics package utilized in this study allows the selection of confidence limits for Duncan's multiple range test at preselected levels only. The analysis shown in tables 28 and 29 was performed at a confidence limit of 90% ($\alpha = 0.10$); therefore, means shown in tables 28 and 29 with the same letter are not significantly different at a confidence limit of 90% (alpha = 0.10).

Table 28. Duncan's Multiple Range Test on Mix Type for Predicted E*

Grouping*	Mean Dynamic Modulus (psi)	n	Mix
A	707,273	576	S-4
B	635,853	792	S-3

*Means with the same letter are not significantly different.

Table 29. Duncan's Multiple Range Test on PG Grade for Predicted E*

Grouping*	Mean Dynamic Modulus (psi)	n	PG Grade
A	1,488,258	456	PG 76-28
A	1,156,376	456	PG 64-22
A	991,615	456	PG70-28

*Means with the same letter are not significantly different.

The results of Duncan's multiple range test show that S-4 mixtures have larger average calculated E* than S-3 mixtures. This difference in average E* is significant with a confidence limit as large as 94 percent. However, at a confidence limit of 95 percent, there is no significant difference in average calculated E* by mix type. The effect of PG binder grade was not statistically significant and there was no significant interaction.

Comparison of Experimental and Predicted E* Data

The predicted dynamic modulus values of the S-3 and S-4 mixtures were compared to measured dynamic modulus values. The comparisons can be made by master curve, which would show the effect of both temperature and frequency. However, frequency has a consistent effect on dynamic modulus and making comparisons at one frequency simplifies the analysis. Table 30 shows the average calculated and measured E* values for the S-3 and S-4 mixtures without recycle. Table 31 shows the percent increase in measured dynamic modulus compared to the predicted or calculated dynamic modulus values at a frequency of 5 Hz. The comparisons between the predicted and measured dynamic modulus values at a frequency of 5 Hz are shown graphically in figures 28 - 30.

The measured E* values at 5 Hz are considerably larger than predicted values. This agrees with the work reported by Birgisson et al. (7). The percent increase in measured E* compared to calculated E* at 5 Hz varied from a low of 1.2 percent to a high of 46.6 percent. The PG 64-22 mixes showed the largest discrepancy between measured and calculated E* values, followed by the PG 70-28 mixtures and the PG 76-28 mixtures. The measured E* values of the S-4 mixtures were slightly closer to the calculated values than the S-3 mixtures.

Table 30. Average Predicted and Measured E* at 5 Hz.

Mix	Method	Temp. (C)	Freq. (Hz)	E* (psi) PG 64-22	PG 70-28	PG 76-28
S-3	Calculated	4.4	5	1,941,680	1,684,486	1,783,171
S-3	Calculated	21.1	5	707,718	674,383	773,022
S-3	Calculated	37.8	5	220,230	242,847	299,540
S-3	Calculated	54.4	5	75,541	93,852	120,788
S-3	Measured	4.4	5	2,979,377	2,699,715	2,594,847
S-3	Measured	21.1	5	1,239,366	974,536	1,009,235
S-3	Measured	37.8	5	386,184	303,479	303,167
S-3	Measured	54.4	5	132,361	175,663	154,308
S-4	Calculated	4.4	5	2,151,371	1,878,395	1,991,668
S-4	Calculated	21.1	5	782,838	751,082	862,239
S-4	Calculated	37.8	5	243,133	270,032	333,596
S-4	Calculated	54.4	5	83,247	104,185	134,322
S-4	Measured	4.4	5	3,196,466	2,561,458	2,871,890
S-4	Measured	21.1	5	1,343,602	885,088	1,063,763
S-4	Measured	37.8	5	391,017	299,855	377,184
S-4	Measured	54.4	5	144,178	148,012	163,132

Table 31. Percent Increase in Measured E* Compared to Calculated E*

Mix	Temp. (C)	Freq. (Hz)	Pct. Increase in E* (psi) PG 64-22	PG 70-28	PG 76-28
S-3	4.4	5	34.8	37.6	31.3
S-3	21.1	5	42.9	30.8	23.4
S-3	37.8	5	43.0	20.0	1.2
S-3	54.4	5	42.9	46.6	21.7
S-4	4.4	5	32.7	26.7	30.6
S-4	21.1	5	41.7	15.1	18.9
S-4	37.8	5	37.8	9.9	11.6
S-4	54.4	5	42.3	29.6	17.7

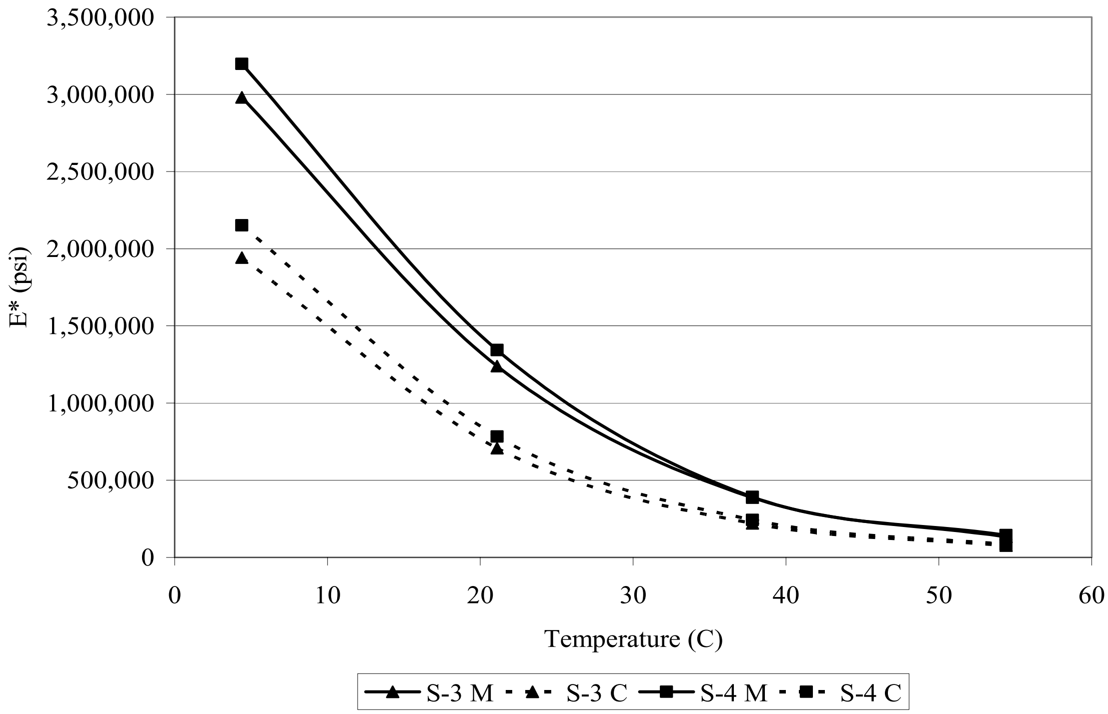

Figure 28 Measured and predicted E* at 5 Hz for PG 64-22 mixtures.

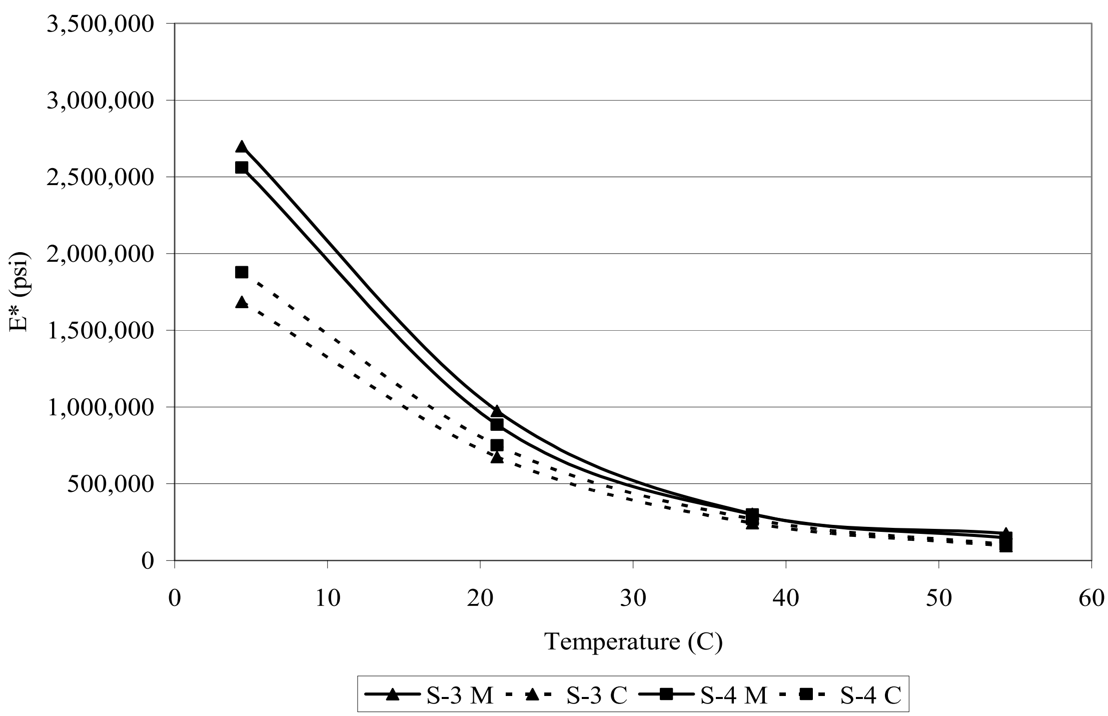

Figure 29 Measured and predicted E*at 5 Hz for PG 70-28 mixtures.

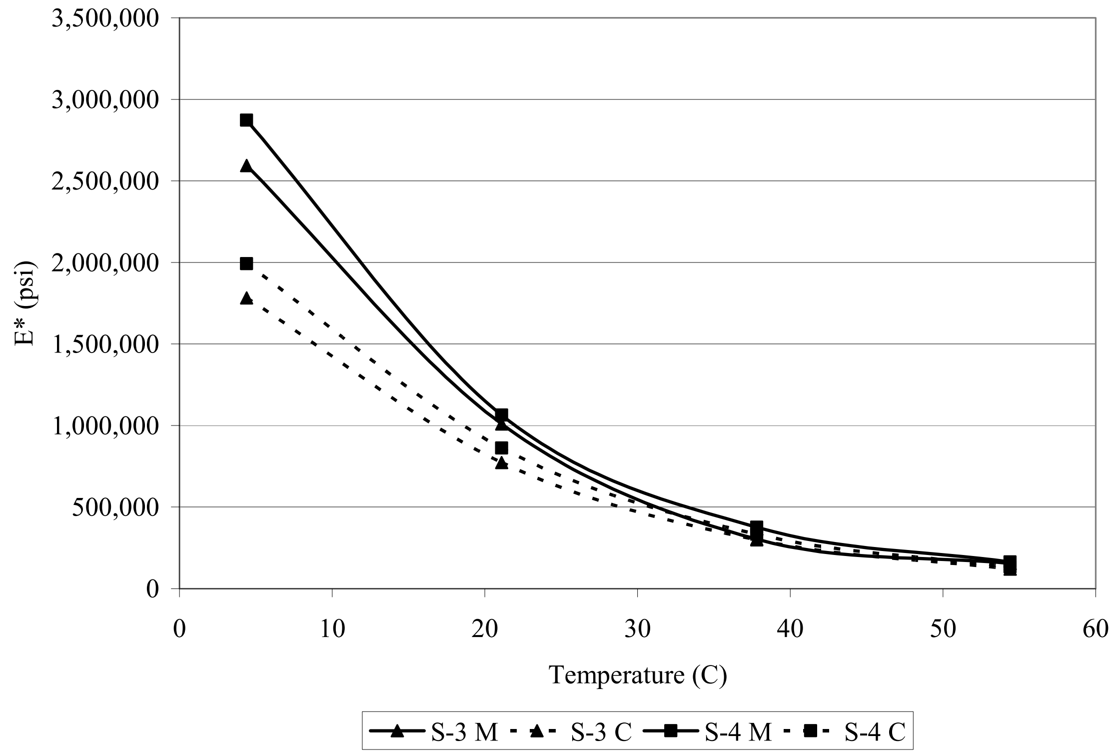

Figure 30 Measured and predicted E* at 5 Hz for PG 76-28 mixtures.

The literature (5,13) has indicated close agreement between predictive equations and measured values when the binder properties used in the predictive equations were from the same binders used in the measured values. The use of default binder properties appears to have a significant effect on the comparisons. Birgisson et al. (7) reported that using A and VTS parameters determined from DSR testing would result in under predicting dynamic modulus. Two other procedures were recommended, using viscosities determined from the Brookfield rotational viscometer on rolling thin film oven aged binders or using mix/laydown conditions reported by Witczak and Fonseca (14).

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Based on the results of this study and for the materials, test methods and equipment evaluated, the following conclusions are warranted.

Field Mixtures

1. Approximately 50% of the S-2 and S-3 mixtures sampled for this study contained 25% RAP in the mix.
2. There were not a sufficient number of S-2 mixtures available for sampling during the time frame of this study to determine typical E* values of ODOT S-2 mixtures.

Dynamic Modulus Testing

1. AASHTO TP 62-03 can be performed on HMA samples at a sufficient number of test temperatures using the equipment available at OSU to determine dynamic modulus values for use in the M-EPDG.
2. Dynamic modulus testing at the lowest test temperature (-10^{o} C) causes significant frost build-up on the test frame, sample and LVDTs and makes determining E* at temperatures below 0^{o}C (32^{o}F) difficult and time consuming. The M-EPDG requires E* values at a minimum of three test temperatures (2). Testing at temperatures below 0^{o}C (32^{o}F) can be eliminated without affecting the operations of the M-EPDG.
3. To produce a test sample of the proper dimensions at 4.5 ± 1.0 % voids, an SGC sample should be compacted to 6.0 ± 1.0 % voids. Approximately 5,700 to 6,300 grams of aggregate will be required, depending on the specific gravity of the aggregates.

Mixture Dynamic Modulus

1. The presence of 25% RAP in a mixture had a significant effect on measured dynamic modulus.
2. The nominal aggregate size (ODOT mix designation) did not have a significant effect on measured dynamic modulus.
3. PG binder grade had a significant effect on measured dynamic modulus.
4. Test temperature had a significant effect on measured dynamic modulus.
5. Test frequency had a significant effect on measured dynamic modulus.
6. Aggregate type did not have a significant effect on measured dynamic modulus.
7. The region of the state where the mix was produced (quarry region) did not have a significant effect on measured dynamic modulus.

8. The region of the state where the mix was placed did not have a significant effect on measured dynamic modulus.

Recycled S-3 Mixtures

1. At the lowest test temperature, 4.4^o C, S-3 recycled mixtures made with PG -28 binders were not significantly different from S-3 mixtures made with PG -22 binders.
2. At intermediate test temperatures, 21.1 and 37.8^o C, S-3 recycled mixtures were not significantly different from S-3 mixtures made with PG 64-22 binder.
3. At the highest test temperature, 54.4^o C, the S-3 recycled mixtures made with PG 64-22 were not significantly different from S-3 mixtures made with PG 70-28.
4. The use of 25% RAP in a mixture appears to raises the PG grade of the new binder approximately one grade. More testing is needed to validate this conclusion.

Predicted Dynamic Modulus

1. ODOT does not routinely gather the necessary binder complex shear modulus (G*) and phase angle (δ) at a sufficient number of temperatures to use the E* predictive equations in the M-EPDG.
2. The analysis of the Witczak E* predictive equation was performed using default A and VTS parameters from the M-EPDG rather than A and VTS parameters of the binders used in this study. Samples of the binders used were tested for complex shear modulus (G*) and phase angle (δ) by an outside vendor. The A and VTS parameters calculated from the test data provided were significantly different than published default values in the M-EPDG and resulted in unreasonable E* values at all test temperatures.
3. The measured E* values at 5 Hz were considerably larger than the predicted values determined using default A and VTS parameters from the M-EPDG. The literature (7,14) confirmed this finding. The percent increase in measured E* compared to calculated E* at 5 Hz varied from a low of 1.2 percent to a high of 46.6 percent. The PG 64-22 mixes showed the largest discrepancy between measured and calculated E* values followed by the PG 70-28 mixtures and the PG 76-28 mixtures. Measured E* values of the S-4 mixtures were closer to calculated values than the S-3 mixtures were. The literature (6) indicated close agreement between predictive equations and measured values when binder properties used in the predictive equations were from the same binders used in measured values. The use of default binder properties appears to have a significant effect on the comparisons.

RECOMMENDATIONS

Dynamic modulus values were determined two ways, measured and calculated. The measured values were determined using a single asphalt source for each PG binder grade.

Predicted or calculated E* values were determined using default binder properties listed in the M-EPDG. The difference in E* varied from 1 to 47 percent with the measured values being larger than predicted or calculated values. Table 32 shows the average measured dynamic module values. These values could be used as level 1 input parameters for dynamic modulus in the M-EPDG. The numbers are larger than those calculated using the predictive equation and could be considered unconservative.

Average E* values determined using the Witczak predictive equation in the M-EPDG are shown in table 33. These values are lower than measured values determined in this study. Use of these values in the M-EPDG would be considered conservative for ODOT mixtures (7,14). These values were determined using average mix properties determined from this study and default A and VTS values from the M-EPDG.

There is a considerable difference in the E* values shown in tables 32 and 33. It is recommended that both sets of numbers be evaluated using the M-EPDG software to determine the effect, if any, on predicted pavement performance. The researchers tried to use the M-EPDG software that was available on the internet. However, there were occasional problems with the software crashing and providing inconsistent results with the same scenario. The software is no longer consistently available on the internet and this task could not be completed. The M-EPDG software is available to DOTs. It is recommended that the E* values be evaluated to verify the results obtained in this study. In the interim, the following E* values shown in table 34 are recommended for use with the M-EPDG. These values are average values from the measured and predicted results.

The three predictive equations, Witczak (2), Hirsch (4) and the new Witczak equation (5), have all been reported to provide sufficiently accurate results. If ODOT chooses, any of the three predictive equations could be used if a sufficiently large data base of binder complex shear modulus (G*) and phase angle (δ) from DSR testing or binder viscosity from Brookfield rotational viscometer testing of Oklahoma asphalts were available. The G* and δ values or Brookfield rotational viscosity would need to be determined at a minimum of three test temperatures. The average binder properties could be used with the average mix properties, shown in table 34, determined from this study.

Additional Recommendations

1. It is recommended that E* values from this study be evaluated using M-EPDG software to verify the results.
2. The E* values of additional ODOT mixtures, such as S-2 mixtures and SMA mixtures, should be evaluated.
3. The effect of RAP on measured E* needs additional investigation.

Table 32. Average Measured E* Values

Test Temp. (C)	Freq. (Hz)	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
		S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix
4.4	25	3,833,227	3,725,928	3,530,615	3,777,899	3,860,246	3,711,173
	10	3,531,295	3,332,566	2,986,995	3,150,206	3,298,432	3,006,940
	5	3,196,466	2,979,377	2,561,458	2,699,715	2,871,890	2,594,847
	1	2,475,537	2,288,795	1,817,068	1,908,877	2,108,561	1,853,657
	0.5	2,215,265	2,051,437	1,561,425	1,647,678	1,847,750	1,605,962
	0.1	1,647,439	1,529,375	1,087,264	1,151,980	1,331,742	1,144,104
21.1	25	2,139,083	1,907,562	1,526,284	1,793,222	1,791,069	1,812,481
	10	1,612,930	1,497,654	1,105,939	1,223,602	1,318,935	1,254,419
	5	1,343,602	1,239,366	885,088	974,536	1,063,763	1,009,235
	1	878,116	780,210	548,325	588,188	659,081	613,778
	0.5	727,541	636,526	447,631	477,721	534,170	490,570
	0.1	468,638	399,018	292,396	311,666	341,519	313,720
37.8	25	653,667	649,842	455,975	469,976	611,940	472,381
	10	507,995	491,837	372,617	374,649	479,483	378,152
	5	391,017	386,184	299,855	303,479	377,184	303,167
	1	222,168	224,240	184,156	187,954	220,461	184,378
	0.5	175,079	177,754	152,575	157,852	180,296	152,513
	0.1	112,294	114,069	111,067	117,456	125,855	109,272
54.4	25	242,634	205,374	202,673	284,256	248,621	194,393
	10	178,465	151,755	173,843	195,519	204,314	176,545
	5	144,178	132,361	148,012	175,663	163,132	154,308
	1	76,576	75,428	80,448	79,408	85,725	75,390
	0.5	64,595	65,259	74,452	69,480	73,182	64,935
	0.1	51,146	54,102	59,905	56,741	57,193	51,522

Table 33. Average Predicted E* Values

Temp. (C)	Freq. (Hz)	PG 64-22		PG 70-28		PG 76-28	
		S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix
4.4	25	2,559,359	2,309,241	2,285,219	2,048,907	2,402,452	2,150,301
	10	2,327,103	2,100,012	2,052,180	1,840,165	2,167,702	1,940,511
	5	2,151,371	1,941,680	1,878,395	1,684,486	1,991,668	1,783,171
	1	1,751,110	1,580,969	1,491,330	1,337,704	1,596,244	1,429,652
	0.5	1,585,322	1,431,524	1,334,844	1,197,482	1,434,900	1,285,369
	0.1	1,225,067	1,106,690	1,003,412	900,446	1,089,857	976,717
21.1	25	1,073,385	969,877	1,035,709	929,569	1,169,879	1,048,312
	10	901,278	814,602	866,835	778,174	988,191	885,746
	5	782,838	707,718	751,082	674,383	862,239	773,022
	1	548,525	496,182	523,368	470,146	610,457	547,599
	0.5	465,038	420,777	442,709	397,779	519,761	466,363
	0.1	308,953	279,738	292,724	263,169	348,467	312,871
37.8	25	372,590	337,252	410,893	369,302	499,409	448,131
	10	293,302	265,590	324,819	292,040	398,611	357,814
	5	243,133	220,230	270,032	242,847	333,596	299,540
	1	154,452	140,008	172,455	155,198	215,821	193,926
	0.5	126,268	114,499	141,216	127,125	177,479	159,525
	0.1	78,454	71,198	87,923	79,209	111,198	100,025
54.4	25	133,840	121,353	166,606	149,969	212,882	191,290
	10	102,250	92,752	127,749	115,041	164,177	147,587
	5	83,247	75,541	104,185	93,852	134,322	120,788
	1	51,593	46,854	64,585	58,225	83,537	75,179
	0.5	42,059	38,209	52,571	47,411	67,966	61,187
	0.1	26,445	24,043	32,824	29,625	42,210	38,029

Table 34. Interim Recommended E* Values for ODOT Mixtures for M-EPDG

Test Temp. (C)	Freq. (Hz)	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
		S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix	S-4 Mix	S-3 Mix
4.4	25	3,196,000	3,018,000	2,908,000	2,913,000	3,131,000	2,931,000
	10	2,929,000	2,716,000	2,520,000	2,495,000	2,733,000	2,474,000
	5	2,674,000	2,461,000	2,220,000	2,192,000	2,432,000	2,189,000
	1	2,113,000	1,935,000	1,654,000	1,623,000	1,852,000	1,642,000
	0.5	1,900,000	1,742,000	1,448,000	1,423,000	1,641,000	1,446,000
	0.1	1,436,000	1,318,000	1,045,000	1,026,000	1,211,000	1,060,000
21.1	25	1,606,000	1,439,000	1,281,000	1,361,000	1,480,000	1,430,000
	10	1,257,000	1,156,000	986,000	1,001,000	1,154,000	1,070,000
	5	1,063,000	974,000	818,000	824,000	963,000	891,000
	1	713,000	638,000	536,000	529,000	635,000	581,000
	0.5	596,000	529,000	445,000	438,000	527,000	478,000
	0.1	389,000	339,000	293,000	287,000	345,000	313,000
37.8	25	513,000	494,000	433,000	420,000	556,000	460,000
	10	401,000	378,000	349,000	333,000	439,000	368,000
	5	317,000	303,000	285,000	273,000	355,000	301,000
	1	188,000	182,000	178,000	172,000	218,000	189,000
	0.5	151,000	146,000	147,000	142,000	179,000	156,000
	0.1	95,000	93,000	99,000	98,000	119,000	105,000
54.4	25	188,000	163,000	185,000	217,000	231,000	193,000
	10	140,000	122,000	151,000	155,000	184,000	162,000
	5	114,000	104,000	126,000	135,000	149,000	138,000
	1	64,000	61,000	73,000	69,000	85,000	75,000
	0.5	53,000	52,000	64,000	58,000	71,000	63,000
	0.1	39,000	39,000	46,000	43,000	50,000	45,000

Table 35. Recommended Mix Properties for E* Predictive Equations

Mix Property	S-3 Mix	S-4 Mix
% Retained 3/4" Sieve	5.5	0
% Retained 3/8" Sieve	27	12
% Retained No. 4 Sieve	49	35
% Passing No. 200 Sieve	3.8	5.3
Va (%)	4.5	4.5
Vbeff (%)	8.5	9.2

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APPENDIX A

MIX PROPERTIES

Table A-1. Mix Design and Physical Properties, Design No. 05059

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 A-2. Mix Design and Physical Properties, Design No. 04006

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 A-3. Mix Design and Physical Properties, Design No. 04063

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 A-4. Mix Design and Physical Properties, Design No. 05018

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 A-5. Mix Design and Physical Properties, Design No. 04179

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 A-6. Mix Design and Physical Properties, Design No. 05066

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

Table A-7. Mix Design and Physical Properties, Design No. 00600

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 A-8. Mix Design and Physical Properties, Design No. 05022

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 A-9. Mix Design and Physical Properties, Design No. 03051

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 A-10. Mix Design and Physical Properties, Design No. 05702

Mix Type	S4 Binder (Changed to S-3)	
Mix ID	Silverstar	
Design Number	3074-EST-05702	

Material	**% in Blend**	
5/8" Chips	23	Hanson Aggregates @ Davis,Okla, (5008)
Screenings	27	Hanson Aggregates @ Davis,Okla, (5008)
Shot	15	Dolese @Davis, Okla, (5002)
sand	10	GMI meridian Pit
Millings	25	Stockpile @Plantsite

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	90
1/2"	97	86
3/8"	87	76
No.4	66	51
No.8	42	27
No.16	33	11
No.30	26	8
No.50	20	5
No.100	10	4
No.200	5.3	2.7

% AC	4.98	4.98	4.98
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.713	2.713	2.713
Gmm	2.508	2.508	2.508
Gsb	2.691	2.691	2.691

VTM (%)	4.0
VMA (%)	14.9
VFA (%)	73.2
DP	0.6

Table A-11. Mix Design and Physical Properties, Design No. 04071

Mix Type	S4	(Changed to S-3)		27
Mix ID	Norman			30
Design Number		3074-OAEST-04071		28
				15

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	95
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 A-12. Mix Design and Physical Properties, Design No. 04062

Mix Type	S3R	
Mix ID	cummins Enid-3	
Design Number	3073-CCC-04062	

Material	**% in Blend**	
#57 Chips	15	Dolese@Richard Spur,OK(1601)
3/8 Chips	29	Dolese@Richard Spur,OK(1601)
Stone Sand	20	Dolese@Cyril,OK(0801)
Screenings	11	Dolese@Richard Spur,OK(1601)
RAP	25	Stockpile@Plantsite

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	97	97
1/2"	89	90
3/8"	85	86
No.4	54	59
No.8	38	42
No.16	23	29
No.30	17	22
No.50	12	16
No.100	7	9
No.200	3.8	4.6

% AC	4.6	4.6	4.6
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.690	2.690	2.690
Gmm	2.503	2.504	2.504
Gsb	2.661	2.661	2.661

VTM(%)	4
VMA(%)	13.9
VFA(%)	71
DP	1.09

Table A-13. Mix Design and Physical Properties, Design No. 05010

Mix Type	S3R	
Mix ID	Evans	
Design Number	3073-OAEST-05010	

Material	**% in Blend**	
3/4' chips	28	Bellco Materials @pawhuska,OK(5703)
1/2" chips	20	Bellco Materials @pawhuska,OK(5704)
Screenigns	15	Bellco Materials @pawhuska,OK(5705)
Mine Chat	10	Bingham Sand & Gravel @ Miami,OK (5804)
Sand	12	Sober Sand @ponca City,OK
MAP	15	Stockpile@Plantsite

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	89	90
3/8"	81	72
No.4	51	47
No.8	36	33
No.16	26	24
No.30	20	18
No.50	13	12
No.100	7	7
No.200	5.7	5.6

% AC	4.3	4.3	4.3
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.643	2.643	2.643
Gmm	2.475	2.476	2.476
Gsb	2.640	2.640	2.640

VTM(%)	4.0
VMA(%)	13.9
VFA(%)	71
DP	1.09

Table A-14. Mix Design and Physical Properties, Design No. 05002

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 A-15. Mix Design and Physical Properties, Design No. 03043

Mix Type	S3 Recycle
Mix ID	East Plant
Design Number	3073-OAEST-03043

Material	**% in Blend**	
1" #67 Rock	23%	Dolese Co. @Richard Spur,OK(1601)
Washed Screening	41%	Martin Marietta@Dacis,OK (5005)
Sand	11%	GMI Meridian Pit
RAP	25%	Stockpile @Plantsite
Sand		

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	
3/4"	97	86
1/2"	88	78
3/8"	81	70
No.4	63	46
No.8	46	29
No.16	35	14
No.30	27	8
No.50	18	4
No.100	8	3
No.200	4.1	1.9

% AC	4.5	4.5	4.5
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.692	2.692	2.692
Gmm	2.509	2.509	2.509
Gsb	2.677	2.677	2.677

VTM(%)	4
VMA(%)	14.1
VFA(%)	71.6
DP	0.45

Table A-16. Mix Design and Physical Properties, Design No. 20610

Mix Type	S3R	
Mix ID	APAC-OKC	
Design Number		3073-APAC-20610

Material	**% in Blend**	
#57 Chips	20	APAC-Oklahoma,Inc@Tulsa,OK(7203)
3/8 Chips	15	APAC-Oklahoma,Inc@Tulsa,OK(7203)
Manufactured Sand	20	Anchor Stone@ Owaso,OK(6603)
Washed Coarse Screenings	20	APAC-Oklahoma,Inc@Tulsa,OK(7212)
RAP	25	APAC-Oklahoma,Inc@Tulsa,OK(7203)

Gradation

Sieve Size	**% Passing(field)**		**%Passing (lab)**
1"	100		100
3/4"	96		96
1/2"	86		88
3/8"	80		85
No.4	55		57
No.8	32		30
No.16	21		18
No.30	12		12
No.50	8		8
No.100	6		6
No.200	4.9		4.4
% AC	4.3	4.3	4
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.657	2.657	2.657
Gmm	2.487	2.487	2.488
Gsb	2.626	2.626	2.626
VTM(%)	4.0		
VMA(%)	13.1		
VFA(%)	69.0		
DP	1.1		

Table A-17. Mix Design and Physical Properties, Design No. 05024

Mix Type	S3		
Mix ID	Arkhola		
Design Number	3073-ARKH-05024		

Material	**% in Blend**	
#67 Chips	35	Arkhola @Zeb,OK(1102)
3/8 Chips	25	Arkhola @Zeb,OK(1102)
Washed Screening	30	Arkhola @Zeb,OK(1102)
Anti-Strip Add. (Perma-Tac Plus)	10	Arkhola @Okay,OK(7302)
RAP		Akzo-Nobel@Waco,TX

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	100	100
1/2"	92	88
3/8"	77	74
No.4	49	41
No.8	31	24
No.16	20	16
No.30	15	10
No.50	10	6
No.100	7	4
No.200	5.1	2.5

% AC	4.8	4.8	4.8
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.679	2.679	2.679
Gmm	2.487	2.487	2.487
Gsb	2.658	2.658	2.658

VTM(%)	4.0
VMA(%)	14.4
VFA(%)	71
DP	0.6

Table A-18. Mix Design and Physical Properties, Design No. 05090

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 A-19. Mix Design and Physical Properties, Design No. 03162

Mix Type	S3 Recycle
Mix ID	Silverstar
Design Number	3073-OAEST-03162

Material	**% in Blend**	
1" chips	28%	Hanson Aggregates @ Davis,Okla, (5008)
Screenings	20%	Hanson Aggregates @ Davis,Okla, (5008)
WashedShot	17%	Dolese @Davis, Okla, (5002)
sand	10%	GMI meridian Pit
Millings	25%	Stockpile @Plantsite

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
1"	100	100
3/4"	96	85
1/2"	81	67
3/8"	71	52
No.4	61	41
No.8	39	20
No.16	30	7
No.30	24	4
No.50	18	3
No.100	9	2
No.200	4.8	2.0

% AC	4.55	4.55	4.55
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.715	2.715	2.715
Gmm	2.526	2.526	2.527
Gsb	2.671	2.671	2.671

VTM(%)	4.0
VMA(%)	13.4
VFA(%)	70.1
DP	0.5

Table A-20. Mix Design and Physical Properties, Design No. 05007

Mix Type	S2	
Mix ID	Stringtown	
Design Number		3072-CCC-05007

Material	**% in Blend**	
#467 Rock	30	Martin-Maireta@ Millcreek,OK(3502)
3/8" Chips	15	Stringtown Matls CO @ Stringtown, OK (0301)
Man Sand	20	Stringtown Matls CO @ Stringtown, OK (0301)
Screenings	21	The Dolese Co. @ Colemen,OK (0302)
Sand	14	PFAFF Sand Co. @Atoka,OK

Gradation

Sieve Size	**% Passing(field)**		**%Passing (lab)**
1"	96		97
3/4"	87		89
1/2"	77		77
3/8"	74		72
No.4	60		55
No.8	42		35
No.16	30		22
No.30	2		15
No.50	19		11
No.100	9		8
No.200	5.6		6
% AC	4.7	4.7	4.7
PG	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.661	2.661	2.661
Gmm	2.476	2.476	2.476
Gsb	2.603	2.603	2.603
VTM(%)	4.0		
VMA(%)	13.2		
VFA(%)	69.6		
DP	1.6		

Table A-21. Mix Design and Physical Properties, Design No. 04068

Mix Type	S2	
Mix ID	Eastplant	
Design Number	3072-OAEST-04068	

Material	**% in Blend**	
11/2" #57 rock	42	Martin Marietta @ Davis, OK (5005)
Washed Screenings	12	Martin Marietta @ Davis, OK (5005)
Stone Sand	11	Martin Marietta @ Davis, OK (5005)
Sand	10	GMI Meridian Pit
RAP	25	Stockpile @plantsite

Gradation

Sieve Size	**% Passing(field)**	**%Passing (lab)**
11/2"	100	100
1"	99	99
3/4"	90	87
1/2"	75	91
3/8"	67	77
No.4	54	48
No.8	41	34
No.16	31	26
No.30	24	20
No.50	15	12
No.100	8	7
No.200	4	3.0

% AC	3.7	3.7	3.7
PG Grade	64-22	70-28	76-28
Gb	1.026	1.0274	1.0288
Gse	2.672	2.672	2.672
Gmm	2.522	2.523	2.523
Gsb	2.654	2.654	2.654

VTM(%)	4.0
VMA(%)	12.1
VFA(%)	66.8
DP	0.9

APPENDIX B

DYNAMIC MODULUS TEST RESULTS

Table B-1. Dynamic Modulus Test Results, Design No. 05059

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3,861,564	3,894,726	3,303,881	3,393,967	4,035,228	3,348,826
4.4	10	3,667,350	3,631,582	2,948,999	3,071,019	3,643,605	3,080,829
4.4	5	3,421,330	3,367,434	2,646,098	2,728,685	3,268,998	2,803,622
4.4	1	2,865,360	2,779,921	1,979,854	2,007,088	2,545,046	2,179,695
4.4	0.5	2,617,471	2,551,861	1,744,321	1,742,812	2,271,811	1,950,765
4.4	0.1	2,068,808	2,030,022	1,267,338	1,251,238	1,677,600	1,476,517
21.1	25	1,604,037	2,089,641	1,903,341	1,771,351	1,991,813	2,168,361
21.1	10	1,451,507	1,639,247	1,506,065	1,372,199	1,544,920	1,688,144
21.1	5	1,274,551	1,398,952	1,234,744	1,119,576	1,259,931	1,392,458
21.1	1	856,148	933,188	788,623	700,744	793,907	866,131
21.1	0.5	714,107	775,405	652,160	571,220	649,889	698,993
21.1	0.1	469,593	498,143	427,600	370,949	413,592	435,279
37.8	25	789,415	731,712	680,098	473,462	642,830	642,830
37.8	10	646,207	576,509	581,105	400,698	561,989	561,989
37.8	5	511,929	446,185	473,155	329,324	447,864	447,864
37.8	1	297,322	251,838	261,467	197,962	268,446	268,446
37.8	0.5	233,776	196,544	210,809	162,196	217,122	217,122
37.8	0.1	142,841	122,545	141,644	113,923	147,130	147,130
54.4	25	325,790	316,956	322,980	256,333	262,427	297,258
54.4	10	254,042	222,744	268,863	228,993	209,040	245,312
54.4	5	216,962	181,181	225,058	207,634	177,377	200,606
54.4	1	94,139	86,914	104,879	81,187	87,063	108,909
54.4	0.5	73,612	71,068	106,689	70,866	71,483	91,621
54.4	0.1	48,607	52,350	88,783	55,340	52,508	73,986

Table B-2. Dynamic Modulus Test Results, Design No. 04006

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	3,403,052	3,621,988	3,510,174	3,711,950	4,172,370	2,497,402
4.4	10	3,191,326	3,434,191	3,336,120	3,185,982	3,428,234	2,257,024
4.4	5	2,907,241	3,099,791	2,806,446	2,704,566	2,960,076	2,035,835
4.4	1	2,303,234	2,359,763	1,982,352	1,895,856	2,183,832	1,575,095
4.4	0.5	2,077,749	2,113,143	1,693,115	1,620,757	1,947,394	1,408,532
4.4	0.1	1,586,928	1,514,325	1,139,107	1,107,842	1,478,689	1,076,120
21.1	25	1,521,031	3,621,988	1,080,691	2,073,489	1,884,801	1,607,441
21.1	10	1,186,494	3,434,191	881,184	1,458,941	1,420,543	1,189,333
21.1	5	965,697	3,099,791	704,111	1,146,609	1,149,052	941,290
21.1	1	585,334	2,359,763	417,011	694,553	710,007	556,524
21.1	0.5	470,968	2,113,143	337,969	554,352	581,369	453,503
21.1	0.1	284,110	1,514,325	222,743	347,500	379,783	299,047
37.8	25	510,907	562,913	289,463	592,797	860,408	553,745
37.8	10	398,260	412,505	241,691	469,558	607,379	387,954
37.8	5	310,660	308,838	198,098	370,152	471,709	299,960
37.8	1	179,682	174,544	131,725	209,627	288,135	183,667
37.8	0.5	145,643	138,650	114,048	169,257	238,025	157,492
37.8	0.1	95,754	88,201	88,764	117,474	166,154	107,782
54.4	25	141,071	120,646	101,512	220,958	273,552	178,275
54.4	10	109,530	82,416	81,539	187,313	237,641	128,414
54.4	5	91,522	70,947	72,876	183,086	158,534	106,529
54.4	1	67,622	41,060	51,465	138,829	81,995	60,245
54.4	0.5	61,059	36,186	46,831	122,236	71,947	53,679
54.4	0.1	60,077	29,137	41,055	124,238	54,058	43,027

Table B-3. Dynamic Modulus Test Results, Design No. 04063

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	4,783,639	3,780,246	2,157,942	2,115,407	2,321,894	3,042,868
4.4	10	4,372,680	3,512,598	1,871,187	1,829,648	1,973,042	2,630,084
4.4	5	3,854,941	3,161,204	1,653,435	1,594,198	1,679,640	2,268,765
4.4	1	2,835,062	2,456,622	1,229,506	1,158,358	1,190,800	1,615,715
4.4	0.5	2,487,409	2,218,217	1,082,315	1,005,071	1,029,844	1,392,885
4.4	0.1	1,694,467	1,713,689	813,059	720,529	735,866	990,732
21.1	25	3,009,159	1,944,976	1,226,808	956,648	846,490	1,044,470
21.1	10	1,980,138	1,564,983	926,557	714,585	643,020	813,544
21.1	5	1,521,412	1,318,939	752,594	570,546	526,841	667,591
21.1	1	877,632	858,796	475,392	366,686	339,112	426,365
21.1	0.5	696,190	711,957	399,151	308,994	283,639	356,471
21.1	0.1	421,149	472,022	276,233	217,783	199,847	249,142
37.8	25	499,966	974,560	403,162	367,750	343,663	432,010
37.8	10	390,154	799,443	351,539	353,823	291,706	364,585
37.8	5	299,134	578,006	286,994	286,562	240,858	301,369
37.8	1	176,958	332,280	189,215	197,424	154,061	193,056
37.8	0.5	142,965	255,194	159,769	164,685	128,957	162,253
37.8	0.1	101,573	156,092	122,180	125,736	96,205	121,377
54.4	25	151,747	205,333	121,540	150,690	138,943	193,511
54.4	10	155,878	176,514	125,107	131,703	124,754	153,949
54.4	5	114,186	142,613	101,888	122,263	111,755	136,617
54.4	1	73,397	82,110	72,427	88,935	71,949	76,435
54.4	0.5	64,809	68,987	65,712	78,777	65,940	67,129
54.4	0.1	49,729	50,947	55,985	67,371	55,736	53,216

Table B-4. Dynamic Modulus Test Results, Design No. 05018

		Dynamic Modulus (psi)					
Temp	Freq	PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	2,652,739	4,254,551	2,016,223	1,887,827	3,249,896	3,163,827
4.4	10	2,507,177	3,759,094	1,705,455	1,580,290	2,715,058	2,653,723
4.4	5	2,278,188	3,281,490	1,470,158	1,346,957	2,323,374	2,292,019
4.4	1	1,826,111	2,395,750	1,022,010	926,664	1,669,968	1,687,599
4.4	0.5	1,630,001	2,090,240	869,547	785,908	1,457,671	1,471,086
4.4	0.1	1,194,223	1,482,044	597,175	544,180	1,062,524	1,067,124
21.1	25	1,717,318	1,348,099	839,797	868,845	1,163,413	1,474,514
21.1	10	1,147,789	1,095,468	602,458	579,396	937,911	1,064,870
21.1	5	931,614	916,164	481,476	446,053	781,975	865,708
21.1	1	600,389	585,588	305,684	275,776	513,064	547,105
21.1	0.5	495,618	474,045	254,716	229,552	431,857	453,572
21.1	0.1	321,087	295,959	179,726	162,676	296,574	300,377
37.8	25	509,894	651,368	332,608	246,072	578,805	636,904
37.8	10	370,729	481,216	266,246	197,950	401,251	402,141
37.8	5	290,783	362,638	214,014	168,819	317,191	311,517
37.8	1	175,934	206,940	145,075	124,762	198,674	194,332
37.8	0.5	140,548	162,605	120,953	109,323	160,553	155,241
37.8	0.1	95,450	104,506	91,222	90,143	112,392	108,612
54.4	25	234,441	359,966	275,326	135,087	290,336	216,134
54.4	10	128,548	182,927	201,427	89,979	281,784	186,628
54.4	5	93,124	158,398	167,724	75,481	238,582	165,033
54.4	1	57,828	78,227	98,287	51,438	102,363	92,564
54.4	0.5	50,972	69,998	79,697	46,548	82,510	77,884
54.4	0.1	42,089	65,770	68,037	41,006	60,347	57,688

Table B-5. Dynamic Modulus Test Results, Design No. 04179

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	3,044,826	2,666,477	3,134,577	3,129,360	4,862,909	2,781,852
4.4	10	2,745,960	2,457,112	2,325,852	2,691,254	4,131,962	2,414,651
4.4	5	2,460,361	2,268,390	1,935,582	2,260,909	3,500,962	2,091,574
4.4	1	1,901,129	1,827,593	1,288,259	1,520,912	2,461,698	1,482,828
4.4	0.5	1,706,096	1,646,452	1,074,178	1,280,373	2,131,674	1,267,333
4.4	0.1	1,284,126	1,246,866	700,173	865,266	1,509,436	858,524
21.1	25	1,334,036	1,367,368	1,120,122	1,238,754	1,692,233	1,045,249
21.1	10	1,074,262	1,082,353	767,534	834,267	1,262,059	803,264
21.1	5	896,969	896,186	594,055	660,003	1,013,623	651,887
21.1	1	575,617	561,171	358,149	394,802	618,791	390,402
21.1	0.5	479,244	456,439	293,024	322,356	499,249	314,091
21.1	0.1	312,193	299,858	191,634	211,744	315,375	199,817
37.8	25	481,005	399,207	277,693	348,715	499,803	283,434
37.8	10	371,686	308,217	219,803	280,523	407,655	223,293
37.8	5	292,661	237,218	177,845	232,862	323,913	178,967
37.8	1	172,627	136,686	117,672	151,397	199,820	116,196
37.8	0.5	137,768	108,388	99,574	125,795	164,428	97,842
37.8	0.1	90,677	71,976	77,257	95,218	116,714	74,286
54.4	25	145,429	182,191	118,323	113,709	167,474	107,214
54.4	10	129,507	119,203	90,038	103,992	123,367	89,834
54.4	5	102,930	105,580	86,393	97,905	106,135	84,714
54.4	1	45,090	52,419	40,519	47,422	55,924	46,090
54.4	0.5	37,370	45,344	35,989	41,220	47,531	40,484
54.4	0.1	27,976	37,924	30,484	34,900	37,172	32,675

Table B-6. Dynamic Modulus Test Results, Design No. 05066

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4,442,424	3,746,540	3,595,700	5,016,456	4,397,105	4,184,389
4.4	10	4,049,586	3,367,650	3,146,992	4,376,151	3,755,259	3,781,504
4.4	5	3,562,183	3,045,181	2,778,824	3,723,385	3,240,354	3,401,216
4.4	1	2,626,489	2,378,695	2,099,374	2,631,853	2,361,043	2,597,990
4.4	0.5	2,317,288	2,139,448	1,837,181	2,257,156	2,053,814	2,300,977
4.4	0.1	1,645,693	1,642,486	1,317,686	1,544,908	1,430,649	1,694,989
21.1	25	3,619,753	1,946,608	1,585,649	2,157,980	2,663,927	2,210,024
21.1	10	2,086,511	1,547,785	1,222,150	1,571,269	1,808,643	1,654,715
21.1	5	1,625,591	1,300,816	1,004,193	1,264,723	1,364,762	1,350,109
21.1	1	975,273	855,502	636,544	788,000	786,123	840,004
21.1	0.5	769,131	706,973	517,081	632,288	618,455	677,503
21.1	0.1	449,597	448,946	329,783	389,716	364,572	423,443
37.8	25	737,086	748,250	467,525	547,374	554,608	626,533
37.8	10	505,026	607,691	394,760	435,182	445,896	483,538
37.8	5	383,926	472,768	306,630	344,430	350,546	380,653
37.8	1	211,849	255,821	181,102	206,875	203,363	219,131
37.8	0.5	163,214	197,389	147,301	169,177	167,289	177,460
37.8	0.1	107,165	120,640	103,733	117,896	121,692	122,340
54.4	25	341,487	213,979	189,456	199,726	231,199	231,954
54.4	10	274,098	165,983	155,483	167,040	213,672	196,044
54.4	5	232,438	137,112	112,830	148,541	187,337	171,961
54.4	1	94,925	77,120	58,402	66,660	109,412	118,761
54.4	0.5	75,876	65,236	48,865	55,149	95,814	107,570
54.4	0.1	54,336	50,580	38,027	42,535	79,309	97,337

Table B-7. Dynamic Modulus Test Results, Design No. 00600

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4,940,512	3,993,712	3,231,059	4,108,197	5,983,457	5,983,457
4.4	10	4,626,734	3,850,768	2,884,007	3,520,676	4,789,674	4,789,674
4.4	5	4,182,096	3,522,248	2,533,854	3,081,314	4,083,966	4,083,966
4.4	1	3,262,162	2,711,460	1,855,923	2,249,078	2,862,981	2,862,981
4.4	0.5	2,940,448	2,408,753	1,628,134	1,953,825	2,493,502	2,493,502
4.4	0.1	2,211,539	1,762,536	1,192,142	1,392,086	1,729,994	1,729,994
21.1	25	2,461,682	1,852,325	1,526,640	1,916,874	2,057,249	2,070,942
21.1	10	1,695,522	1,417,244	1,157,556	1,434,576	1,618,466	1,566,802
21.1	5	1,373,622	1,187,905	932,916	1,164,742	1,334,811	1,287,477
21.1	1	873,477	758,055	578,726	724,747	831,439	819,397
21.1	0.5	705,080	612,004	478,261	597,040	669,189	664,744
21.1	0.1	424,514	381,229	318,451	388,015	418,310	420,116
37.8	25	690,218	664,221	458,020	527,323	763,499	833,225
37.8	10	518,400	529,101	357,852	428,911	596,469	643,286
37.8	5	399,464	417,766	289,326	346,653	468,744	478,393
37.8	1	230,428	225,730	177,061	213,163	255,450	262,515
37.8	0.5	181,849	179,268	147,322	176,766	208,075	211,490
37.8	0.1	116,486	109,208	107,444	127,931	144,383	140,917
54.4	25	242,166	289,055	257,749	306,352	320,389	344,218
54.4	10	209,447	174,365	205,917	297,226	230,293	213,956
54.4	5	175,525	133,430	186,066	247,402	187,160	166,258
54.4	1	131,768	54,887	101,750	93,909	86,091	76,588
54.4	0.5	116,115	42,974	89,583	83,338	70,582	61,126
54.4	0.1	97,356	31,277	71,702	64,630	53,750	44,938

Table B-8. Dynamic Modulus Test Results, Design No. 05022

Temp (C)	Freq (Hz)	PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	4,446,691	3,797,947	7,168,405	5,008,715	4,174,114	3,564,347
4.4	10	3,843,738	3,483,187	4,910,970	4,407,323	3,578,069	3,152,522
4.4	5	3,383,512	3,187,871	3,904,133	3,814,788	3,080,786	2,835,089
4.4	1	2,540,852	2,538,399	2,611,637	2,614,378	2,245,465	2,214,255
4.4	0.5	2,213,803	2,285,863	2,199,716	2,208,395	1,935,166	1,958,059
4.4	0.1	1,540,862	1,740,414	1,467,650	1,475,854	1,347,330	1,441,795
21.1	25	2,072,460	2,714,857	2,268,833	1,884,724	2,395,780	2,340,409
21.1	10	1,562,036	1,841,353	1,391,277	1,275,013	1,476,769	1,609,959
21.1	5	1,290,903	1,498,525	1,065,276	1,019,802	1,146,907	1,285,796
21.1	1	836,799	957,139	633,043	634,733	689,225	817,709
21.1	0.5	683,608	776,756	503,771	510,173	540,235	653,963
21.1	0.1	424,104	481,394	320,664	323,131	334,581	414,463
37.8	25	699,076	808,887	604,065	679,481	704,464	834,281
37.8	10	566,742	646,036	484,333	497,908	608,992	683,615
37.8	5	441,549	502,755	384,787	388,036	481,179	534,223
37.8	1	247,443	278,611	221,519	220,460	242,992	279,095
37.8	0.5	196,733	220,737	184,360	179,870	196,350	225,049
37.8	0.1	129,366	144,238	133,251	123,257	133,951	152,616
54.4	25	335,520	276,381	247,824	225,212	268,611	456,447
54.4	10	247,847	222,401	228,874	217,995	228,466	405,871
54.4	5	199,799	151,105	182,508	150,542	174,675	236,840
54.4	1	102,054	85,659	105,184	85,875	87,296	109,930
54.4	0.5	80,683	73,231	93,288	73,655	74,207	91,414
54.4	0.1	61,615	58,581	78,322	56,074	56,123	63,233

Dynamic Modulus (psi)

Table B-9. Dynamic Modulus Test Results, Design No. 03051

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3,877,717	3,766,886	2,973,969	3,418,469	2,876,660	3,344,881
4.4	10	3,751,634	3,446,160	2,624,668	2,864,794	2,605,012	2,956,796
4.4	5	3,389,695	3,179,687	2,316,389	2,500,801	2,340,485	2,583,944
4.4	1	2,675,424	2,621,920	1,699,882	1,842,311	1,809,127	1,857,820
4.4	0.5	2,429,978	2,400,295	1,494,549	1,623,591	1,608,331	1,619,704
4.4	0.1	1,895,896	1,920,967	1,087,640	1,185,339	1,207,483	1,152,565
21.1	25	1,929,598	2,257,987	1,596,778	2,181,202	1,498,156	1,535,471
21.1	10	1,578,626	1,764,157	1,164,139	1,409,886	1,204,145	1,197,142
21.1	5	1,324,708	1,486,626	935,116	1,103,504	1,015,018	978,254
21.1	1	878,824	1,026,676	566,119	651,332	658,591	612,175
21.1	0.5	734,024	886,836	463,626	528,115	539,928	495,207
21.1	0.1	490,217	617,067	307,247	342,318	349,523	317,997
37.8	25	760,906	812,159	402,469	467,856	603,299	497,788
37.8	10	638,780	673,877	319,868	360,896	475,690	399,750
37.8	5	503,143	555,194	265,756	287,984	376,377	317,500
37.8	1	288,980	340,556	158,283	168,740	225,700	190,398
37.8	0.5	226,744	270,548	132,774	137,659	183,285	155,388
37.8	0.1	138,887	170,395	101,625	97,323	126,100	108,866
54.4	25	279,986	330,494	200,085	239,331	179,576	174,882
54.4	10	200,722	297,224	186,830	211,524	151,691	152,633
54.4	5	180,455	262,859	166,521	201,707	129,443	127,354
54.4	1	74,006	140,267	55,722	68,316	80,683	67,032
54.4	0.5	58,233	118,379	47,069	56,918	70,218	56,076
54.4	0.1	39,310	89,962	37,274	43,168	58,431	43,219

Table B-10. Dynamic Modulus Test Results, Design No. 05702

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	4,612,066	3,771,521	3,973,902	3,749,878	4,041,841	3,093,442
4.4	10	4,102,728	3,543,996	3,534,220	3,518,469	3,717,151	2,878,943
4.4	5	3,711,988	3,240,664	3,114,766	3,113,757	3,268,132	2,602,629
4.4	1	2,931,438	2,628,970	2,349,160	2,274,235	2,510,396	2,014,531
4.4	0.5	2,658,037	2,390,986	2,083,001	1,987,154	2,224,957	1,814,654
4.4	0.1	2,090,840	1,853,451	1,546,069	1,398,492	1,621,774	1,387,673
21.1	25	2,038,871	1,815,439	2,122,924	1,997,418	1,875,049	1,273,645
21.1	10	1,801,154	1,475,148	1,620,079	1,328,761	1,488,576	1,046,410
21.1	5	1,569,143	1,229,843	1,315,726	1,033,269	1,243,770	884,933
21.1	1	1,106,432	800,888	847,852	640,974	814,036	580,054
21.1	0.5	952,491	660,235	704,811	514,662	666,184	482,694
21.1	0.1	653,146	434,139	463,810	327,809	428,203	319,915
37.8	25	698,254	898,955	662,353	573,168	804,448	637,247
37.8	10	579,660	590,596	557,606	467,890	622,408	510,648
37.8	5	490,243	452,447	458,778	379,084	490,168	405,905
37.8	1	308,331	269,482	267,498	232,826	284,126	238,785
37.8	0.5	250,123	212,617	218,010	190,615	226,234	191,931
37.8	0.1	165,432	137,199	147,582	130,881	147,354	126,943
54.4	25	407,000	215,109	391,755	224,870	428,248	260,768
54.4	10	352,367	171,908	337,728	210,645	302,782	193,415
54.4	5	290,179	137,072	255,452	181,710	262,540	154,300
54.4	1	147,705	82,967	102,327	76,031	119,036	80,739
54.4	0.5	121,462	70,618	82,466	62,170	94,891	66,417
54.4	0.1	92,286	55,372	58,063	45,183	64,877	47,982

Table B-11. Dynamic Modulus Test Results, Design No. 04071

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	2,556,453	2,770,396	3,123,827	2,648,975	2,417,993	3,133,616
4.4	10	2,379,105	2,566,174	2,448,317	2,334,160	2,268,584	2,823,842
4.4	5	2,128,068	2,362,993	2,027,012	2,087,827	2,055,676	2,533,468
4.4	1	1,599,476	1,926,446	1,375,385	1,560,913	1,577,522	1,924,607
4.4	0.5	1,441,412	1,751,400	1,161,094	1,362,697	1,406,984	1,692,432
4.4	0.1	1,076,560	1,370,219	797,844	980,669	1,063,815	1,228,745
21.1	25	1,293,963	1,845,535	1,058,616	1,239,363	1,369,514	1,427,478
21.1	10	1,087,251	1,379,150	809,007	967,696	1,040,211	1,075,382
21.1	5	900,938	1,118,803	664,334	803,369	853,141	886,740
21.1	1	529,179	695,490	425,015	510,941	525,201	562,476
21.1	0.5	416,074	572,644	354,891	428,183	427,382	464,507
21.1	0.1	239,310	367,701	242,461	290,335	275,781	303,664
37.8	25	397,356	544,864	375,414	489,659	408,695	475,050
37.8	10	292,189	439,806	295,590	378,486	322,718	384,967
37.8	5	234,363	351,728	246,963	301,843	264,024	310,654
37.8	1	124,422	210,277	163,944	184,529	160,274	194,045
37.8	0.5	97,307	169,260	142,254	155,653	133,054	161,018
37.8	0.1	65,414	109,250	116,164	114,957	95,717	116,735
54.4	25	172,007	223,289	524,141	552,491	186,942	250,881
54.4	10	106,822	139,891	210,328	326,361	155,156	226,295
54.4	5	89,709	110,913	183,188	280,295	120,261	203,931
54.4	1	62,254	60,301	80,966	100,437	54,458	99,278
54.4	0.5	55,862	49,358	67,003	84,832	46,465	86,095
54.4	0.1	47,358	36,155	51,854	69,387	36,649	67,975

Table B-12. Dynamic Modulus Test Results, Design No. 04062

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 (S) Sample 1	PG 70-28 (S) Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	3,565,090	3,238,163	3,264,546	3,534,483	4,758,350	3,560,012
4.4	10	3,090,221	3,074,608	2,984,824	3,129,588	4,402,063	3,347,472
4.4	5	2,808,590	2,802,344	2,728,004	2,848,758	3,970,341	3,092,009
4.4	1	2,316,030	2,221,563	2,164,587	2,296,989	3,174,553	2,534,782
4.4	0.5	2,114,702	2,007,696	1,946,512	2,080,263	2,836,050	2,320,414
4.4	0.1	1,718,096	1,561,263	1,496,317	1,607,872	2,116,366	1,828,841
21.1	25	1,650,805	1,447,632	2,033,918	1,959,632	2,128,213	1,640,694
21.1	10	1,440,839	1,214,437	1,435,915	1,558,687	1,804,951	1,400,150
21.1	5	1,281,066	1,061,552	1,159,156	1,302,591	1,559,324	1,218,449
21.1	1	920,926	728,735	739,325	858,166	1,069,196	830,342
21.1	0.5	790,378	625,642	611,076	721,119	904,399	699,086
21.1	0.1	553,063	454,302	416,405	487,451	617,515	469,761
37.8	25	807,855	687,628	706,691	608,670	957,174	752,328
37.8	10	759,353	580,070	599,183	559,738	852,600	680,010
37.8	5	616,486	468,718	472,584	470,967	710,863	554,288
37.8	1	372,326	280,019	279,193	300,502	429,024	330,131
37.8	0.5	303,700	224,057	227,314	248,455	348,816	259,541
37.8	0.1	183,431	145,641	157,331	171,441	227,799	162,343
54.4	25	291,584	288,267	238,510	341,803	459,209	352,149
54.4	10	239,798	256,382	196,042	298,192	404,830	323,083
54.4	5	221,539	216,383	179,763	284,499	339,514	262,307
54.4	1	100,383	157,396	92,987	129,320	230,184	175,578
54.4	0.5	83,300	143,866	76,179	105,546	205,914	155,867
54.4	0.1	61,347	113,097	55,674	75,950	159,739	121,500

Table B-13. Dynamic Modulus Test Results, Design No. 05010

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	4,190,510	3,747,737	3,111,698	4,443,106	4,508,149	4,709,793
4.4	10	3,806,061	3,416,457	3,082,945	3,806,901	4,097,801	4,162,284
4.4	5	3,526,038	3,147,507	2,741,897	3,412,489	3,676,096	3,711,517
4.4	1	2,893,865	2,496,282	1,981,178	2,581,737	2,834,145	2,901,561
4.4	0.5	2,647,590	2,255,372	1,749,071	2,300,583	2,536,379	2,623,510
4.4	0.1	2,118,009	1,732,445	1,288,299	1,705,444	1,914,714	2,036,901
21.1	25	2,475,630	1,762,385	3,196,089	2,446,813	2,161,755	2,229,175
21.1	10	1,876,889	1,450,226	2,227,593	1,875,442	1,730,823	1,797,845
21.1	5	1,612,985	1,240,784	1,710,660	1,508,909	1,457,719	1,534,197
21.1	1	1,086,904	816,915	997,760	936,929	965,589	1,032,615
21.1	0.5	907,665	675,925	790,210	778,389	801,677	864,594
21.1	0.1	589,201	453,946	495,218	515,915	524,118	575,009
37.8	25	885,733	812,013	712,898	792,941	759,214	916,783
37.8	10	709,689	669,063	690,840	661,937	617,615	793,125
37.8	5	566,387	504,210	600,099	554,926	498,795	637,652
37.8	1	331,368	297,963	367,299	335,303	306,853	374,519
37.8	0.5	263,897	235,408	296,915	273,397	251,431	299,184
37.8	0.1	164,512	152,854	195,011	184,810	174,135	204,708
54.4	25	390,058	246,239	450,567	422,080	442,026	413,327
54.4	10	265,494	231,319	400,394	256,371	298,509	299,331
54.4	5	202,566	181,544	366,498	218,538	331,246	281,547
54.4	1	90,720	76,580	133,459	116,744	108,737	110,203
54.4	0.5	71,604	64,259	110,605	99,904	88,877	90,437
54.4	0.1	48,101	50,306	83,063	74,200	65,484	65,069

Table B-14. Dynamic Modulus Test Results, Design No. 05002

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4,278,188	4,002,868	3,489,649	3,282,251	2,808,352	2,229,945
4.4	10	3,836,247	3,377,414	2,854,568	3,013,130	2,495,188	2,055,476
4.4	5	3,413,623	2,913,365	2,456,283	2,661,470	2,224,449	1,820,538
4.4	1	2,580,828	2,099,839	1,707,523	1,940,144	1,669,621	1,328,114
4.4	0.5	2,281,282	1,830,627	1,460,026	1,704,817	1,469,959	1,159,494
4.4	0.1	1,682,691	1,292,757	995,081	1,248,321	1,067,717	837,372
21.1	25	2,610,018	1,641,199	1,285,725	1,545,133	987,892	1,855,368
21.1	10	2,153,669	1,322,811	958,295	1,251,553	816,833	1,469,738
21.1	5	1,789,276	1,076,765	747,312	1,015,184	679,260	1,179,398
21.1	1	1,061,237	641,291	440,552	625,629	429,401	624,130
21.1	0.5	818,886	510,241	360,084	514,638	355,173	453,099
21.1	0.1	435,121	312,570	244,080	341,737	245,062	270,192
37.8	25	617,163	513,454	330,635	556,026	346,731	289,976
37.8	10	520,951	382,390	283,315	453,808	298,948	239,837
37.8	5	404,388	294,908	232,014	358,310	239,216	196,589
37.8	1	232,693	175,074	161,891	230,044	153,337	132,985
37.8	0.5	183,881	139,247	142,121	190,468	128,086	113,754
37.8	0.1	115,968	92,260	107,409	135,515	93,791	86,264
54.4	25	150,463	114,640	112,925	153,285	106,389	116,169
54.4	10	110,828	77,688	111,490	118,790	102,936	111,243
54.4	5	96,428	66,625	100,252	103,429	89,168	96,451
54.4	1	63,721	52,105	53,097	70,587	45,915	45,854
54.4	0.5	59,070	45,925	49,357	65,751	41,463	40,978
54.4	0.1	57,992	37,605	42,033	56,042	34,197	33,477

Table B-15. Dynamic Modulus Test Results, Design No. 03043

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	3,922,072	3,389,775	3,964,234	5,384,388	3,638,493	3,454,908
4.4	10	3,616,204	3,132,448	3,483,002	4,440,501	3,336,347	3,033,130
4.4	5	3,252,953	2,874,775	3,080,809	3,703,912	2,998,318	2,683,699
4.4	1	2,519,484	2,322,077	2,344,339	2,592,048	2,269,381	2,021,254
4.4	0.5	2,269,385	2,126,414	2,063,843	2,194,795	2,005,088	1,815,783
4.4	0.1	1,770,434	1,679,137	1,497,690	1,460,760	1,454,263	1,389,491
21.1	25	1,948,435	1,856,092	1,628,978	2,041,536	1,648,862	1,552,774
21.1	10	1,561,063	1,515,997	1,249,262	1,484,327	1,284,449	1,304,132
21.1	5	1,326,309	1,303,382	1,006,353	1,215,543	1,068,217	1,123,220
21.1	1	900,348	850,623	647,274	752,444	700,426	747,370
21.1	0.5	762,375	704,865	531,605	619,358	582,586	621,592
21.1	0.1	514,916	461,313	354,286	404,417	382,485	405,175
37.8	25	726,494	974,625	660,596	728,245	587,008	623,869
37.8	10	612,989	892,908	545,633	611,347	491,835	520,906
37.8	5	494,858	690,112	450,623	508,098	401,088	422,120
37.8	1	302,708	387,858	269,377	311,531	242,213	256,324
37.8	0.5	244,375	297,759	223,036	254,885	198,219	209,304
37.8	0.1	157,645	178,409	159,440	176,114	138,579	147,174
54.4	25	286,453	301,900	271,866	365,005	218,150	302,096
54.4	10	204,872	218,405	222,869	320,860	174,806	228,994
54.4	5	176,534	199,963	180,740	261,302	160,093	186,720
54.4	1	87,699	88,590	83,099	123,834	77,496	94,584
54.4	0.5	72,143	72,320	70,153	98,709	67,805	77,064
54.4	0.1	52,445	53,155	52,495	70,005	49,249	58,673

Table B-16. Dynamic Modulus Test Results, Design No. 20610

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	7,944,575	7,151,464	6,320,968	4,783,536	6,014,581	7,247,908
4.4	10	6,822,746	6,725,318	5,477,536	4,356,709	5,851,709	6,323,065
4.4	5	6,058,661	5,998,355	4,759,996	3,830,626	5,248,132	5,685,630
4.4	1	4,749,941	4,774,237	3,605,339	2,926,815	4,113,127	4,566,575
4.4	0.5	4,345,022	4,339,739	3,248,383	2,577,349	3,756,274	4,196,542
4.4	0.1	3,393,416	3,403,805	2,481,634	1,876,641	2,904,061	3,359,576
21.1	25	3,572,307	4,171,774	4,433,407	4,380,558	5,468,295	4,941,294
21.1	10	2,892,194	3,263,972	2,709,979	2,714,102	3,634,206	3,646,786
21.1	5	2,447,469	2,805,673	2,217,629	2,200,769	2,982,741	3,120,502
21.1	1	1,656,149	2,057,315	1,514,911	1,468,464	2,089,617	2,279,139
21.1	0.5	1,394,165	1,751,608	1,260,895	1,234,408	1,778,816	1,958,414
21.1	0.1	926,818	1,213,152	852,049	848,890	1,229,201	1,376,935
37.8	25	1,322,337	1,589,666	1,073,323	1,480,825	1,438,271	1,883,631
37.8	10	1,087,500	1,345,840	935,796	1,339,315	1,194,713	1,761,394
37.8	5	888,709	1,120,424	752,107	1,086,936	992,065	1,508,819
37.8	1	551,637	694,933	449,192	592,751	591,528	784,795
37.8	0.5	447,518	554,228	368,481	464,119	479,788	629,330
37.8	0.1	291,335	341,848	252,138	293,972	313,300	426,064
54.4	25	609,414	648,893	417,074	558,447	672,678	722,280
54.4	10	601,054	573,153	314,353	416,730	643,258	601,276
54.4	5	510,002	487,118	296,432	374,778	512,557	598,082
54.4	1	265,728	260,566	144,008	217,705	239,033	255,125
54.4	0.5	215,572	208,225	121,639	184,864	191,667	205,242
54.4	0.1	155,780	142,096	92,927	139,780	127,573	144,367

Table B-17. Dynamic Modulus Test Results, Design No. 05024

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	3,691,766	3,905,933	3,031,045	3,030,840	5,096,811	3,691,232
4.4	10	3,334,695	3,552,139	2,572,589	2,779,904	4,129,936	3,239,939
4.4	5	2,926,690	3,046,494	2,241,912	2,441,929	3,478,609	2,866,597
4.4	1	2,226,636	2,285,670	1,595,183	1,752,518	2,419,728	2,156,446
4.4	0.5	1,975,164	2,011,090	1,361,084	1,510,454	2,085,874	1,896,975
4.4	0.1	1,447,243	1,482,546	914,435	1,055,014	1,455,829	1,376,809
21.1	25	2,227,934	2,325,408	1,536,068	1,479,039	2,127,905	1,668,075
21.1	10	1,544,471	1,798,873	1,039,216	1,084,746	1,494,668	1,359,316
21.1	5	1,257,145	1,443,272	812,812	850,677	1,206,971	1,120,929
21.1	1	755,709	873,403	486,089	508,760	729,767	688,300
21.1	0.5	612,891	695,921	394,971	420,318	595,425	559,731
21.1	0.1	373,198	411,743	258,368	284,338	376,345	356,043
37.8	25	682,317	702,387	383,529	494,642	801,134	634,613
37.8	10	466,326	571,605	316,605	400,761	613,395	534,155
37.8	5	361,874	415,077	257,264	318,771	467,781	406,487
37.8	1	221,977	241,087	161,638	191,915	269,160	237,990
37.8	0.5	179,959	194,165	137,299	160,197	212,818	192,663
37.8	0.1	126,025	131,194	105,366	115,133	145,307	135,288
54.4	25	363,749	436,291	197,051	293,487	307,567	218,840
54.4	10	212,233	348,867	189,082	249,454	249,217	194,150
54.4	5	153,147	255,139	161,007	215,026	204,461	190,644
54.4	1	55,249	94,209	70,357	90,903	95,301	81,523
54.4	0.5	49,201	78,957	61,180	77,376	80,991	68,787
54.4	0.1	41,226	70,260	49,623	62,836	64,476	52,346

Table B-18. Dynamic Modulus Test Results, Design No. 05090

Temp (C)	Freq (Hz)	Dynamic Modulus (psi) PG 64-22 Sample 1	PG 64-22 Sample 2	PG 70-28 Sample 1	PG 70-28 Sample 2	PG 76-28 Sample 1	PG 76-28 Sample 2
4.4	25	4,848,955	3,705,964	6,537,171	4,748,885	6,734,403	6,143,536
4.4	10	4,065,518	3,238,279	5,063,716	3,998,300	4,802,792	4,047,837
4.4	5	3,525,872	2,921,718	4,093,256	3,454,688	3,980,980	3,219,237
4.4	1	2,585,110	2,221,318	2,690,917	2,453,948	2,597,756	2,064,692
4.4	0.5	2,307,508	1,968,997	2,251,933	2,122,721	2,171,787	1,719,005
4.4	0.1	1,594,536	1,401,375	1,478,792	1,441,440	1,449,296	1,145,843
21.1	25	1,299,499	2,382,697	3,723,928	1,715,033	3,305,082	2,520,893
21.1	10	1,030,395	1,665,177	1,890,789	1,337,454	1,754,451	1,477,457
21.1	5	846,672	1,371,143	1,418,702	1,108,768	1,336,738	1,145,332
21.1	1	531,031	877,955	811,763	674,155	805,987	692,263
21.1	0.5	432,118	721,386	632,145	540,090	639,874	549,397
21.1	0.1	272,988	457,175	385,866	339,284	404,997	342,545
37.8	25	534,787	1,018,052	533,546	604,208	590,406	567,109
37.8	10	398,605	588,103	428,326	476,903	454,380	448,926
37.8	5	310,394	435,354	350,293	384,671	366,742	354,240
37.8	1	186,653	235,268	202,480	233,723	209,229	209,061
37.8	0.5	150,734	184,314	167,622	194,272	172,302	173,217
37.8	0.1	102,034	118,345	124,780	141,882	122,738	123,971
54.4	25	187,445	184,669	220,047	271,749	233,740	306,568
54.4	10	140,199	140,672	206,680	192,153	227,776	284,630
54.4	5	137,178	114,728	186,659	183,254	211,499	256,358
54.4	1	81,254	69,517	103,588	102,558	104,824	105,078
54.4	0.5	75,179	60,067	93,466	91,445	89,428	88,763
54.4	0.1	75,478	48,960	77,269	76,907	71,304	66,924

Table B-19. Dynamic Modulus Test Results, Design No. 03162

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	4,598,203	4,500,865	3,978,440	4,066,612	4,429,134	5,401,978
4.4	10	3,928,665	3,988,027	3,460,730	3,576,574	4,127,298	4,313,151
4.4	5	3,445,138	3,569,562	3,012,822	3,159,632	3,612,181	3,719,490
4.4	1	2,600,651	2,740,194	2,233,539	2,372,992	2,621,939	2,709,371
4.4	0.5	2,325,520	2,440,522	1,918,938	2,077,350	2,281,041	2,369,400
4.4	0.1	1,740,509	1,795,797	1,306,740	1,492,807	1,619,365	1,689,422
21.1	25	3,324,086	2,499,101	1,839,981	1,746,447	2,049,643	2,026,270
21.1	10	1,984,020	1,914,243	1,274,954	1,335,060	1,498,741	1,555,249
21.1	5	1,506,409	1,653,665	1,005,107	1,095,730	1,232,246	1,300,155
21.1	1	926,999	1,078,425	603,242	699,677	781,960	836,379
21.1	0.5	729,781	883,954	481,026	566,659	630,593	675,910
21.1	0.1	450,758	558,257	299,426	363,760	399,634	425,949
37.8	25	749,376	950,179	564,225	618,293	740,010	717,116
37.8	10	649,978	754,732	413,291	493,651	605,855	603,843
37.8	5	533,951	583,696	319,728	400,310	477,301	472,056
37.8	1	297,385	312,382	170,943	232,657	260,624	262,649
37.8	0.5	234,807	244,238	138,475	191,295	209,057	210,458
37.8	0.1	202,877	154,124	98,133	135,432	141,908	140,935
54.4	25	233,651	554,982	251,242	386,916	246,057	242,583
54.4	10	213,941	946,482	245,334	322,731	226,859	206,738
54.4	5	159,608	334,866	172,955	221,864	154,734	173,040
54.4	1	75,417	145,809	85,637	118,856	81,898	85,828
54.4	0.5	62,144	111,914	74,199	104,261	70,182	71,936
54.4	0.1	44,796	73,242	60,572	85,067	54,775	53,880

Table B-20. Dynamic Modulus Test Results, Design No. 05007

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	5,179,856	4,797,904	3,325,808	3,936,204	3,598,170	5,461,196
4.4	10	4,467,055	4,115,422	2,900,352	3,372,102	3,126,082	4,883,394
4.4	5	3,944,666	3,629,857	2,542,812	2,918,065	2,765,930	4,181,153
4.4	1	2,999,992	2,747,642	1,852,204	2,053,168	2,077,181	2,938,343
4.4	0.5	2,680,015	2,402,212	1,635,953	1,762,354	1,825,987	2,521,053
4.4	0.1	1,995,410	1,691,639	1,214,968	1,198,919	1,316,948	1,689,646
21.1	25	3,235,140	2,413,600	1,658,996	1,666,620	2,021,523	2,499,111
21.1	10	2,293,603	1,806,102	1,205,721	1,037,336	1,484,843	1,700,455
21.1	5	1,800,862	1,487,904	948,472	763,260	1,186,222	1,350,312
21.1	1	1,085,672	935,729	572,993	434,824	740,108	792,682
21.1	0.5	853,100	747,980	455,058	348,081	589,522	616,882
21.1	0.1	498,362	429,653	288,444	232,700	367,878	363,642
37.8	25	775,961	1,035,566	487,921	582,129	706,300	516,976
37.8	10	588,862	795,443	402,598	523,489	594,484	489,917
37.8	5	439,934	600,003	323,883	389,178	500,333	395,260
37.8	1	231,232	269,720	186,111	204,135	263,633	222,705
37.8	0.5	179,684	203,073	153,093	167,302	208,550	183,555
37.8	0.1	109,811	123,228	111,703	121,439	136,137	129,967
54.4	25	270,630	238,651	158,858	175,334	236,698	227,120
54.4	10	191,099	174,384	122,709	167,719	197,354	195,688
54.4	5	147,446	139,798	107,190	101,263	163,166	140,459
54.4	1	73,529	63,608	63,959	66,042	77,830	80,528
54.4	0.5	63,336	53,977	61,169	59,137	62,710	67,487
54.4	0.1	50,242	47,184	50,194	49,193	45,050	51,375

Table B-21. Dynamic Modulus Test Results, Design No. 04068

Temp	Freq	Dynamic Modulus (psi)					
		PG 64-22		PG 70-28		PG 76-28	
(C)	(Hz)	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
4.4	25	6,298,206	7,454,824	6,029,968	6,221,142	9,491,806	5,985,860
4.4	10	5,845,355	6,352,043	5,562,103	5,406,511	8,534,365	4,911,551
4.4	5	5,215,966	5,447,429	4,905,387	4,641,402	7,421,111	4,341,700
4.4	1	4,045,879	4,160,910	3,518,725	3,306,896	5,216,040	3,343,949
4.4	0.5	3,654,174	3,758,439	3,020,490	2,883,282	4,524,083	2,998,616
4.4	0.1	2,798,269	2,869,153	1,769,891	2,061,805	3,143,696	2,260,962
21.1	25	3,326,882	2,563,862	2,854,852	2,106,341	4,507,724	2,415,322
21.1	10	2,925,190	2,256,420	2,140,593	1,767,689	3,343,133	1,944,962
21.1	5	2,434,039	1,943,704	1,685,110	1,485,477	2,875,709	1,648,477
21.1	1	1,625,144	1,341,509	1,034,287	983,997	1,700,681	1,139,379
21.1	0.5	1,327,782	1,113,850	823,907	807,604	1,359,801	952,542
21.1	0.1	858,930	732,925	541,354	534,851	852,137	644,342
37.8	25	1,376,783	1,314,909	964,883	759,378	1,331,005	1,492,246
37.8	10	1,090,781	1,074,915	796,736	654,040	1,187,345	1,185,601
37.8	5	871,492	880,334	656,990	516,413	1,032,110	959,065
37.8	1	479,855	478,976	354,088	292,263	542,813	509,302
37.8	0.5	381,130	376,392	292,082	240,931	427,668	402,955
37.8	0.1	240,966	232,525	206,238	170,059	267,238	252,250
54.4	25	347,302	496,322	336,352	322,693	652,900	391,731
54.4	10	303,861	385,725	295,897	301,076	486,889	355,126
54.4	5	212,286	252,174	174,779	185,903	373,847	256,512
54.4	1	108,702	121,920	128,336	122,571	167,503	130,278
54.4	0.5	93,095	101,938	113,091	107,143	133,587	107,027
54.4	0.1	73,007	74,997	94,974	85,189	89,818	80,135

APPENDIX C

PREDICTED DYNAMIC MODULUS

Table C-1. Predicted Dynamic Modulus Test Results, Design No. 05059

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	3,051,910	2,710,777	2,818,811
	10	2,773,185	2,432,579	2,541,619
	5	2,562,417	2,225,254	2,333,890
	1	2,082,801	1,763,970	1,867,736
	0.5	1,884,350	1,577,696	1,677,746
	0.1	1,453,622	1,183,684	1,271,946
21.1	25	1,272,510	1,222,045	1,365,991
	10	1,067,219	1,021,560	1,152,533
	5	926,094	884,290	1,004,709
	1	647,349	614,687	709,668
	0.5	548,210	519,365	603,575
	0.1	363,205	342,449	403,566
37.8	25	438,571	481,797	579,785
	10	344,685	380,265	462,059
	5	285,365	315,730	386,230
	1	180,724	201,027	249,137
	0.5	147,545	164,389	204,604
	0.1	91,379	102,022	127,786
54.4	25	156,454	194,164	245,721
	10	119,308	148,612	189,169
	5	97,000	121,032	154,558
	1	59,922	74,784	95,812
	0.5	48,781	60,788	77,844
	0.1	30,575	37,832	48,188

Table C-2. Predicted Dynamic Modulus Test Results, Design No. 04006

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,850,677	2,515,983	2,677,609
	10	2,591,012	2,258,447	2,414,988
	5	2,394,608	2,066,468	2,218,128
	1	1,947,509	1,639,145	1,776,181
	0.5	1,762,433	1,466,501	1,595,974
	0.1	1,360,541	1,101,127	1,210,872
21.1	25	1,191,462	1,136,713	1,300,147
	10	999,729	950,695	1,097,490
	5	867,866	823,272	957,087
	1	607,244	572,844	676,676
	0.5	514,481	484,235	575,771
	0.1	341,244	319,651	385,401
37.8	25	411,840	449,301	553,138
	10	323,890	354,847	441,097
	5	268,288	294,776	368,890
	1	170,123	187,918	238,238
	0.5	138,967	153,755	195,759
	0.1	86,180	95,547	122,420
54.4	25	147,335	181,520	234,981
	10	112,438	139,036	181,030
	5	91,466	113,297	147,991
	1	56,578	70,098	91,861
	0.5	46,084	57,011	74,677
	0.1	28,922	35,528	46,288

Table C-3. Predicted Dynamic Modulus Test Results, Design No. 04063

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,239,587	1,983,138	2,093,632
	10	2,037,084	1,781,626	1,889,790
	5	1,883,813	1,631,295	1,736,879
	1	1,534,527	1,296,273	1,393,202
	0.5	1,389,767	1,160,737	1,252,883
	0.1	1,074,997	873,470	952,593
21.1	25	942,366	901,478	1,022,264
	10	791,788	754,994	864,049
	5	688,102	654,527	754,306
	1	482,790	456,703	534,733
	0.5	409,562	386,559	455,561
	0.1	272,514	255,992	305,881
37.8	25	328,415	358,878	437,788
	10	258,759	283,950	349,722
	5	214,650	236,218	292,876
	1	136,589	151,111	189,784
	0.5	111,748	123,831	156,181
	0.1	69,556	77,234	98,024
54.4	25	118,424	146,005	187,210
	10	90,563	112,063	144,517
	5	73,789	91,462	118,325
	1	45,812	56,798	73,718
	0.5	37,375	46,268	60,023
	0.1	23,540	28,938	37,342

Table C-4. Predicted Dynamic Modulus Test Results, Design No. 05018

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,107,802	1,923,532	2,015,651
	10	1,917,718	1,728,590	1,819,919
	5	1,773,814	1,583,122	1,673,053
	1	1,445,745	1,258,795	1,342,826
	0.5	1,309,720	1,127,524	1,207,937
	0.1	1,013,801	849,145	919,117
21.1	25	889,045	876,297	986,147
	10	747,348	734,265	833,911
	5	649,734	636,809	728,269
	1	456,319	444,784	516,769
	0.5	387,282	376,645	440,452
	0.1	257,981	249,711	296,063
37.8	25	310,740	349,746	423,315
	10	244,995	276,904	338,371
	5	203,337	230,474	283,510
	1	129,553	147,620	183,936
	0.5	106,051	121,036	151,450
	0.1	66,096	75,590	95,177
54.4	25	112,368	142,645	181,448
	10	85,996	109,565	140,170
	5	70,107	89,473	114,829
	1	43,584	55,636	71,634
	0.5	35,577	45,347	58,359
	0.1	22,437	28,399	36,355

Table C-5. Predicted Dynamic Modulus Test Results, Design No. 04179

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,756,480	2,454,068	2,603,011
	10	2,505,263	2,202,739	2,347,573
	5	2,315,259	2,015,396	2,156,107
	1	1,882,761	1,598,430	1,726,307
	0.5	1,703,745	1,429,987	1,551,069
	0.1	1,315,048	1,073,541	1,176,623
21.1	25	1,151,538	1,108,255	1,263,422
	10	966,137	926,803	1,066,390
	5	838,639	802,519	929,896
	1	586,679	558,292	657,326
	0.5	497,012	471,890	559,256
	0.1	329,583	311,431	374,264
37.8	25	397,808	437,828	537,261
	10	312,813	345,742	428,383
	5	259,086	287,183	358,222
	1	164,246	183,032	231,292
	0.5	134,152	149,741	190,031
	0.1	83,172	93,028	118,808
54.4	25	142,234	176,797	228,128
	10	108,529	135,399	175,726
	5	88,277	110,320	143,638
	1	54,590	68,238	89,136
	0.5	44,461	55,492	72,453
	0.1	27,895	34,572	44,898

Table C-6. Predicted Dynamic Modulus Test Results, Design No. 05066

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,704,897	2,440,237	2,552,813
	10	2,459,674	2,191,627	2,303,610
	5	2,274,114	2,006,210	2,116,720
	1	1,851,407	1,593,175	1,696,845
	0.5	1,676,293	1,426,159	1,525,495
	0.1	1,295,704	1,072,357	1,158,984
21.1	25	1,135,428	1,106,839	1,243,995
	10	953,541	926,530	1,050,972
	5	828,350	802,918	917,142
	1	580,621	559,686	649,549
	0.5	492,329	473,506	553,131
	0.1	327,216	313,212	370,984
37.8	25	394,542	439,509	531,493
	10	310,656	347,520	424,313
	5	257,566	288,954	355,167
	1	163,693	184,619	229,873
	0.5	133,848	151,205	189,069
	0.1	83,202	94,184	118,512
54.4	25	141,867	178,363	226,746
	10	108,410	136,799	174,911
	5	88,280	111,587	143,132
	1	54,737	69,204	89,055
	0.5	44,630	56,342	72,470
	0.1	28,074	35,193	45,027

Table C-7. Predicted Dynamic Modulus Test Results, Design No. 00600

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,474,247	2,222,093	2,328,181
	10	2,250,171	1,995,944	2,101,145
	5	2,080,596	1,827,262	1,930,862
	1	1,694,245	1,451,438	1,548,232
	0.5	1,534,165	1,299,440	1,392,054
	0.1	1,186,183	977,383	1,057,924
21.1	25	1,039,606	1,008,776	1,135,433
	10	873,238	844,607	959,435
	5	758,708	732,041	837,387
	1	532,016	510,484	593,290
	0.5	451,197	431,960	505,313
	0.1	300,014	285,861	339,062
37.8	25	361,669	400,979	485,567
	10	284,847	317,136	387,745
	5	236,217	263,745	324,622
	1	150,200	168,595	210,204
	0.5	122,843	138,112	172,930
	0.1	76,401	86,074	108,451
54.4	25	130,194	162,889	207,348
	10	99,519	124,967	159,994
	5	81,059	101,959	130,954
	1	50,286	63,267	81,521
	0.5	41,011	51,520	66,354
	0.1	25,810	32,198	41,248

Table C-8. Predicted Dynamic Modulus Test Results, Design No. 05022

Temp (C)	Frequency (Hz)	Average E* (psi) PG 64-22	PG 70-28	PG 76-28
4.4	25	2,289,276	2,031,926	2,129,910
	10	2,082,718	1,825,891	1,922,973
	5	1,926,348	1,672,152	1,767,708
	1	1,569,889	1,329,417	1,418,624
	0.5	1,422,105	1,190,708	1,276,046
	0.1	1,100,638	896,588	970,794
21.1	25	965,126	925,273	1,041,634
	10	811,224	775,227	880,749
	5	705,212	672,281	769,116
	1	495,184	469,466	545,649
	0.5	420,230	397,509	465,026
	0.1	279,865	263,484	312,512
37.8	25	337,135	369,105	446,923
	10	265,770	292,193	357,197
	5	220,557	243,175	299,254
	1	140,488	155,716	194,104
	0.5	114,990	127,660	159,805
	0.1	71,649	79,706	100,402
54.4	25	121,844	150,465	191,477
	10	93,234	115,555	147,896
	5	75,999	94,354	121,145
	1	47,235	58,656	75,554
	0.5	38,553	47,803	61,546
	0.1	24,307	29,929	38,330

Table C-9. Predicted Dynamic Modulus Test Results, Design No. 03051

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
	25	2,580,437	2,296,875	2,412,767
	10	2,346,347	2,062,721	2,177,083
4.4	5	2,169,222	1,888,097	2,000,344
	1	1,765,766	1,499,145	1,603,314
	0.5	1,598,645	1,341,886	1,441,306
	0.1	1,235,471	1,008,796	1,094,818
	25	1,082,549	1,041,257	1,175,179
	10	909,025	871,526	992,721
21.1	5	789,604	755,180	866,228
	1	553,329	526,281	613,347
	0.5	469,136	445,194	522,246
	0.1	311,715	294,403	350,175
	25	375,899	413,209	501,803
	10	295,929	326,673	400,549
37.8	5	245,324	271,587	335,236
	1	155,865	173,469	216,909
	0.5	127,431	142,055	178,383
	0.1	79,187	88,456	111,778
	25	135,070	167,588	213,956
	10	103,197	128,511	165,017
54.4	5	84,024	104,812	135,016
	1	52,081	64,982	83,979
	0.5	42,459	52,897	68,330
	0.1	26,700	33,031	42,441

Table C-10. Predicted Dynamic Modulus Test Results, Design No. 05702

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,181,951	1,940,894	2,063,056
	10	1,983,612	1,742,635	1,861,129
	5	1,833,566	1,594,811	1,709,734
	1	1,491,891	1,265,661	1,369,745
	0.5	1,350,408	1,132,629	1,231,061
	0.1	1,043,060	850,970	934,574
21.1	25	913,699	878,410	1,003,322
	10	766,958	734,949	847,245
	5	666,003	636,643	739,076
	1	466,364	443,335	522,934
	0.5	395,265	374,896	445,112
	0.1	262,405	247,699	298,203
37.8	25	316,561	347,907	427,652
	10	249,089	274,910	341,198
	5	206,413	228,463	285,455
	1	131,017	145,788	184,529
	0.5	107,070	119,336	151,692
	0.1	66,468	74,235	94,960
54.4	25	113,503	140,834	182,012
	10	86,670	107,936	140,303
	5	70,537	87,993	114,747
	1	43,677	54,499	71,300
	0.5	35,592	44,345	57,988
	0.1	22,360	27,663	35,981

Table C-11. Predicted Dynamic Modulus Test Results, Design No. 04071

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,307,825	2,057,857	2,172,518
	10	2,097,006	1,846,617	1,958,830
	5	1,937,591	1,689,195	1,798,695
	1	1,574,845	1,338,957	1,439,357
	0.5	1,424,758	1,197,531	1,292,909
	0.1	1,099,013	898,397	980,123
21.1	25	962,052	927,520	1,052,610
	10	806,811	775,320	888,086
	5	700,097	671,113	774,154
	1	489,332	466,462	546,770
	0.5	414,375	394,109	465,011
	0.1	274,508	259,834	310,888
37.8	25	331,484	365,595	446,678
	10	260,507	288,534	355,960
	5	215,664	239,555	297,530
	1	136,567	152,510	191,900
	0.5	111,488	124,708	157,591
	0.1	69,040	77,386	98,412
54.4	25	118,223	147,301	189,269
	10	90,148	112,736	145,699
	5	73,288	91,809	119,036
	1	45,268	56,722	73,783
	0.5	36,850	46,103	59,943
	0.1	23,094	28,690	37,102

Table C-12. Predicted Dynamic Modulus Test Results, Design No. 05002

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,587,631	2,327,906	2,410,589
	10	2,352,720	2,090,419	2,174,950
	5	2,174,985	1,913,323	1,998,257
	1	1,770,184	1,518,911	1,601,374
	0.5	1,602,525	1,359,466	1,439,447
	0.1	1,238,229	1,021,793	1,093,180
21.1	25	1,084,858	1,054,697	1,173,483
	10	910,845	882,657	991,163
	5	791,101	764,743	864,780
	1	554,230	532,801	612,163
	0.5	469,841	450,653	521,175
	0.1	312,088	297,920	349,352
37.8	25	376,402	418,252	500,759
	10	296,271	330,601	399,648
	5	245,574	274,814	334,437
	1	155,970	175,472	216,321
	0.5	127,497	143,673	177,873
	0.1	79,200	89,432	111,420
54.4	25	135,147	169,518	213,374
	10	103,235	129,966	164,536
	5	84,041	105,982	134,602
	1	52,073	65,683	83,692
	0.5	42,446	53,460	68,085
	0.1	26,682	33,370	42,274

Table C-13. Predicted Dynamic Modulus Test Results, Design No. 05024

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	1,814,379	1,607,444	1,692,118
	10	1,651,886	1,445,653	1,528,932
	5	1,528,791	1,324,837	1,406,404
	1	1,247,883	1,055,171	1,130,604
	0.5	1,131,282	945,887	1,017,812
	0.1	877,304	713,816	775,983
21.1	25	770,076	736,472	832,151
	10	648,153	617,894	704,541
	5	564,066	536,435	615,892
	1	397,166	375,651	438,113
	0.5	337,479	318,485	373,844
	0.1	225,467	211,781	252,013
37.8	25	271,211	295,899	359,402
	10	214,198	234,667	287,748
	5	178,016	195,579	241,403
	1	113,790	125,673	157,109
	0.5	93,283	103,190	129,543
	0.1	58,338	64,664	81,684
54.4	25	98,798	121,468	154,999
	10	75,757	93,477	119,961
	5	61,851	76,447	98,416
	1	38,584	47,700	61,605
	0.5	31,542	38,937	50,263
	0.1	19,958	24,467	31,419

Table C-14. Predicted Dynamic Modulus Test Results, Design No. 05090

Temp (C)	Frequency (Hz)	Average E* (psi)		
		PG 64-22	PG 70-28	PG 76-28
4.4	25	2,273,637	2,027,625	2,115,188
	10	2,069,360	1,822,892	1,910,550
	5	1,914,657	1,670,059	1,756,946
	1	1,561,782	1,329,108	1,411,367
	0.5	1,415,384	1,191,015	1,270,116
	0.1	1,096,685	897,952	967,458
21.1	25	962,222	926,550	1,037,730
	10	809,409	776,908	878,103
	5	704,072	674,166	767,268
	1	495,162	471,535	545,169
	0.5	420,517	399,556	464,947
	0.1	280,564	265,325	313,013
37.8	25	337,696	371,128	446,927
	10	266,494	294,100	357,556
	5	221,341	244,962	299,791
	1	141,271	157,172	194,827
	0.5	115,734	128,967	160,539
	0.1	72,264	80,691	101,072
54.4	25	122,600	151,895	192,201
	10	93,924	116,790	148,626
	5	76,632	95,448	121,852
	1	47,729	59,462	76,154
	0.5	38,991	48,504	62,092
	0.1	24,634	30,432	38,752