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AN INVESTIGATION OF DYNAMIC MODULUS AND FLOW NUMBER PROPERTIES OF ASPHALT MIXTURES IN WASHINGTON STATE

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ABSTRACT

Pavement design is now moving toward more mechanistic based design methodologies for the purpose of producing long lasting and higher performance pavements in a cost-effective manner. The recent Mechanistic-Empirical pavement design guide (MEPDG) is a product under such direction and is making progresses in improving current design methods. Dynamic Modulus is proposed by the MEPDG as an important material characterization property and key input parameter which correlates material properties to field fatigue cracking and rutting performance. Washington State has strong background and has put many efforts in moving toward the M-E based design procedures. In addition, Washington State has developed comprehensive PMS database which makes it possible to use local pavement performance data to calibrate design models and optimize pavement design. However, there is still one important thing missing in this implementation step, which is a comprehensive local material database. Given the limited resources (equipment and time), such database will help the designer to select material properties that are more applicable to local materials and thus develop more reasonable level III design. Therefore, the objectives of this study are to conduct dynamic modulus (E*) tests on asphalt mixtures most popularly used in the State of Washington under different climate conditions, generate material database for the implementation of MEPDG design procedure in Washington State, and provide an evaluation method for recommending potential performing mixes by correlating E* test results to field rutting

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<tr><td colspan="4">performance using WSPMS data. Both lab prepared mixtures based on designs typically used in Western, Central, and Eastern Washington region, and field cored samples from representative field sites will be measured for dynamic modulus over a wide time-temperature domain. Results will be correlated to pavement performance, so that desirable material properties and E* values can be recommended for Washington material and climate conditions.</td></tr>
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EXECUTIVE SUMMARY

Dynamic Modulus (|E*|) is one of the key elements of a mechanistic-empirical based flexible pavement design procedure. It is used to characterize the material properties of asphalt mixtures and determine the stress strain responses of a pavement at different loading conditions, and is a direct input parameter in several pavement performance models to estimate the field fatigue cracking and rutting performance. As part of the asphalt mixture performance tests, the flow number has been found to be able to correlate well with the field rutting depth by a number of projects. Therefore, to provide a better understanding of the local materials and prepare the Washington State Department of Transportation (WSDOT) moving toward a more mechanistic based pavement design system, this study aims to test asphalt mixtures typically used in Washington State, and establish a material catalog for dynamic modulus and flow numbers.

In this study, seven plant produced mixtures from different regions of Washington State were sampled and tested. These mixes represented the typical asphalt binder, gradation, and mix designs of the state. One warm mix project was also included in the analysis. Based on the experimental results, mix properties include air voids, binder properties, and aggregate gradations were found to have important impact on the dynamic modulus and flow number. The measured dynamic modulus data were compared to the prediction results using the traditional Witczak E* model, the new Witczak E* model, and the Hirsch model. The Hirsch model was found to be most promising and was further modified based on the testing results. The modified Hirsch model provided significantly improved prediction quality, which can be used as both a design tool and a screening tool to estimate the dynamic modulus of a mix at the early stage of the mix design. A flow number prediction model was also proposed in this study which was mostly applicable for none polymer modified mixtures. Future studies were recommended to improve the flow number prediction models based on a larger database.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Pavement design is currently in the trend of moving toward more mechanistic based design methodologies for the purpose of producing more durable and higher performance pavements in a cost-effective manner. The recent Mechanistic-Empirical pavement design guide (MEPDG) is a product under such direction and is making progresses in improving current design methods. Dynamic Modulus (|E*|) is proposed by the MEPDG as an important asphalt material characterization property and a key input parameter which correlates material properties to field fatigue cracking and rutting performance.

The AASHTO M-E design guide have three hierarchical levels which either requires the direct laboratory testing for dynamic modulus or using the Witczak model to predict dynamic modulus values which was based on conventional multivariate regression analysis. The NCHRP Projects 9-19 (Witczak 2007), Superpave Support and Performance Models Management, and project 9-29 (Bonaquist 2008), Simple Performance Tester (SPT) for Superpave Mix Design, have stated the detailed experimental procedures to conduct simple performance tests (recently renamed as asphalt mixture performance tests, AMPT) and documented the possibility of using the simple performance tests for evaluating the resistance of asphalt mixtures to permanent deformation and fatigue cracking. In the case of using Witczak model to estimate |E*| values, many researchers evaluated the predictive capability of the Witczak model through the comparison of predicted and measured dynamic modulus using various mixtures across the United States (Ceylan 2009). The Witczak model was also refined and revised to give better prediction results (Bari and Witczak 2006). A good understanding of the dynamic modulus properties of the local mixtures will provide mechanistic based knowledge for improving pavement serviceability and its expected long-term field performance.

As part of the AMPT tests, the flow number test was found to be able to correlate with field rut depth as verified by field projects at MNRoad, Westrack, and the FHWA Pavement Testing Facility in the NCHRP project 9-19 (Witczak 2007). It has been recommended by the NCHRP project 9-33 (NCHRP report 673) for evaluating the rutting potential of the mix. Testing the flow number properties of the local mix as part of the local material characterization plan will be very beneficial for evaluating the mix, developing material-performance relationship, and improving the overall quality of the pavement system.

Washington State has strong background and has put many efforts in moving toward the M-E based pavement design procedures. Washington State also developed their own pavement management system (PMS) and a comprehensive pavement conditioning/performance database which makes it possible to use local pavement performance data to calibrate design models and optimize pavement design. However, the material characterization with respect to typical state asphalt mixture has not been completed yet. Given the limitation of the resources (equipment and experimental time), it may not be practical to require level 3 testing for all M-E based pavement designs. A material database that consists of the modulus properties of the typical asphalt mixture designs used in the state is more efficient. Based on such database, a locally calibrated dynamic modulus prediction model can be developed which can provide better accuracy for level 1 and 2 designs for Washington mix. In general, a dynamic modulus database and a locally calibrated dynamic modulus prediction model may help the designer in a number ways:

- Help the designer thoroughly understand local materials and select cost-effective material combinations for different design purpose;
- Assist with the mechanical stress strain analysis and performance prediction through an accurate modulus prediction based on locally calibrated performance prediction models;
- Generate input material properties that are more representative to local materials;
- Develop dynamic modulus predictive model with locally calibrated model coefficients;

- Develop more reasonable level 2 and 3designs when MEPDG are used for pavement design.

Tashman and Elangovan (2007) conducted a preliminary study for Washington State which tested 7 mixtures for their dynamic modulus. This study initiated Washington's process of local material property evaluation. However, the results were not complete to be used as a material catalog. The limited material sources and design variables made it difficult to actually use these testing results for further statewide pavement design and pavement structural analysis including the MEPDG design. In addition, only the impact of #200 sieve (with ± 2% variation) on dynamic modulus was evaluated which cannot give a thorough understanding of the correlations between material properties and dynamic modulus, as well as the relations between dynamic modulus and pavement performance.

In addition, material sources and observed performance are changing, which should be taken into account in the development of the material database. With the new trend of including more RAP mixtures and warm mix asphalt (WMA) mixtures into the pavement construction, mainly for the environment and energy saving concern, it is necessary the dynamic modulus properties of asphalt mixtures with RAP be included in the material database. These considerations therefore initiated this study.

1.2 OBJECTIVES AND SCOPE

The primary objective of this study is to evaluate the dynamic modulus and flow number properties of asphalt mixtures sampled at the field projects of Washington State constructed in 2011, and prepare locally calibrated material data for the implementation of MEPDG in Washington State.

In this study, seven plant produced mixtures from different regions of Washington State were sampled and tested. These mixes represented the typical asphalt binder, gradation, and mix designs of the state. One warm mix project was also included in the analysis. The measured dynamic modulus data were compared with the prediction results using the traditional Witczak E* model, the new Witczak E* model, and the Hirsch model. A modified Hirsch model was proposed which was found to be more suitable for predicting the dynamic modulus of the asphalt mixtures used in Washington State.

CHAPTER 2 LITERATURE REVIEW

The Superpave mix design method has been adopted by many agencies in the United States. However, unlike the traditional Marshall and Hveem mix design method, the Superpave method does not have a performance evaluation to complement the volumetric mixture design. Some researchers and designers (Cominsky et al. 1998) have raised the question that whether the volumetric design method alone can provide a sufficient design over a wide range of loading conditions. To address this concern, a set of Asphalt Mixtures Performance Tests (AMPT) have been proposed and evaluated by the National Cooperative Highway Research Program (NCHRP) for estimating the mechanical performance of the mixtures (Witczak et al. 2002). These tests include the dynamic modulus test and flow number test.

2.1 DYNAMIC MODULUS

Although at this moment, most states in the United States are still following the traditional empirical based pavement design procedures (AASHTO 1993) for flexible pavement design, many states have realized the advantages of the new Mechanistic-Empirical Pavement Design Guide, and are initiating the preparation efforts for the future implementation (Hall 2010 and Flintsch et al. 2008). In the *2002 Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (MEPDG), there are significant changes in relating material properties, traffic information, and the climatic impact to pavement distress models and long term performance. A thorough characterization of asphalt materials and obtaining appropriate input of fundamental material properties can thus be very critical to the design of new and rehabilitated flexible pavements using the MEPDG.

The MEPDG design guide includes three analysis hierarchy levels. Level 1 is for the highest priority pavements with high traffic volume, or where safety and economic considerations for an early failure are a concern. It requires the most accurate material properties input including indirect tensile strength, creep compliance, and dynamic modulus.

These properties are usually measured directly from the laboratory testing. Level 3 designs provide the lowest level of accuracy and might be used for designs where there are minimal consequences of early failure. Usually in this level, the pavement designers input the default property values for typical binders and mixes. In between is the level 2 design which provides an intermediate level of accuracy and could be used when resources or testing equipments are not available.

In MEPDG, for asphalt pavement, dynamic modulus is one of the most important material properties. Dynamic modulus is an input to pavement response model to determine the stress/strain responses which are needed by the performance models to predict pavement performance. Dynamic modulus itself is also a direct input in the performance models to predict fatigue cracking (both top-down and bottom-up) and rutting. Therefore, accurate characterization of dynamic modulus of HMA is of paramount importance to pavement design and analysis, based on the MEPDG.

The Level 1 input for dynamic modulus need direct laboratory measurement, in accordance with *AASHTO TP 62 Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)*. Cyclic loads are applied to a cylindrical specimen across a range of frequencies and temperatures. A master curve of dynamic modulus is then developed by the program based on the time-temperature superposition principle. This master curve of dynamic modulus is then used in the MEPDG for pavement performance prediction to account for the effects of temperature and traffic speed variations. For Level 2 design input, dynamic modulus test is not needed. Instead, the dynamic modulus is predicted by the Witczak model (Witczak and Fonesca 1996), based on the aggregate gradation, loading frequency, volumetrics of HMA, and viscosity of asphalt binder, as shown in Equation 1. The viscosity of asphalt binder needs to be measured directly. For level 3, the Witczak model is also used. However, the viscosity of asphalt binder is estimated, not measured.

In addition to the Witczak's 1996 model as used in the 2002 MEPDG design guide, there are a number of other dynamic modulus E^* prediction equations available, such as the new Witczak's model (Bari and Witczak 2006) and the Hirsch model (Christensen et al. 2003).

2.1.1 Witczak traditional model (Witczak and Fonseca 1996; Witczak, et al, 2002)

The traditional Witczak E* predictive model was developed based on a database of 2750 dynamic modulus measurements from 205 different asphalt mixtures tested over the last 30 years in the laboratories of the Asphalt Institute, the University of Maryland, and the Federal Highway Administration. This model can predict the dynamic modulus of mixtures using both modified and conventional asphalt binders. This model is considered as the most popularly used E* prediction model which is also adopted by the MEPDG for correlating mixture material properties with the dynamic modulus. The equation is shown in Equation 1.

$$\log|E^*| = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \quad (1)$$

Where,

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

η= bitumen viscosity, 10^6 Poise

f = loading frequency, Hz

V_a = air void content, %

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

ρ_{34} = cumulative % retained on the 19-mm (3/4) sieve

ρ_{38} = cumulative % retained on the 9.5-mm (3/8) sieve

ρ_4 = cumulative % retained on the 4.76-mm (No. 4) sieve

ρ_{200} = % passing the 0.075-mm (No. 200) sieve

As shown in Equation 1, the viscosity of the asphalt binder (η) at the temperature of interest is a critical material input. For unaged asphalt binder, the ASTM viscosity temperature relationship (equation 2) can be used.

$$\log\log\eta = A + VTS\log T_R \tag{2}$$

Where:

η = bitumen viscosity, cP.

TR = temperature, Rankine

A = regression intercept

VTS = regression slope of viscosity temperature susceptibility.

At hierarchical Level 1 and 2 of the MEPDG design, the A and VTS regression parameters (un-aged) can be determined using dynamic shear rheometer test. Alternatively, at Level 3 the A and VTS can be estimated based on the binder PG grade according to the default value provided by MEPDG design program.

2.1.2 New Witczak model (Bari and Witczak 2006)

Bari and Witczak in 2006 developed a new Witczak model based on a more comprehensive study and included a larger database with 7400 data points from 346 HMA mixtures. The new model was selected from a number of candidate models based on the tests on rationality, accuracy, precision, bias, trend, sensitivity, and overall performance. The binder's dynamic shear modulus (*G**) and phase angle (δ) was used to replace the binder viscosity (η) and loading frequency (f). The new Witczak model is shown in Equation 3.

$$\log(|E^*|) = -0.349 + 0.754\left(|G_b^*|^{-0.0052}\right)\cdot\begin{pmatrix} 6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^2 - 0.011\rho_4 - 0.0001\rho_4^2 \\ + 0.006\rho_{38} - 0.00014\rho_{38}^2 - 0.08V_a - 1.06\left(\dfrac{V_{beff}}{V_a + V_{beff}}\right) \end{pmatrix} + \frac{2.558 + 0.032V_a + 0.713\left(\dfrac{V_{beff}}{V_a + V_{beff}}\right) + 0.0124\rho_{38} + 0.0001\rho_{38}^2 - 0.0098\rho_{34}}{1 + e^{(-0.7814 - 0.5785\log|G_b^*| + 0.8834\log(\delta_b))}} \tag{3}$$

Where,

$|E^*|$ = dynamic modulus, psi;

ρ_{200} = % (by weight of total aggregate) passing the 0.075-mm (No. 200) sieve;

$\rho 4$ = cumulative % (by weight) retained on the 4.76-mm (No. 4) sieve;

$\rho 34$ = cumulative % (by weight) retained on the 19-mm (3/4-in.) sieve;

$\rho 38$ = cumulative % (by weight) retained on the 9.5-mm (3/8-in.) sieve;

Va = air void content (by volume of the mix), %;

Vbeff = effective binder content (by volume of the mix), %;

|Gb*| = dynamic shear modulus of binder, psi;

δb = phase angle of binder associated with |Gb*|, degree.

2.1.3 Hirsch Model (Christensen et al. 2003)

Hirsch model is a rational, though semi-empirical method for predicting asphalt concrete modulus. It is based on the theory of composite material which combines series and parallel elements of the phases. Comparing to the Witczak models, Hirsch model is considered relatively simpler which relates the dynamic modulus of the asphalt concrete (|E*|) with binder modulus (G*), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA), as shown in Equation 4 and 5.

$$|E^*| = Pc\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\cdot VMA}{10{,}000}\right)\right]+(1-Pc)\left[\frac{1-\frac{VMA}{100}}{4{,}200{,}000}+\frac{VMA}{VFA\cdot 3|G^*|_{binder}}\right]^{-1} \quad (4)$$

Where:

|E*| = dynamic modulus, psi

$|G^*|_{binder}$ = binder dynamic modulus, psi

VMA= voids in the mineral aggregate, %

VFA = voids filled with asphalt, %

Pc = aggregate contact factor, where

$$Pc = \frac{\left(20+\frac{VFA\cdot 3|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\frac{VFA\cdot 3|G^*|_{binder}}{VMA}\right)^{0.58}} \quad (5)$$

2.1.4 **Prediction Model of Idaho mixtures (Abdo et al. 2009)**

Abdo et al. (2009) proposed s model to predict E* from the properties of the asphalt mixture constituents. The model parameters were determined by dimensional analysis and s new mix design mechanistic parameter, the Gyratory Stability (GS), was included in the model. The model was shown in Equation (6)

$$E^* = 1.08\left(\frac{G^* \cdot GS \cdot \%G_{mm}}{P_b(1-P_b)}\right)^{0.558} \tag{6}$$

where,

E*: Dynamic Modulus for Asphalt Mix, MPa,

G*: Dynamic Shear Modulus for RTFO Aged Binder, MPa,

Pb: Percent Binder Content,

GS: Gyratory Stability, kNm,

Gmb: Bulk Specific gravity of Mix, Gmb = Gmm (1-AV%),

Gmm: Maximum Specific gravity of Mix, and

AV%: Air Voids.

2.1.5 **Prediction Model of Florida mixtures (Yang et al. 2011)**

Yang et al (2011) developed a predicting model of dynamic modulus for characterizing Florida asphalt mixtures based on 20 selected Florida Superpave mixtures. The model including variables related to aggregate gradation, mixture volumetrics, and percent weight of asphalt content, loading frequencies, and temperatures. The model was shown in Equation (7)

$$\log\left|E^*\right| = 2.312 + 0.01\rho_{200} + 0.01\rho_8 - 0.013\rho_4 - 0.002\rho_{3/8} + 0.024P_b - 0.043VFA + \frac{\left[-1.34 - 0.019\rho_8 + 0.022\rho_4 + 0.004\rho_{3/8} - 0.055P_b + 0.052VFA\right]}{1 + e^{(-8.267 - 0.722\log f + 5.397\log T)}} \tag{7}$$

where,

$|E^*|$ = dynamic modulus, in 10_5 psi

T= Test temperature, in °C

f= load frequency, in Hz

VFA= Voids filled with asphalt, % by volume

P_b= Percent weight of asphalt, % by weight

$\rho_{8/3}$□= cumulative percent retained on 3/8 in (9.5mm) sieve, % by weight

ρ_4= cumulative percent retained on No. 4 (4.75mm) sieve, % by weight

ρ_8= cumulative percent retained on No. 8 (2.36mm) sieve, % by weight

ρ_{200}= percent passing on No. 200 (0.075mm) sieve, % by weight

2.1.6 Comparison of the predictive models

Bari and Witczak (2006) compared the three prediction methods, original Witczak model (1996), new Witczak model (2006), and Hirsch model (2003). Table 1 listed the regression statistics among the models, and Figure 1 showed the comparisons between the predicted and the measured E* values.

Table 1. Comparison of dynamic modulus prediction models (Error! Bookmark not defined.)

Parameters	E* Predictive Models		
	Witczak 1999	Hirsch 2003	New Model 2005
Total Mixes	346	346	346
Mixes with Modified Binders	17	17	17
Data Points	7400	7400	7400
Goodness of Fit in Normal (Arithmetic) Scale			
Se/Sy	0.60	0.88	0.45
R^2	0.65	0.23	0.80
Goodness of Fit in Logarithmic Scale			
Se/Sy	0.35	0.62	0.32
R^2	0.88	0.61	0.90

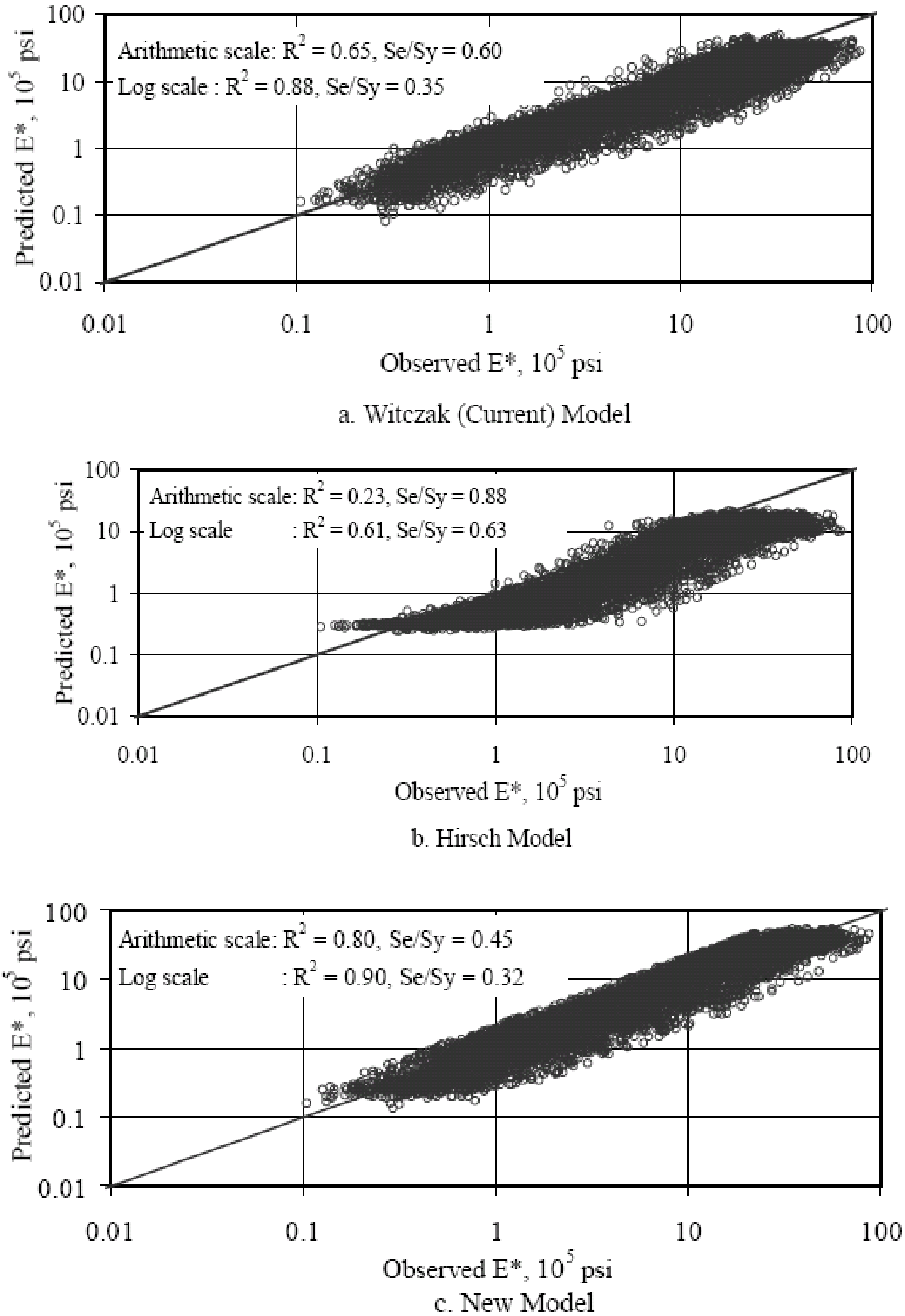
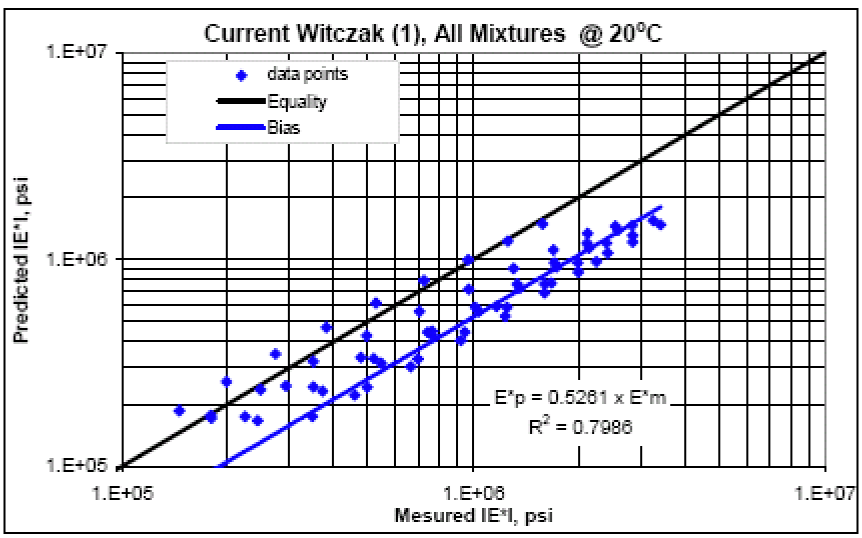


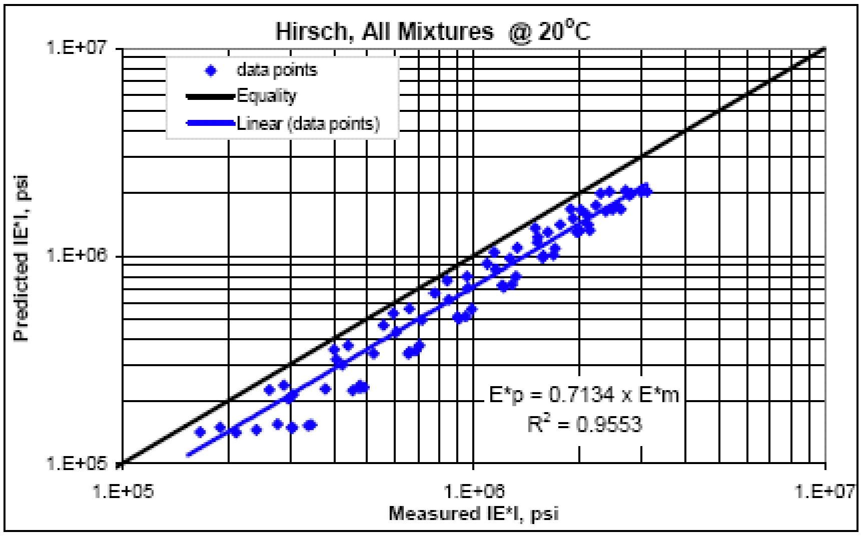
Figure 1 Predicted versus measured E* for three models (Error! Bookmark not defined.)

Based on the statistics analysis data, Bari and Witczak concluded that the new Witczak model showed the best predictive strength in comparison with the previous models. It must be noted, however, that the comparison against the Hirsch model was not completely "fair", because an important part of the |Gb*| data included in the "new database" are only "estimates" and not direct measurements from the lab tests. A more reliable comparison should be done with "measured" data (Garcia et al. 2007).

Garcia and Thompson (2007) also compared the three models based on their E* data for Illinois mixtures (Figure 2). They found that the most promising model was the Hirsch model which showed the highest precision and the lowest bias. However in general, the model "under predicted" the E*. In a study conducted by Abdo et al. (2009), both the traditional and the new Witczak models were found to significantly over-estimated the dynamic modulus, as shown in Figure 3.

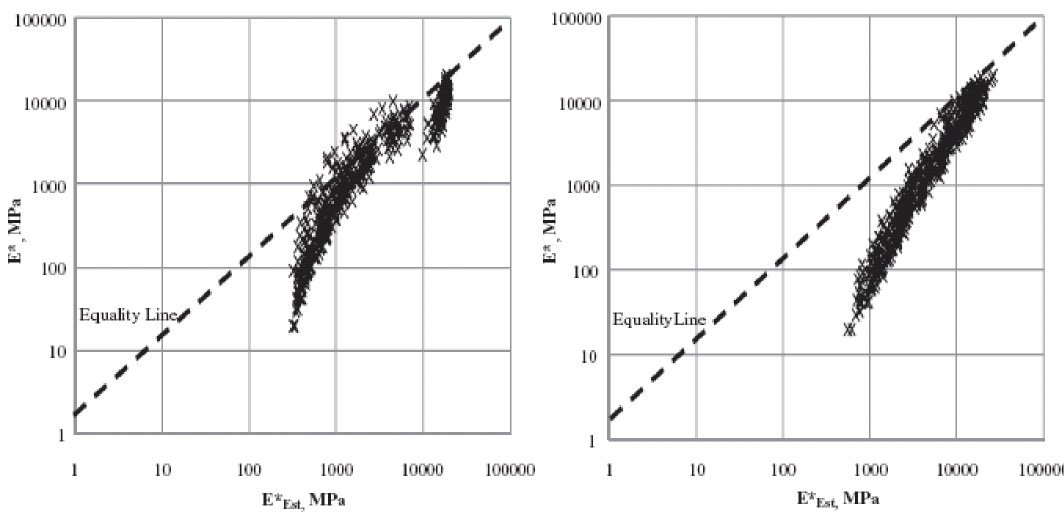


(a) Results for All Mixtures, Applying Current Witczak Model.



(b) Results for All Mixtures, Applying Hirsch Model.

Figure 2 Predicted Versus Observed E*(Garcia and Thompson, 2007)



(a) Traditional Witczak model. (b) New Witczak Model

Figure 3. Predicted versus measured E* (Abdo et al., 2009)

The simplicity of the prediction models are another important criterion for evaluating the models as it will directly affect the easiness of obtaining input information and the required time/cost for achieving a reasonable prediction. Both the traditional and new Witczak predictive equations require eight input parameters, which can be obtained through experimental testing, based on mix design information, or based on suggested values. The

Hirsch model needs only three input parameters, which are available from the routine Superpave mix design process. Specifically, the Witczak models consider the effect of aggregates by four sieve sizes while the Hirsch model accounts for the overall gradation impact through a volumetric term, voids in mineral aggregate, VMA.

2.2 FLOW NUMBER

2.2.1 Introduction of flow number

The repeated load flow number (Fn) test is a dynamic creep test where a haversine type of loading is applied with rest periods between loadings. As shown in Figure 4, the typical results between the measured permanent strain and load cycle can be divided into three major zones. In the primary phase, the strain rate (slope of the permanent strain curve) decreases; in the secondary phase, the permanent strain rate is constant; and in the tertiary phase the permanent strain rate dramatically increases. At low stress levels, the material may mainly exhibit primary and/or secondary permanent strain. In this case, the permanent strain rate may approach a value equal to zero as the total strain reaches a certain value. This also suggests that at this very low stress level the tertiary flow region may never appear within a reasonable amount of time. At higher stress levels, the occurrence of the constant secondary permanent strain rate phase will depend on the stress level applied.

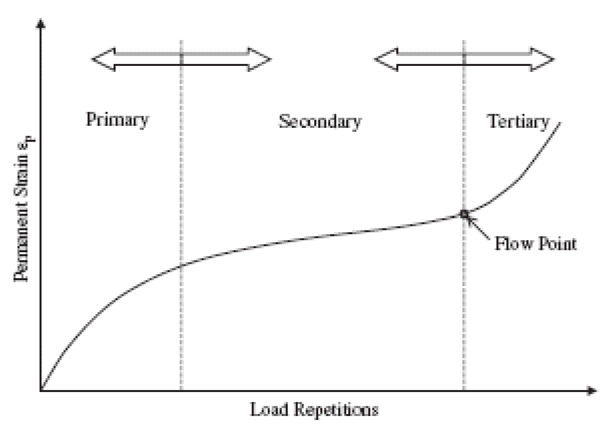


Figure 4. Typical repeated load permanent deformation behavior of pavement materials.

2.2.2 **Flow number testing methods**

The flow number test protocol was developed in the NCHRP 9-19 project (Witczak 2007) although the testing procedures and set-ups were not fully standardized. NCHRP Project 9-19 recommended testing the flow numbers at the effective pavement temperature using either unconfined tests with axial stress between 10 and 30 psi or confined tests with confining pressure between 5 and 30 psi and deviatoric stress between 70 and 140 psi. Using the effective pavement temperature and the range of stress levels recommended in the NCHRP 9-19 Project, many mixtures did not exhibit flow within 10,000 cycles (approximately 2.8 hours testing time), the recommended maximum number of load cycles. Therefore, many researchers as listed in

Table **2** have modified testing conditions such as either increasing the temperature, deviatoric stress or both to ensure that flow would occur in the mixtures within 10,000 load cycles.

Table **2** provided a summary of the testing conditions and evaluation criteria used for flow number test.

Table 2. Approaches for Rutting Resistance from Flow Number Test Data

Method	Air Voids	Temperature	Confining Stress, psi	Deviatoric Stress, psi	Pulse	Criteria
NCHRP 9-33 (Christensen, et al. 2009)**Error! Bookmark not defined.**	7 %	50 % reliability high pavement temperature from LTPPBind at depth of 20 mm for surface courses and top of layer for other layers	0	87	0.1 sec with 0.9 sec dwell	Flow number > critical value as a function of traffic
NCAT(Willis, J.R., et al, 2009)	7 %	50 % reliability PG grade – 6 °C	10	70	0.1 sec with 0.9 sec dwell	Flow number > critical value as a function of traffic and allowable rut depth
NCHRP 9-30A(Quintus, H. V.,2010)	Avg.; In Place (Specs.)	Option A: 3 Temps. (50% reliability PG minus 5°C, 20°C, mid-range). Option B: Effective temperature based on rutting (MEPDG).	10	70	0.1 sec with 0.9 sec dwell	Slope and intercept of permanent deformation curve<critical values as a function of traffic (rut depth<threshold value).
UNR(Hajj, E. Y., et al, 2010))	7 %	Effective temperature for rutting	Variable*	Variable*	Variable*	Slope and intercept of permanent deformation curve<critical values as a function of traffic
NCHRP 9-26A	7%	3 temperatures: Binder high PG, PG minus 6°C, PG minus 12°C	0	29	0.1 sec with 0.9 sec dwell	Rutting calculated from Minimum Strain Rate at 3 temperatures, aging index, and pavement temperature frequencies < critical rutting

* using developed predictive equations.

2.2.3 Flow number and rutting

Ideally, the large increase in permanent strain generally occurs at a constant volume within the tertiary zone. The flow number is therefore defined as the postulated cycle when shear deformation, under constant volume, starts, indicating the start of tertiary flow in the mixture. Practically, the flow number can be determined as the load cycle at which the rate of the change of permanent strain reaches the minimum value.

Permanent deformation (rutting) of the HMA pavement is caused by a combination effect of densification and shear deformation under repetitive loading. Rutting can be categorized into three types: one-dimensional densification or vertical compression, lateral flow or plastic movement, and mechanical deformation. Factors affecting rutting vary since rutting is a complex phenomenon between aggregate, asphalt, and aggregate-asphalt interface, and the properties of those component are changing with the change of time, loading and temperature (Witczak, M.W., 2007).

Several testing methods have been proposed by Witczak et al. (**Error! Bookmark not defined.**007) for evaluating the rutting resistance including the dynamic modulus (E*) test, flow number (Fn) test, and flow time (Ft) test. Particularly, the flow number test was found to be able to correlate with field rut depth as verified by field projects at MNRoad (Figure 5), Westrack (Figure 6), and the FHWA Pavement Testing Facility (Figure 7) in the NCHRP project 9-19 (Witczak 2007). During the NCHRP project 9-19, the relationship between the reduced flow number and field rut depth at a specific traffic level were studied. Temperature-reduced flow numbers were calculated with the following equation 8:

$$\log(F_{tr}) = \frac{\ln\left(\dfrac{\alpha}{\log(\sigma)-\delta} - 1\right) - \beta}{\gamma} \tag{8}$$

σ = applied stress,

tr = Ft or Fn at the reference temperature,

δ = minimum stress that will cause damage,

δ + α = maximum stress that will cause instantaneous damage, and β, γ = parameters describing the shape of the sigmoidal function.

α will be a linear function of δ.

The parameters in the equation were determined from a global temperature shifted master curve analysis.

Christensen (2008) proposed a resistivity/rutting equation which gives allowable traffic as a function of mixture composition, compaction and air voids based on data regression. Equation 9 is expressed as below:

$$TR = 9.85 \times 10^{-5} \left(\mathrm{P} N_{eq} K_s\right)^{1.373} V_d^{1.5185} V_{IP}^{-1.4727} M \tag{9}$$

where:

TR = allowable traffic in million ESALs to an average rut depth of 7.2 mm (50 % confidence level)

= allowable traffic in million ESALs to a maximum rut depth of 12 mm (95 % confidence level)

P = resistivity, s/nm

$= \dfrac{\left(|G^*|/\sin\delta\right) S_a^2 G_a^2}{49 VMA^3}$

$|G^*|/\sin\delta$ = Estimated *aged* PG grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPPBind, Version 3.1 (units of Pa/s); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short term projects of 1 to 2 years.

S_a = specific surface of aggregate in mixture, m^2/kg

≅ the sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0

≅ 2.05 + (0.623 × percent passing the 75 micron sieve)

G_a	=	the bulk specific gravity of the aggregate blend
VMA	=	design voids in the mineral aggregate for the mixture, volume
N_{et}	=	design gyrations
K_s	=	speed correction
	=	$(v/70)^{0.8}$, where v is the average traffic speed in km/hr
V_d	=	design air void content, volume %
V_{IP}	=	air void content, volume %, in-place
M	=	7.13 for mixtures containing typical polymer-modified binders, 1.00 otherwise

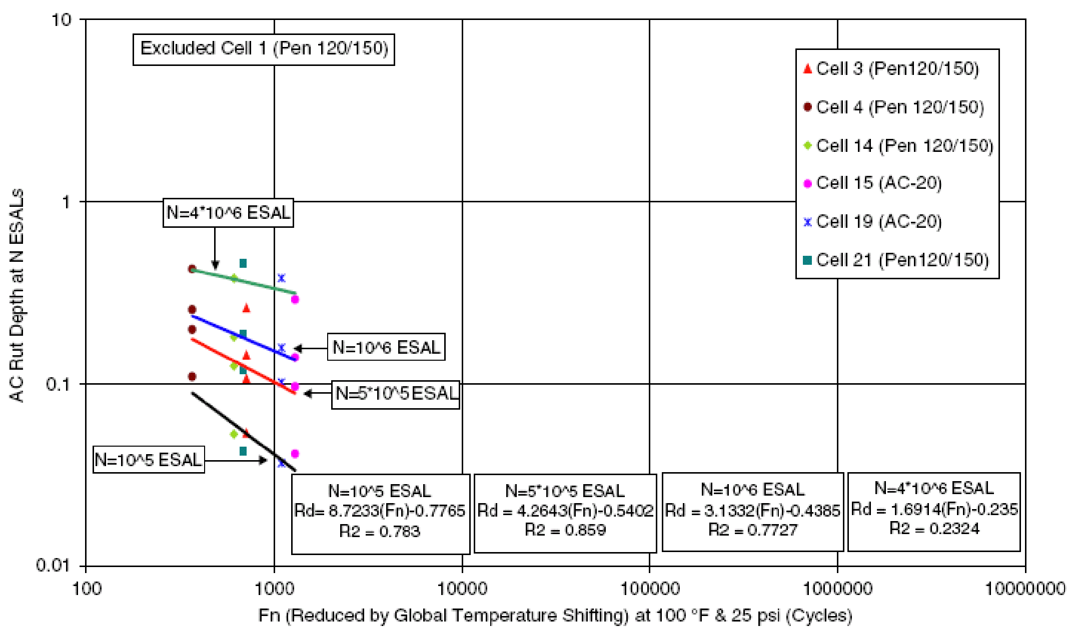


Figure 5. Flow number (reduced by global temperature shifting) at 100° F and 150 psi (1034 kPa) V.S. rut depth at N ESALs for MnRoad plant mixes (unconfined).

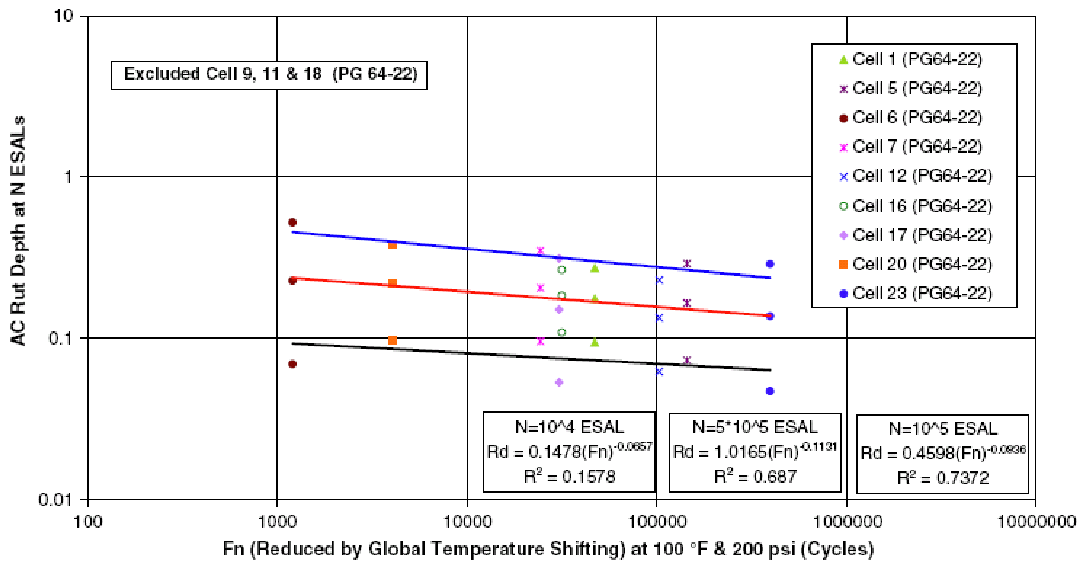


Figure 6 Flow number versus rut depth at Westrack

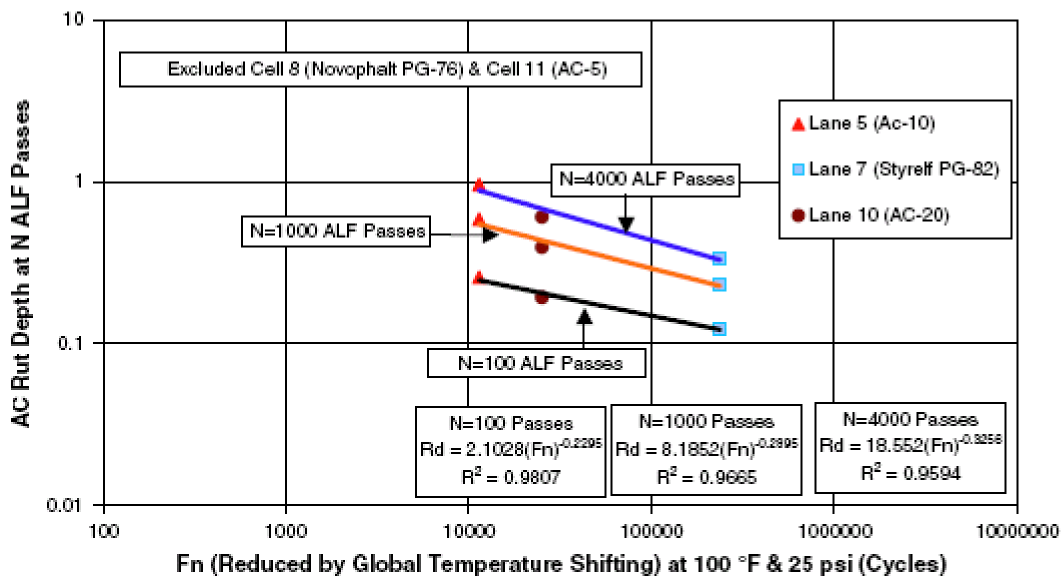


Figure 7. Flow number (reduced by global temperature shifting) at 100F and 25psi (172 kPa) versus rut depth at N ALF passes and 136.4F for ALF field

2.2.4 Flow number prediction models

Over the past few years, there have been significant effects to establish a testing method to evaluate the material properties of asphalt mixture design, such that it would be indicative of field performance. And the majority of interest has centered around dynamic modulus with primary efforts on the predictive models. However, some researchers (Witczak,1996; Bhasin, 2004) felt that additional test should be employed in conjunction with dynamic modulus for rutting performance evaluation of mixtures, and the flow number has been proved to be a effective tool as a rutting performance indicator.

Flow number test provides information concerning the three phases of flow (primary, secondary and tertiary) within an asphalt mix with particular emphasis on tertiary flow. Flow number is obtained from the repeated load permanent deformation test to evaluate the resistance of an asphalt mixture to tertiary flow. In order to predict the flow number of asphalt mixture, some researchers have been proposed different prediction models to provide guidance on the understanding of flow characteristics.

Kaloush (2001) provided the first attempt in predicting the Flow Number of an HMA mixture based on mixtures volumetric properties, binder type, and test temperature. The model used 135 unconfined laboratory FN tests and was presented as follows:

$$FN = (432367000)T^{-2.215}Visc^{0.312}{V_{beff}}^{-2.6604}{V_a}^{-0.1525} \tag{10}$$

Where,

FN = Flow Number

T = Test Temperature, °F

Visc = Binder Viscosity at 70°F, 106 poise

Vbeff = Effective Asphalt Content, % volume

Va = Air Voids, %

Another study by Kvasnak et al (2007) presented a Flow Number predictive equation based on 17 dense graded mixtures from the State of Wisconsin.

$$\log FN = 2.866 + 0.00613Gyr + 3.86Visc - 0.072VMA + 0.0282P_4 - 0.051P_{16} + 0.075P_{200} \tag{11}$$

In this model, the number of gyrations (Gyr) was found to be the most significant factor. The authors pointed out that the model should only be applied within the data ranges used for the dense graded HMA mixes.

Rodezno, M. C. and Kaloush, et al (2010) proposed an equation to predicted flow number as following

$$\log FN = 2.174 + 0.649 Log V_1 + 0.101 P_{200} + 18.465 Log p + 0.0140 R_{04} - 0.084 V_a \\ - 18.901 \log q - 0.872 R_{34} + 0.182 q - 0.193 p - 0.871 \log T \quad (12)$$

In this final model, it can be seen that the variables that are significant in the model are: the viscosity at testing temperature (V_1), the air voids level, the temperature, three variables related with the gradation of the mix: $\%P_{200}$, $\%R_{04}$ and $\%R_{34}$ and the shear and normal stresses (p and q) that contribute to the model in the arithmetic and logarithmic terms. The presence of the p and q variables indicates the importance of the combination of stress levels applied to the samples.

Christensen (2008) applied various statistical techniques to relate the flow number with complex modulus, air void content and applied stress level, and proposed a model based on data regression:

$$N_f = 4.96 \times 10^{-8} \beta_i |E^*|^{2.478} \sigma^{-0.089VTM - 0.187|E^*|} \quad (13)$$

where,

N_f = flow number

β_i = indicator variable, adjusting regression constant for i_{th} projects/sections

$|E^*|$ = complex modulus (lb/in^2) at 10 Hz and same temperature as flow number test

VTM = air voids in flow number test specimen, volume %

σ = deviator stress for flow number stress, lb/in^2

2.3 SUMMARY OF LITERATURE REVIEW

This chapter presented a literature review on topics related to dynamic modulus and flow number testing. Emphasis is given on the various dynamic modulus prediction models that have been developed by the researchers, and a comparison of those dynamic modulus prediction models is stated. It is found that though the traditional Witczak model, New Witczak model and Hirsch are developed based on a large data base, it still needs local calibration for state implementation.

This chapter also demonstrated the strong correlation between the flow number and the field rutting performance of the pavements. Flow number test is thus recommended to be used for evaluating the rutting potential of the asphalt mix. At the end of this chapter, a number of existing flow number prediction models is presented which becomes the basis of the modified flow number in this study.

CHAPTER 3 PROJECTS DESCRIPTION

3.1 PROJECTS GENERAL INFORMATION

The dynamic modulus and flow number testing was conducted based on plant mixed lab compacted gyratory samples. Loose asphalt mixtures were sampled in 2011 from HMA plants directly with the assistance of WSDOT engineers and contractors. The plant mixed asphalt mixture is more representative of the materials used in the field, when compared to the lab mixed asphalt mixtures. To build a catalog of dynamic modulus in the State of Washington and conduct subsequent model verification and calibration, the material procurements have covered a range of typical materials and mix designs for the state, in terms of asphalt binder, aggregate type, gradation, and usage of RAP and warm mix asphalt technologies.

Based on the selection criteria, seven paving projects were identified with the assistance of the WSDOT material's lab. Table 3 listed a summary of the seven projects, and Figure 8 indicated the geographic location of each project. The details of the geographic locations of each project can refer to Appendix A.

Table 3. Asphalt mixture general information

	Contract No.	Project Section	Region
#1	C8046	Ritzville to Tokio - Paving of Outside Lanes Only	Eastern
#2	C8017	Lee Rd to Vic I-90 Paving	Eastern
#3	C8013	Grant County Line to SR 17 - Paving	North central
#4	C8033	SR 124 Intesection Build Interchange	South central
#5	C8016	Joe Leary Slough to Nulle Rd. Vicinity - Paving	Northwest
#6	C7879	SR 510 - Yelm Loop - Phase 1	Northwest
#7	C7465	Grand Mound to Maytown Stage One - Add Lanes	Northwest

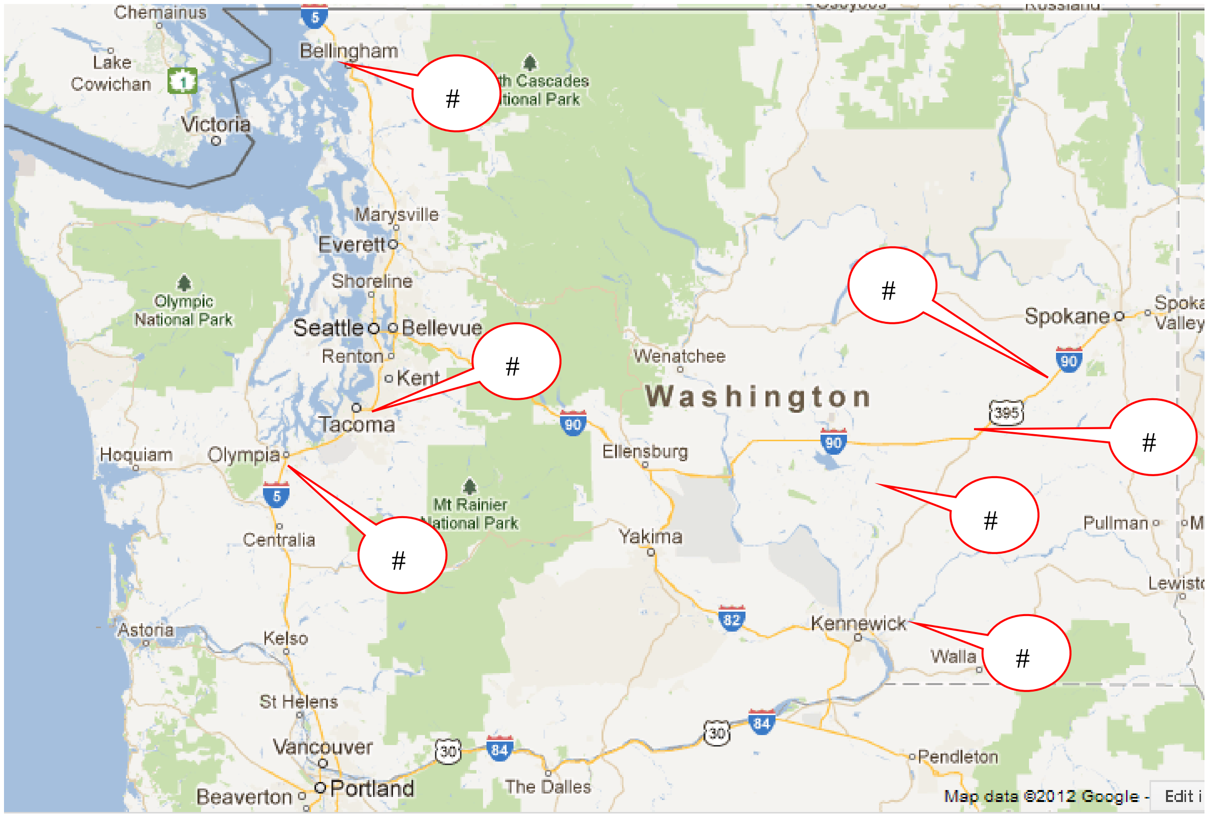


Figure 8. Geographic locations for all projects

3.2 MATERIALS SUMMARY

Loose mixtures were collected from the dump trucks at the asphalt plants and transported to the Washington State University for testing. Once acquired, mixtures were only allowed to be reheated once for specimen compaction to minimize the effect of reheating on the mix.

A copy of the job mix formula (JMF) for each project is obtained. The basic properties of the mixtures are shown in Table 4. A summary of the mix designs of each project is attached in Appendix B. For project #4 (C8033), both the HMA and WMA (foaming technology) were evaluated. The gradations of the mixtures are shown in Table 5 and plotted in Figure 9. As shown, all mixtures have a nominal maximum aggregate size (NMAS) of 12.5 mm. Four asphalt binder types (PG76-28, PG70-28, PG64-28, and PG64-22) are included, which are the typical asphalt binders based on local climatic and traffic conditions. The design asphalt content varies from 5.2% to 5.7%. Most mixtures included approximately 20% recycled asphalt pavement (RAP) material.

Table 4. Basic properties of asphalt mixture

	Contract No.	Asphalt	HMA/WMA	RAP	Design AC (%)
#1	C8046	PG 76-28	HMA	20%	5.4
#2	C8017	PG 70-28	HMA	20%	5.7
#3	C8013	PG 64-28	HMA	20%	5.2
#4	C8033	PG 64-28	HMA/WMA	20%	5.2
#5	C8016	PG 64-22	HMA	20%	5.3
#6	C7879	PG 64-22	HMA	0	5.4
#7	C7465	PG 64-22	HMA	18%	5.6

Table 5. Mixture Gradations

Sieve	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
	19mm	12.5mm	9.5mm	4.75mm	2.36mm	1.18mm	0.6mm	0.3mm	0.15mm	0.075mm
C8046	100	96	81	53	31	20	14	11	8	6.3
C8017	100	94	82	55	36	24	18	15	9	6.3
C8013	100	95	83	53	33	23	18	14	8	5.7
C8033	100	93	85	53	35	24	16	11	8	5.5
C8016	100	94	83	60	46	33	22	12	7	5.1
C7879	100	95	78	54	36	24	17	12	8	6
C7564	100	95	82	55	35	23	16	10	7	4.9

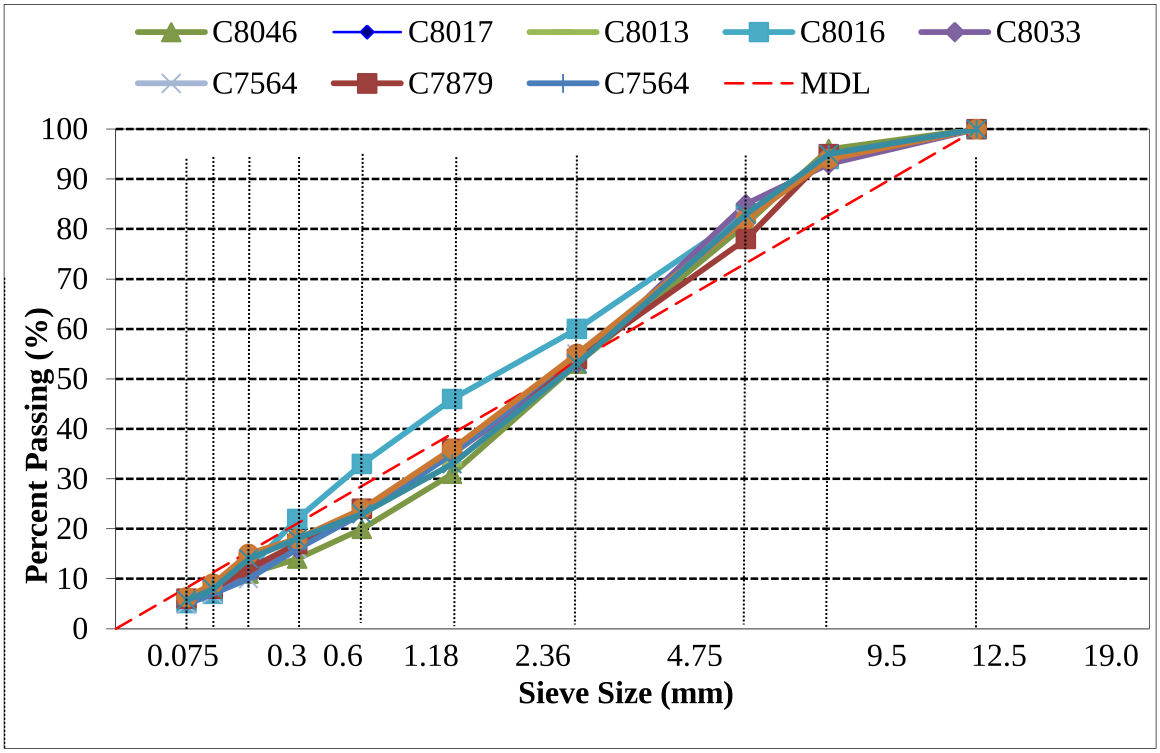


Figure 9.Asphalt mixture gradations

3.3 SAMPLE PREPARATION

The dynamic modulus test was conducted in accordance with AASHTO TP 62-03. The specimens were compacted with a Superpave gyratory compactor into 150 mm in diameter and approximately 170 mm in height. To ensure the quality of each specimen prepared for testing, great care was given to maintain a consistent compaction process. The stored asphalt mixtures were subjected to short term aging in oven at compaction temperature for 2 hours before compaction. Then specimens were cored from the center into 100 mm in diameter, and approximately 10 mm were sawed from each end of the test specimen. Sawing operations were performed carefully to ensure the ends maintained as parallelism as possible. The bulk specific gravities and air void contents for each test specimen were measured voids in accordance with AASHTO T-269, Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures. Three target air void levels, 4%±0.5%, 7%±0.5%, and 9%±0.5%, are used, to evaluate the effect of air voids on dynamic modulus and flow numbers. If any specimen was outside the required air void range, the specimen was discarded and a new sample will be made. The volumetrics information of all samples is shown in Appendix C. Once the specimens were prepared, they were stored at room temperature at dry condition until testing.

3.4 DYNAMIC MODULUS TEST

The dynamic modulus test specimen is 100 mm (4.0 in) in diameter and 150 mm (6.0 in) in height, sawed and cored from the 150 mm by 170 mm gyratory compacted specimen. The mixtures were aged in accordance with the short-term oven aging procedure in AASHTO PP2, and compacted in according with Section 9 of AASHTO T312. The procedures for dynamic modulus tests are following the NCHRP report 614 (Bonaquist, 2008).

- Attach six targets to the specimen using epoxy. The distance of two targets should satisfy that the measure gauge length is around 100mm and the angle between each set of two targets is 120 degrees. Wait for around 30 minutes to let the epoxy consolidate and then move to next step.
- Place one rubber membrane on each end of the specimen, and place the spherical stainless steel ball at the center and on top of the top platens.
- Put the specimen and the platens inside the environmental chamber on the loading pedestal; make sure that the loading cell is in line with the axis of the end platen and the specimen when put the specimen.
- Place LVDTs on the specimen, and adjusts them to allow the full range of the LVDTs to be available for the measurement of deformation.
- Set the chamber temperature to the specific value, and allow the specimen to be conditioned for a required time. As shown in Table 7, each dynamic modulus samples are done under six frequencies (25, 20, 5, 1, 0.5, 0.1Hz) and four temperatures (40, 70, 100, 130^{o}F). A 60-second rest period was used between each frequency to allow some specimen recovery before applying the new loading at the next lower frequency.

The dynamic modulus testing was conducted using the IPC Asphalt Mixture Performance Tester (AMPT), also called Simple Performance Tester (Figure 10). The IPC AMPT equipment is a relatively small, computer-controlled testing machine that can perform various tests (dynamic modulus test, flow number test, and flow time test) on HMA over the temperature ranging from 4 to 60^{o}C.

Figure 10. Asphalt Mixture Pavement Tester

Testing was conducted at four temperatures (40, 70,100,130°F) and six frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz.). Three different air void levels were conducted for each type of mixture including 4%, 7% and 9%. The condition time for each temperature are shown in Table 6.

Table 6. Condition time for different testing temperature

Test Temperature (^{o}F)	40	70	100	130
Condition Time	Overnight	3 hours	2 hours	1 hour

Table 7. Frequencies and temperatures used in the dynamic modulus testing

Frequency (Hz)	40(^{o}F)	70(^{o}F)	100(^{o}F)	130(^{o}F)
25	√	√	√	√
10	√	√	√	√
5	√	√	√	√
1	√	√	√	√
0.5	√	√	√	√
0.1	√	√	√	√

3.5 FLOW NUMBER TEST

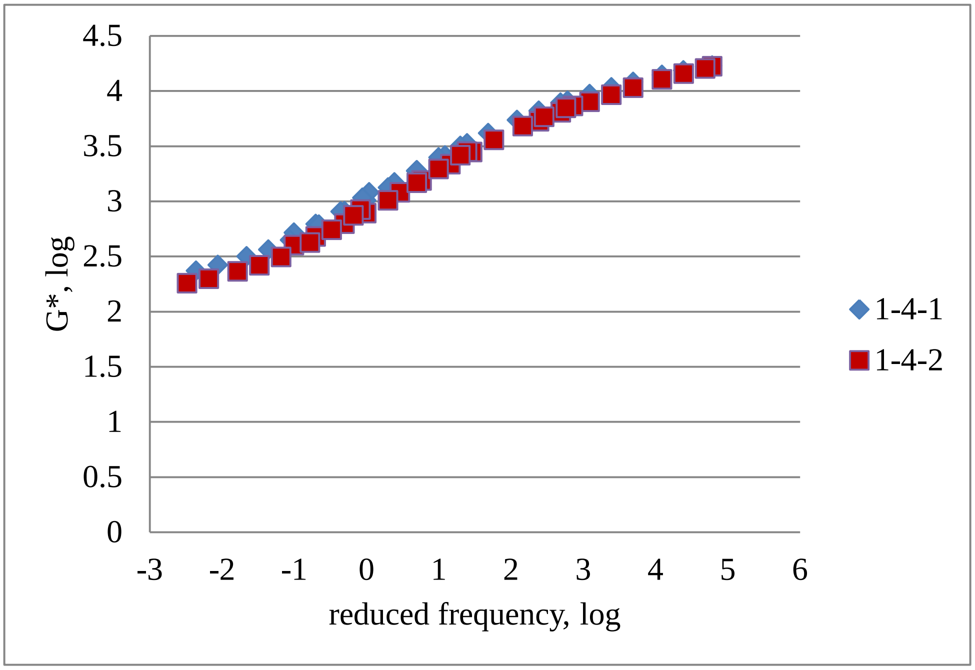
The flow number test (F_N) is a repeated-load permanent deformation test which was found to be able to correlate with the field rut depths and is recommended by the NCHRP report 465 (Witczak 2002) and NCHRP report 580 (Witczak 2007) as a testing method to evaluate the rutting potential of the mixtures. Tests were performed by applying a uniaxial compressive load to a cored cylindrical specimen which has the same geometry as dynamic modulus samples (100mm in diameter and 150 mm tall). In the flow number test, the compressive load is applied in haversine form with a loading time of 0.1 seconds and a rest duration of 0.9 seconds for a maximum of 10,000 cycles or until a deformation of 50,000 microstrains is reached. A deviatorical stress of 600 kPa is applied to the specimen until the flow point is reached. The flow point represents failure of the specimen, as evidenced by an increasing rate of total permanent strain during the test. Flow number tests are run at the average 7-day maximum pavement temperature 20 mm from the surface, at 50 % reliability as determined using LTPPBind version 3.1. Flow number testing was performed at 0 kPa confining pressure state. Because the dynamic modulus test is considered non-destructive, the samples were reused in the unconfined flow number evaluation.

CHAPTER 4 EXPERIMENTAL RESULTS

4.1 DYNAMIC MODULUS RESULTS

Dynamic modulus testing was conducted for each asphalt mixture at three target air void levels: 4%, 7%, and 9%. Two replicate samples at each air void level were tested to verify the repeatability of the testing results. The master curves of the replicate samples are shown in Figure 11 to Figure 18. It should also be noted that the naming system of all the specimens following some specific rules. X-Y-Z refers to a sample belonging to project # X, air void level Y, and sample number Z. The relation between project number and contract number can refer to Table 3. In other words, a sample number of 3-4-2 means that this sample belongs to project number 3 (contract C8013 according to Table 3), at 4% target air voids, and is the second replicate samples.

As shown from Figure 11 to Figure 18, the master curves of the replicate samples match each other well, indicating good repeatability of the testing results. Figure 22 shows the master curves of all samples with the same air voids levels. The detailed experimental dynamic modulus results can refer to Appendix D.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G*, log
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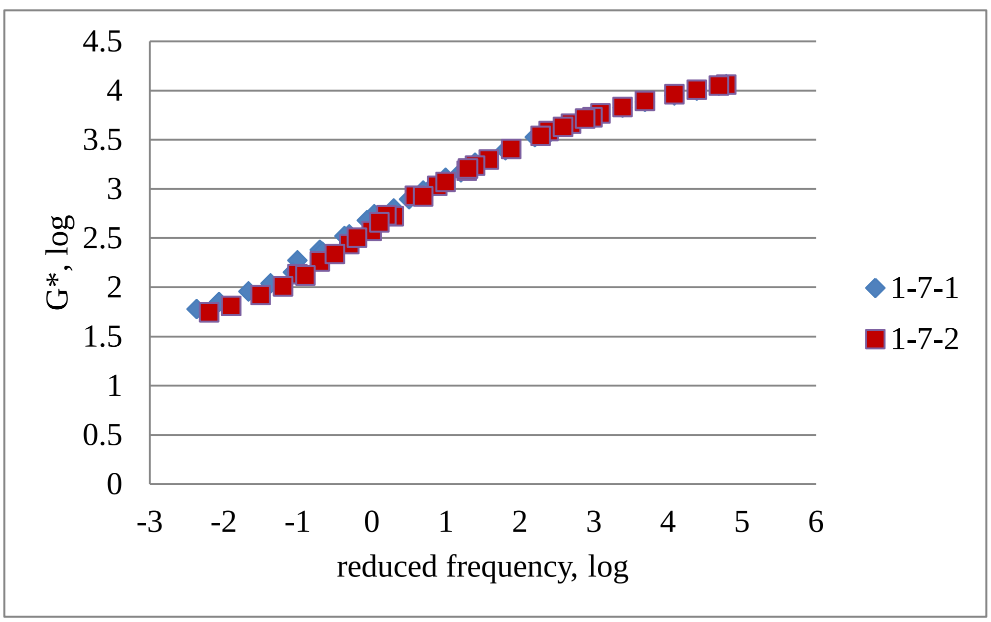
reduced frequency, log
1-4-1
1-4-2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reduced frequency, log
1-7-1
1-7-2

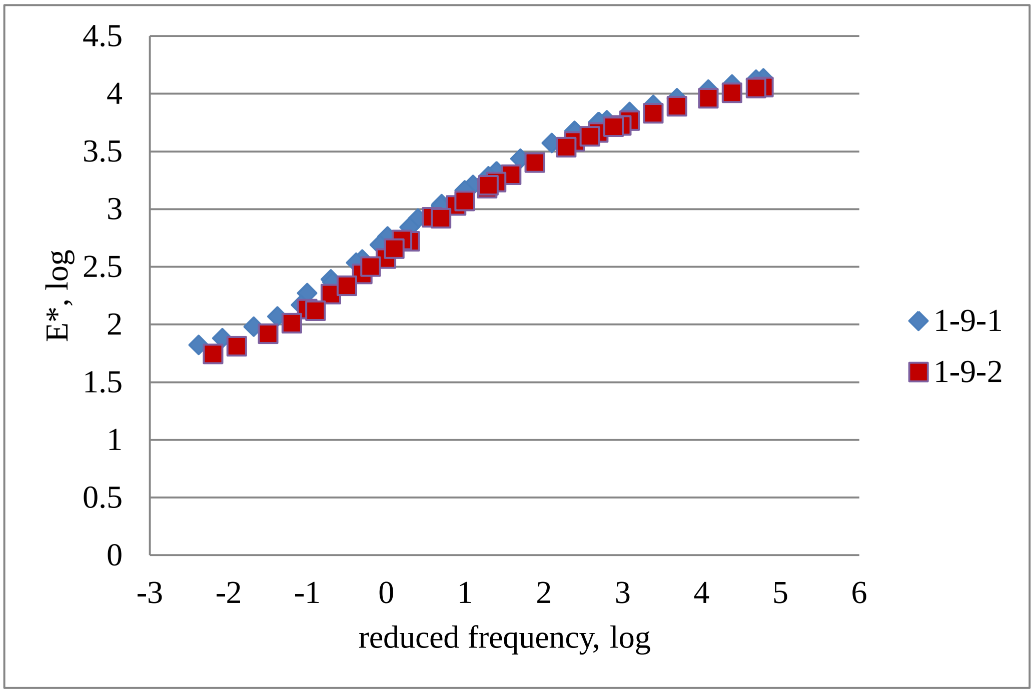
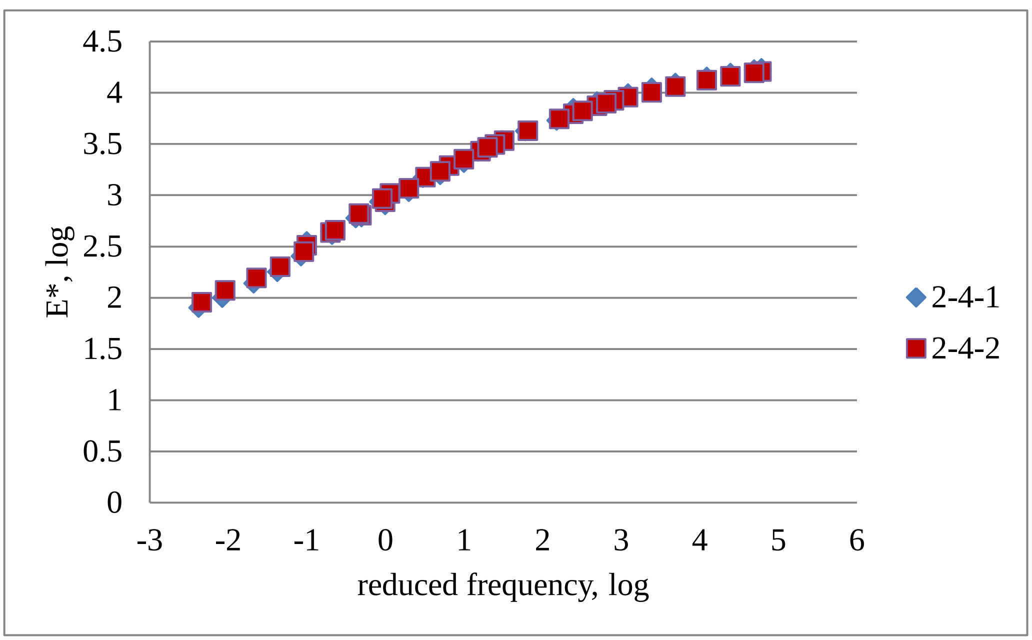


Figure 11. |E*| master curves of project C8046 at 100^{o}F for repeating samples



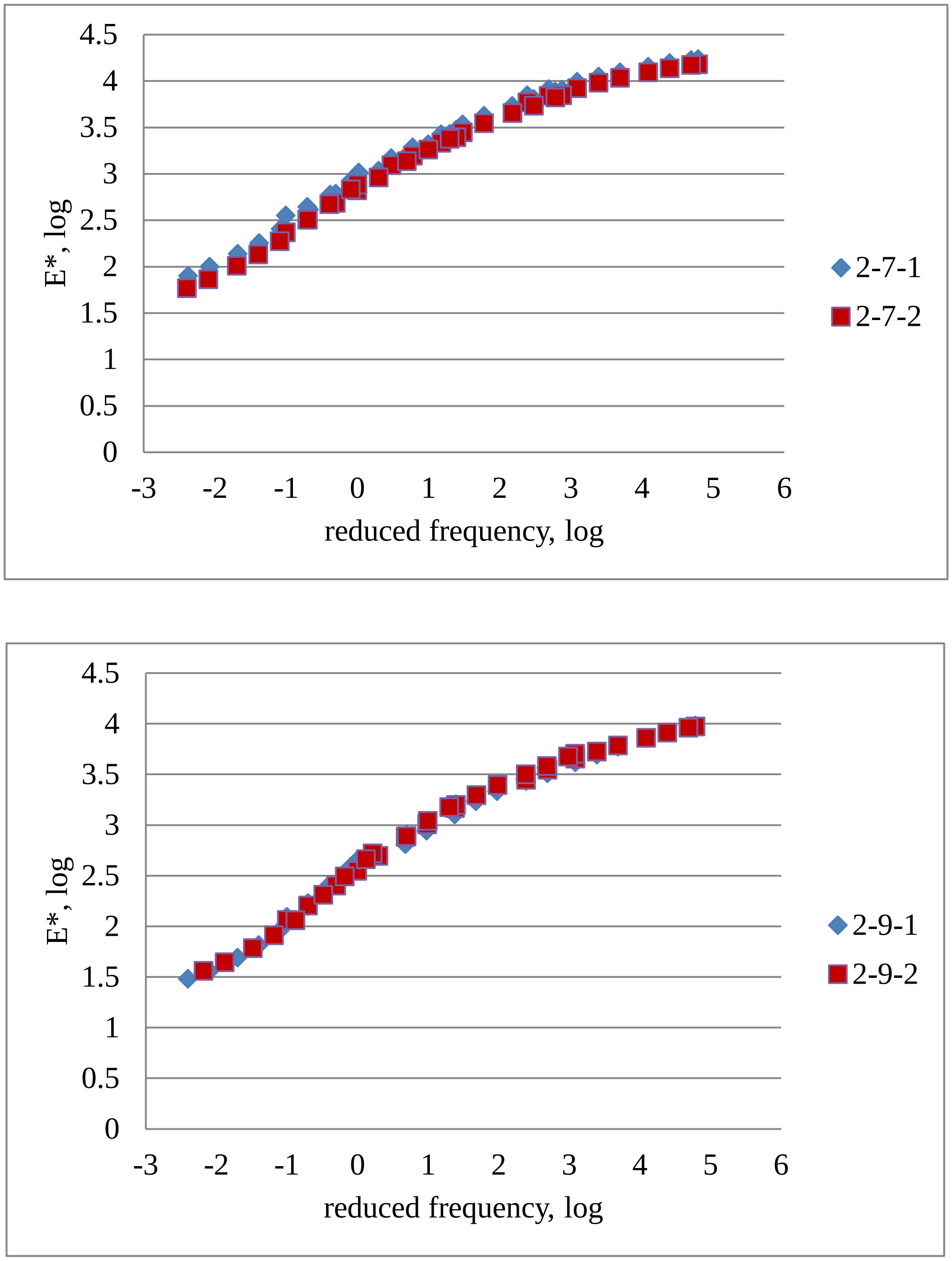
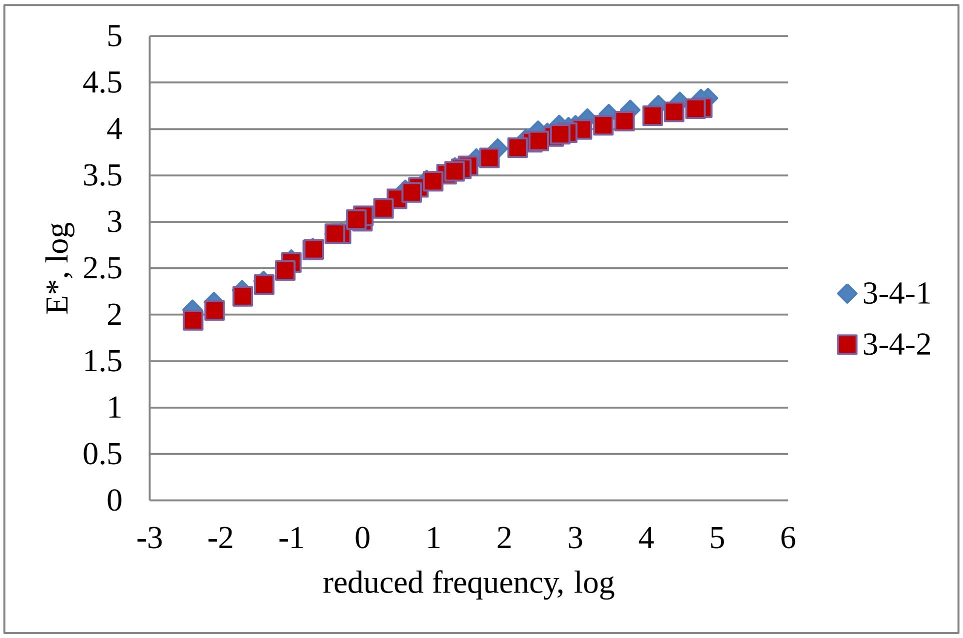


Figure 12. |E*| master curves of project C8017 at 100°F for repeating samples



5
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E*, log
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reduced frequency, log
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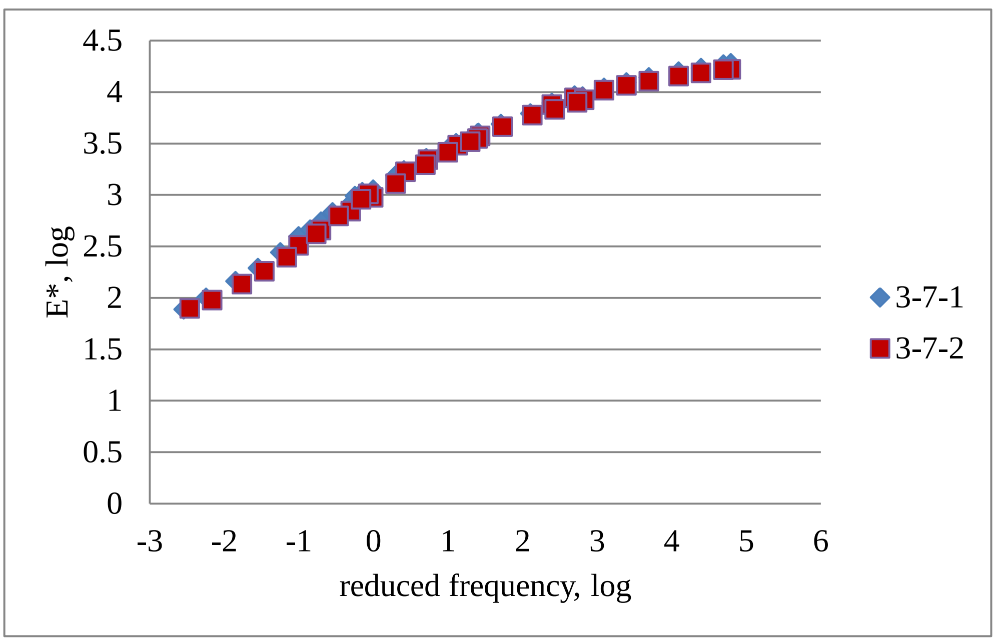
3-4-2



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E*, log
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reduced frequency, log
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3-7-2

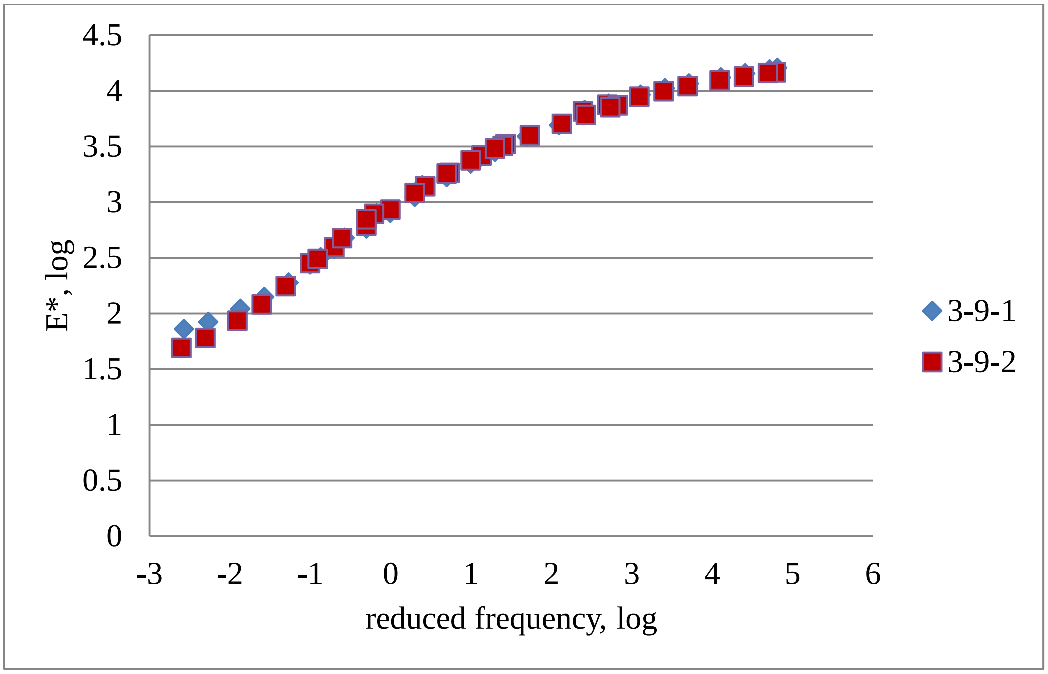
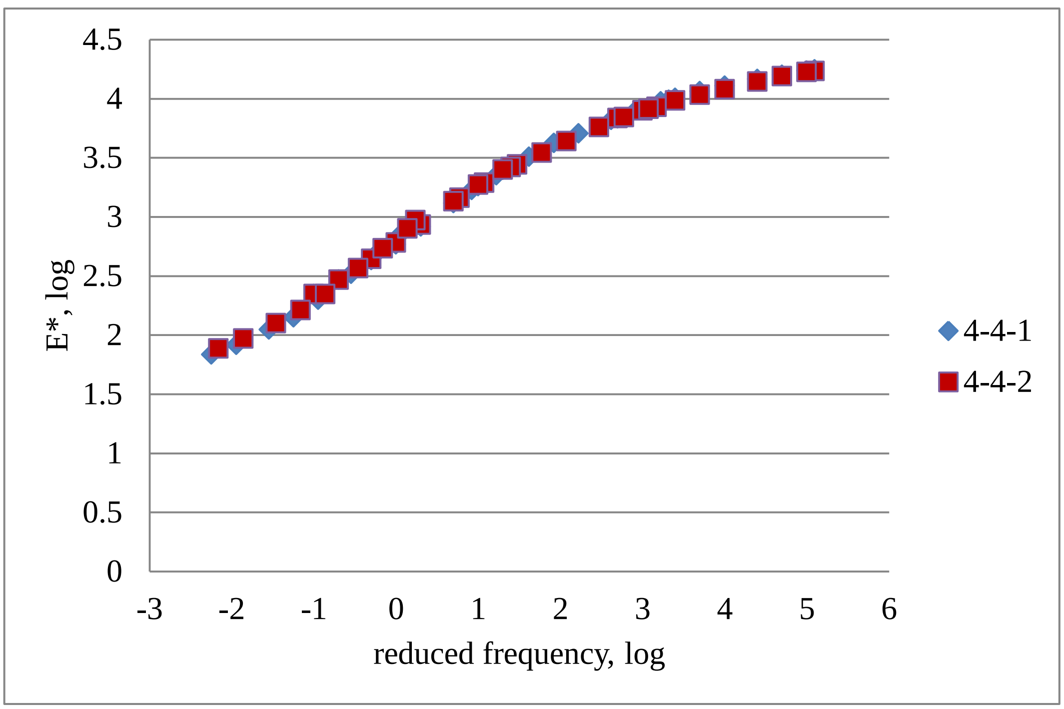
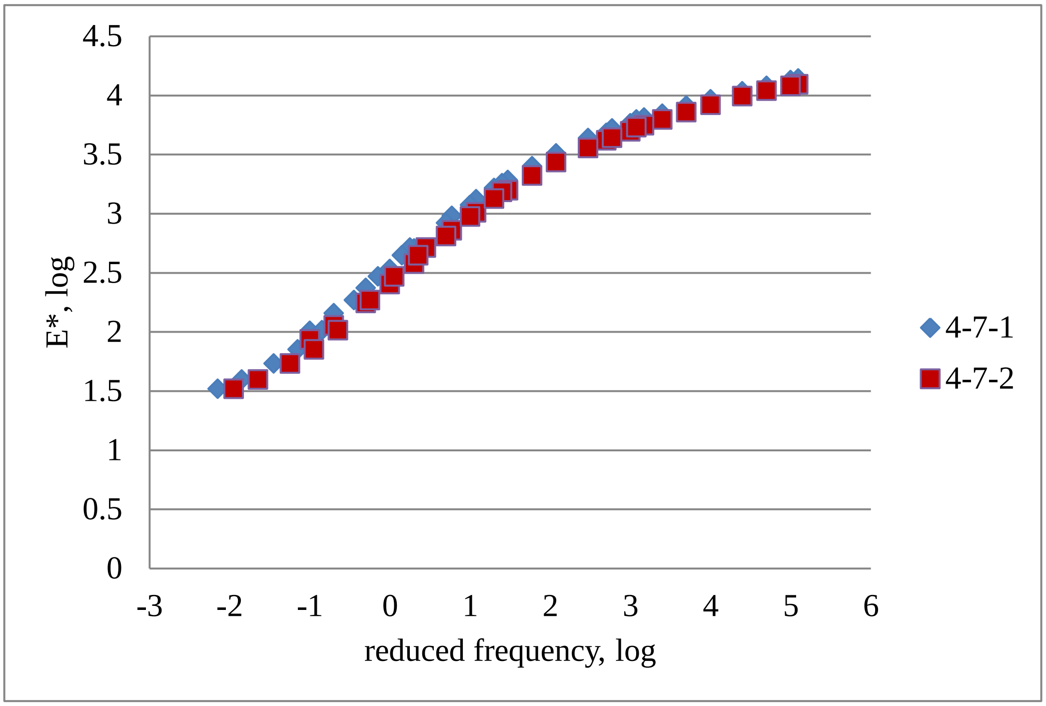


Figure 13. |E*| master curves of project C8013 at 100^{o}F for repeating samples





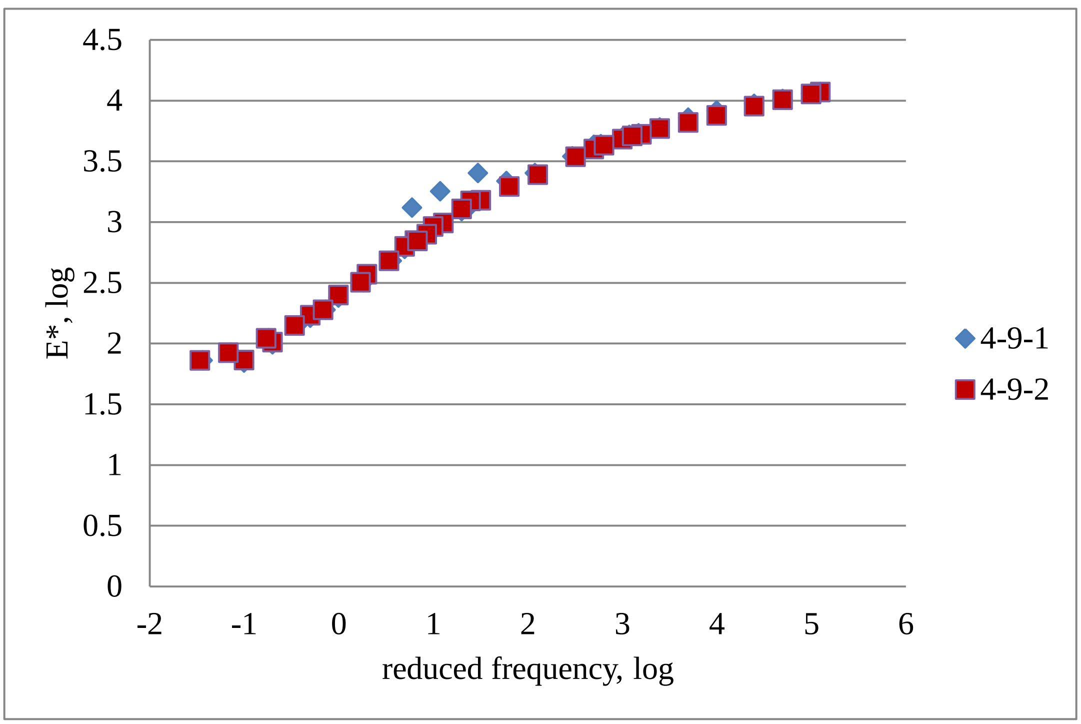
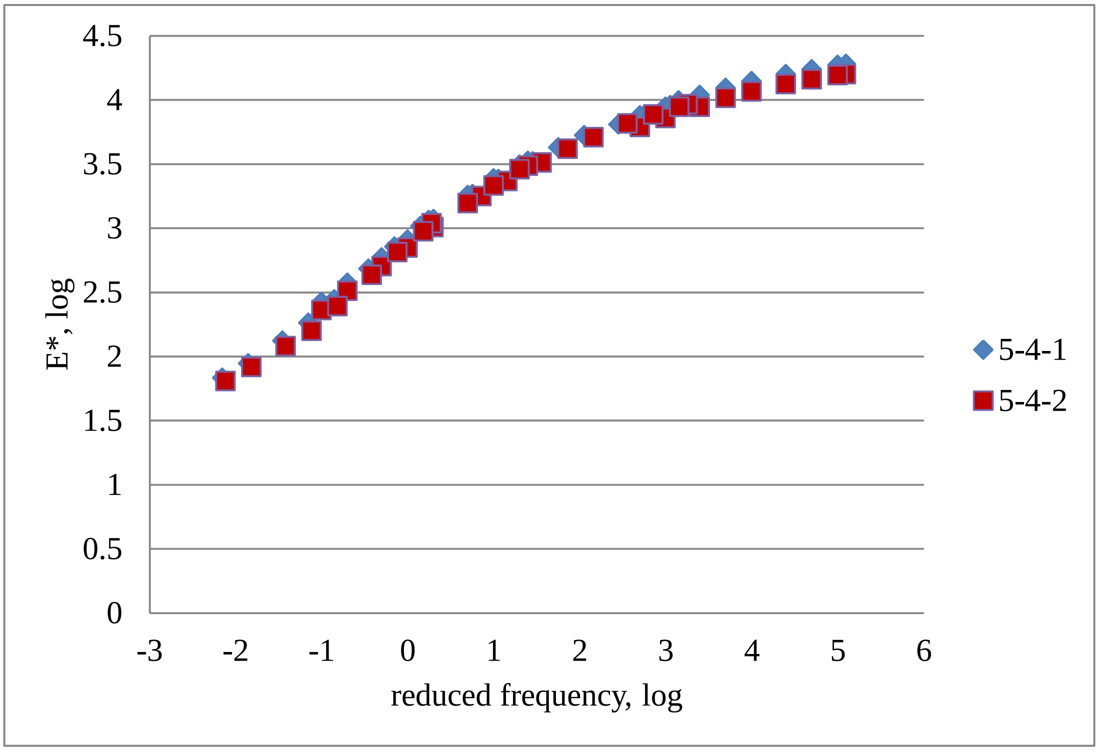


Figure 14. |E*| master curves of project C8033 at 100^{o}F for repeating samples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reduced frequency, log
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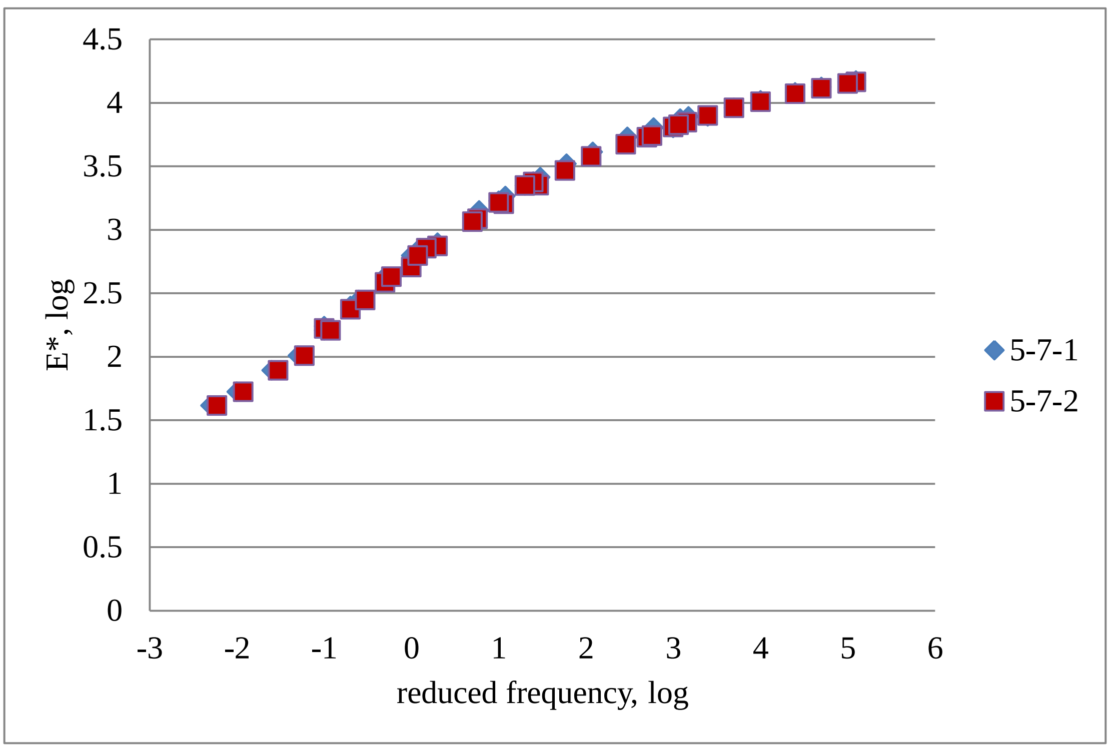
5-4-2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reduced frequency, log
5-7-1
5-7-2

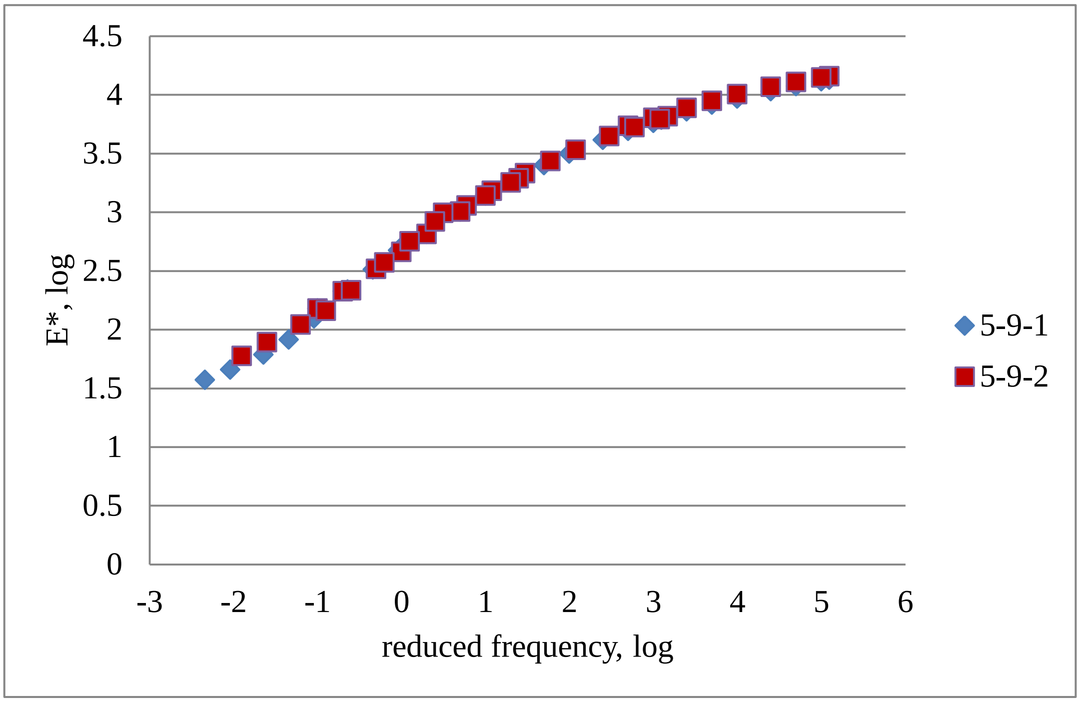
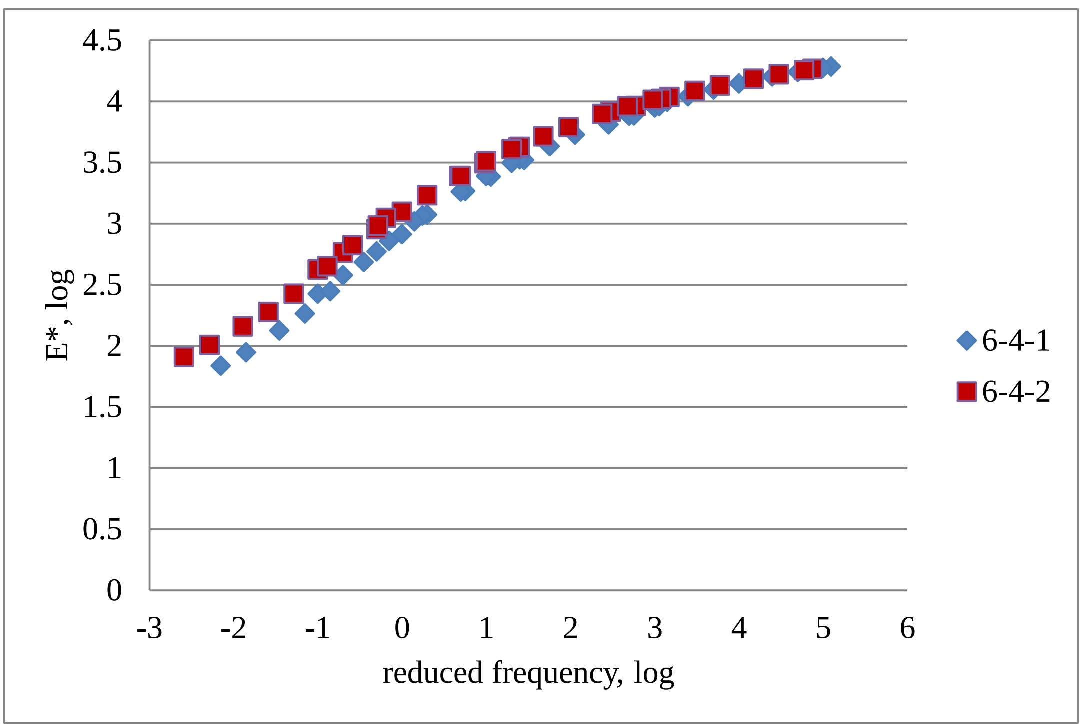
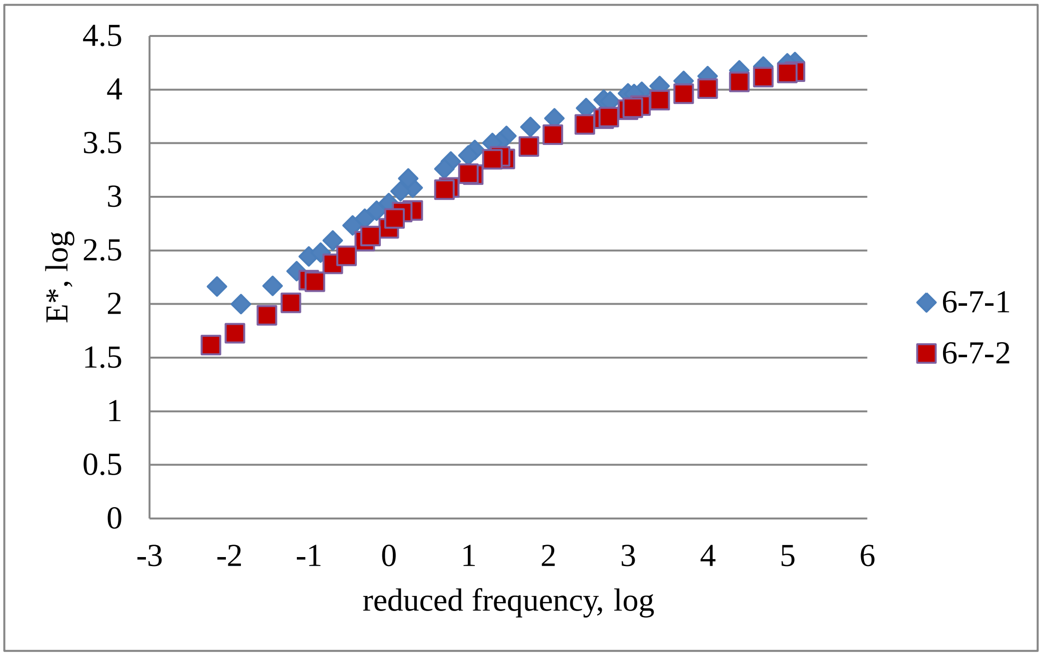


Figure 15. |E*| master curves of project C8016 at 100°F for repeating samples





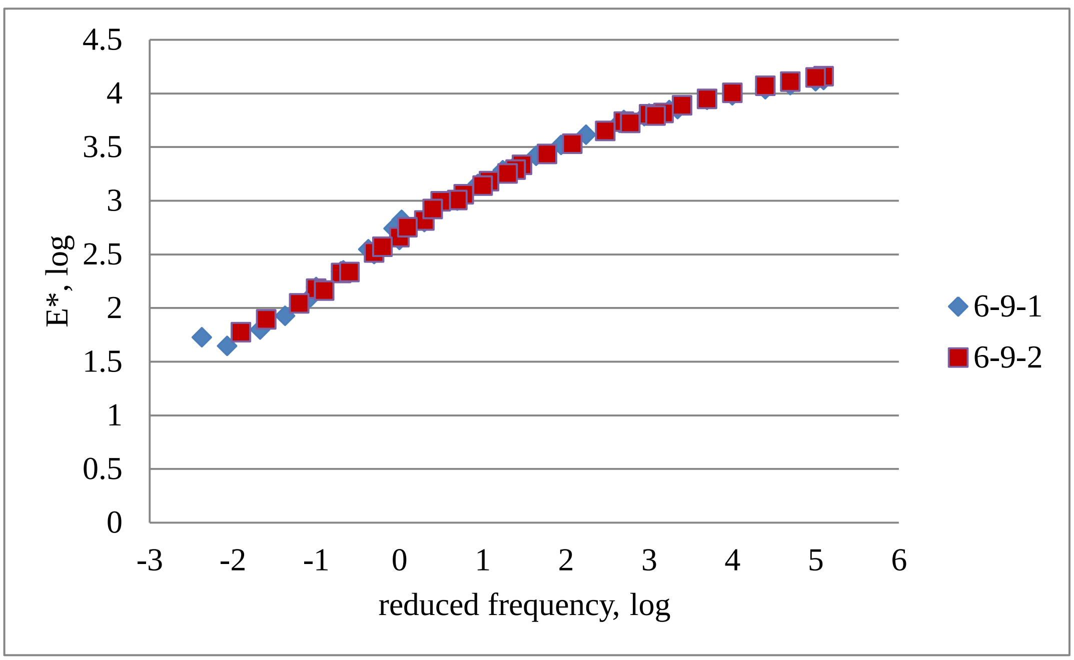
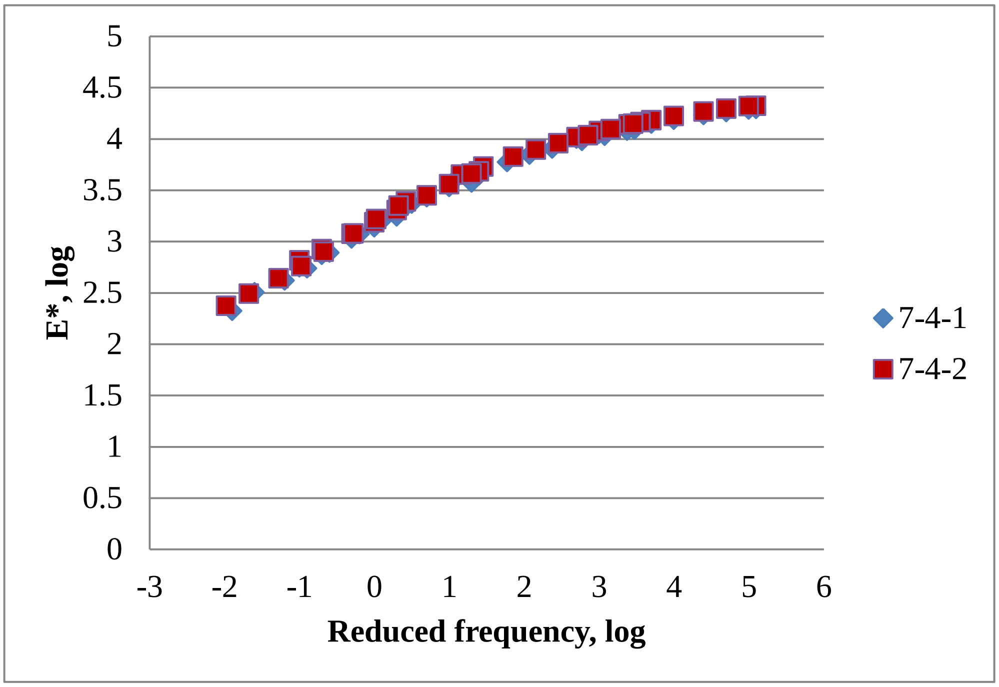
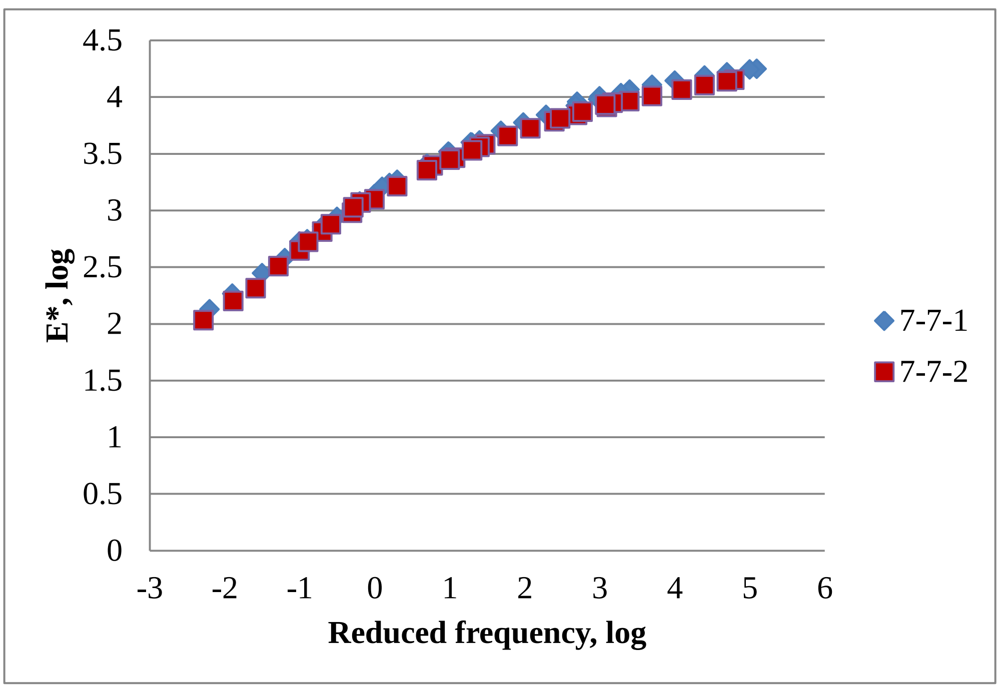


Figure 16. |E*| master curves of project C7879 at 100°F for repeating samples


E*, log
Reduced frequency, log
7-4-1
7-4-2


E*, log
Reduced frequency, log
7-7-1
7-7-2

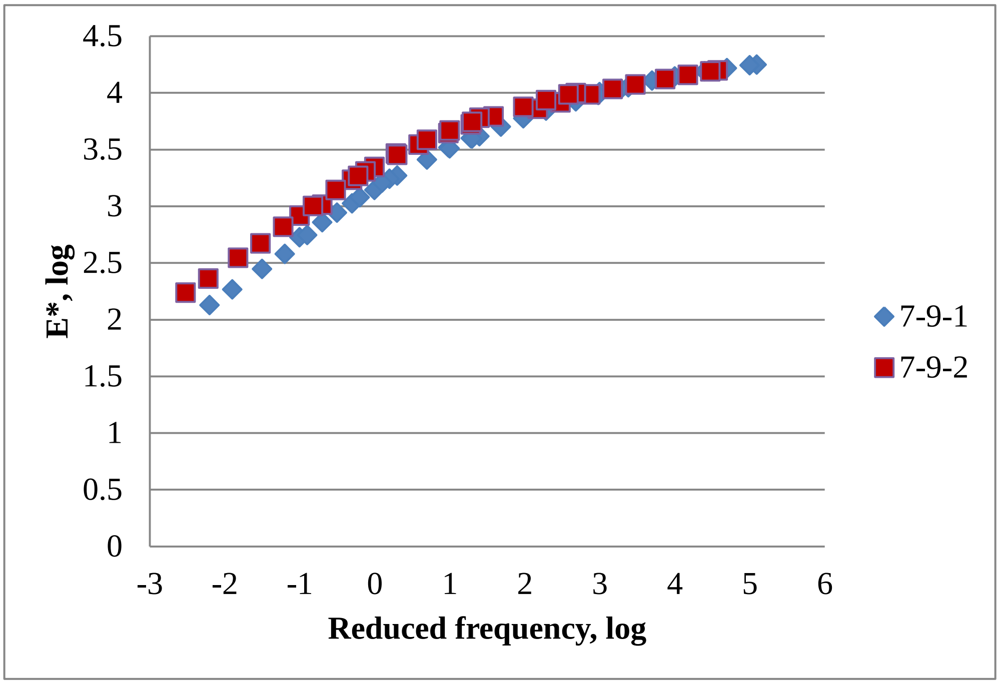
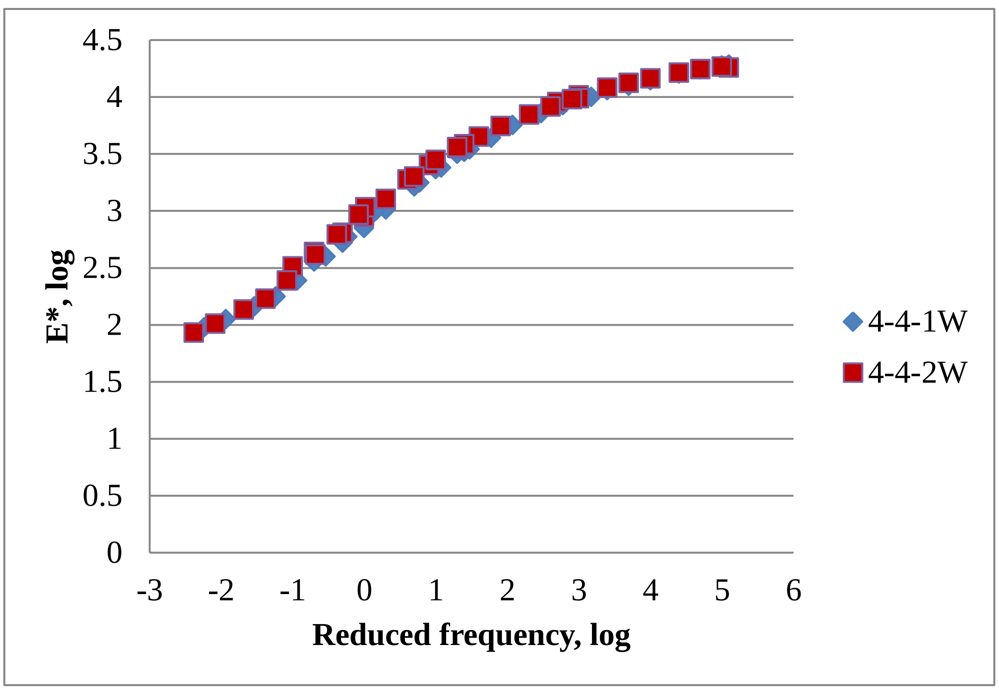
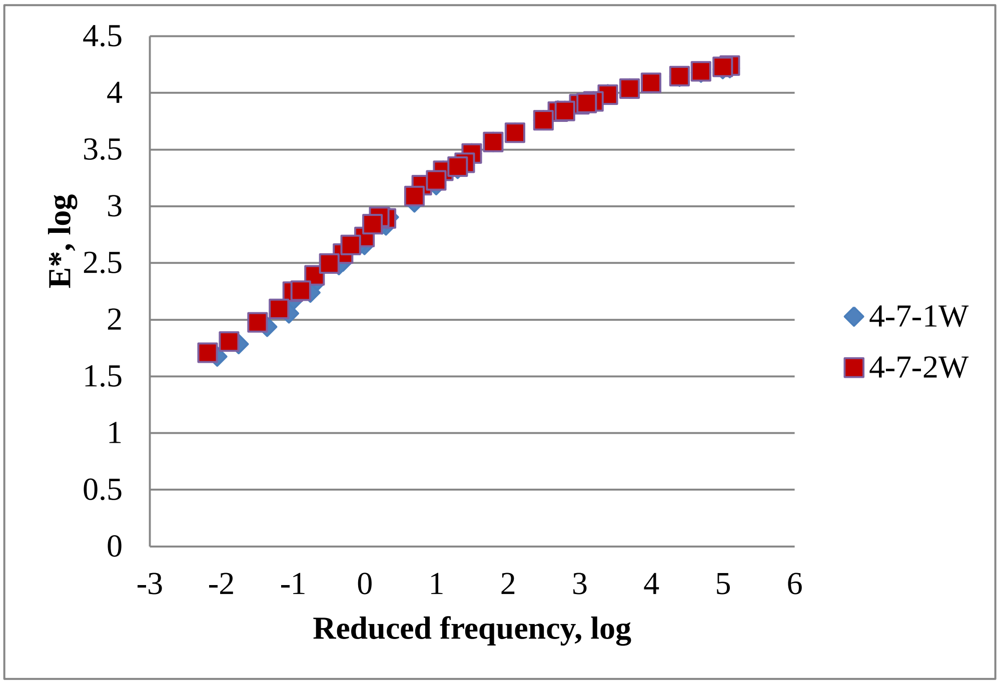


Figure 17. |E*| master curves of project C7465 at 100°F for repeating samples





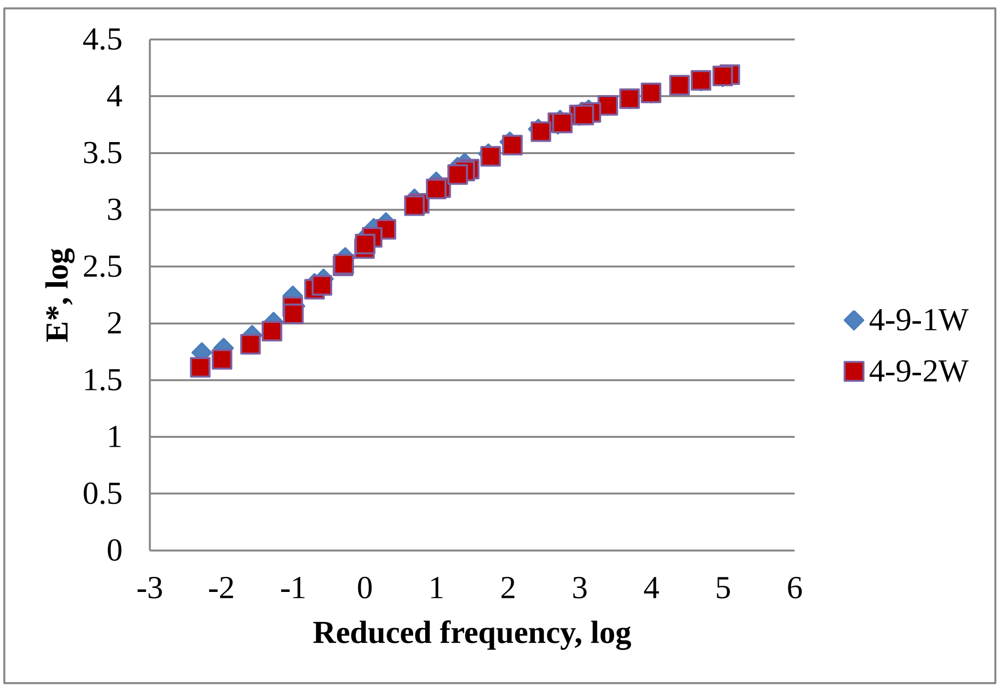
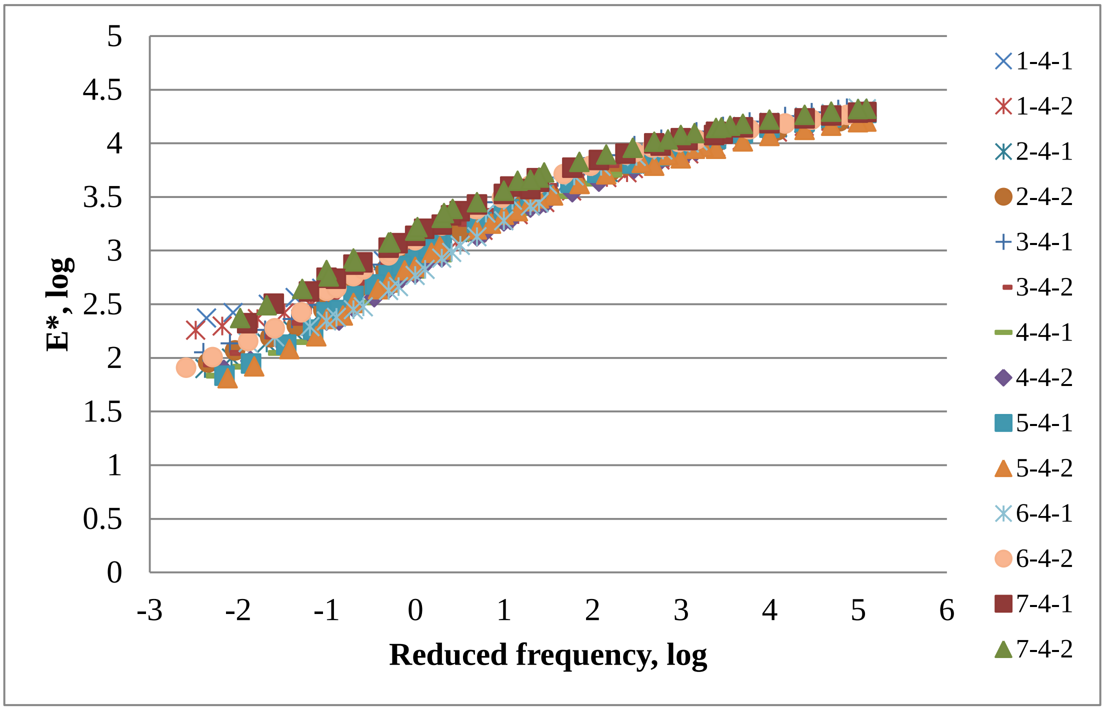
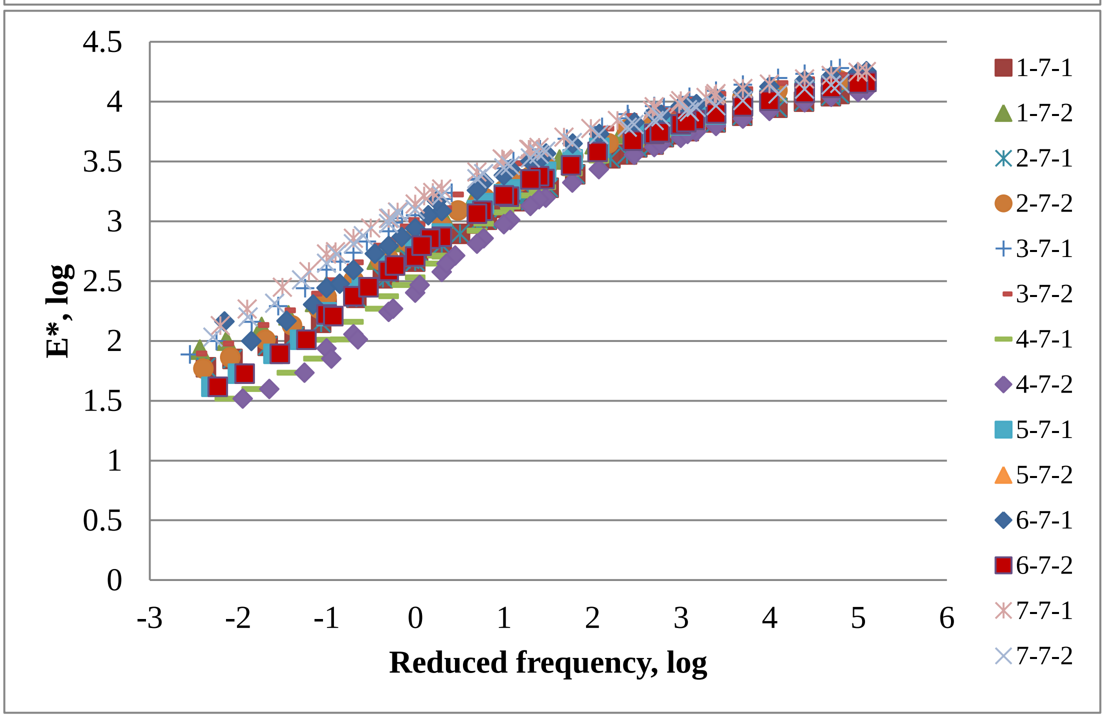


Figure 18. |E*| master curves of project C8033 warm mix at 100^{o}F for repeating samples


5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
E*, log
-3
-2
-1
0
1
2
3
4
5
6
Reduced frequency, log
1-4-1
1-4-2
2-4-1
2-4-2
3-4-1
3-4-2
4-4-1
4-4-2
5-4-1
5-4-2
6-4-1
6-4-2
7-4-1
7-4-2


4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
E*, log
-3
-2
-1
0
1
2
3
4
5
6
Reduced frequency, log
1-7-1
1-7-2
2-7-1
2-7-2
3-7-1
3-7-2
4-7-1
4-7-2
5-7-1
5-7-2
6-7-1
6-7-2
7-7-1
7-7-2

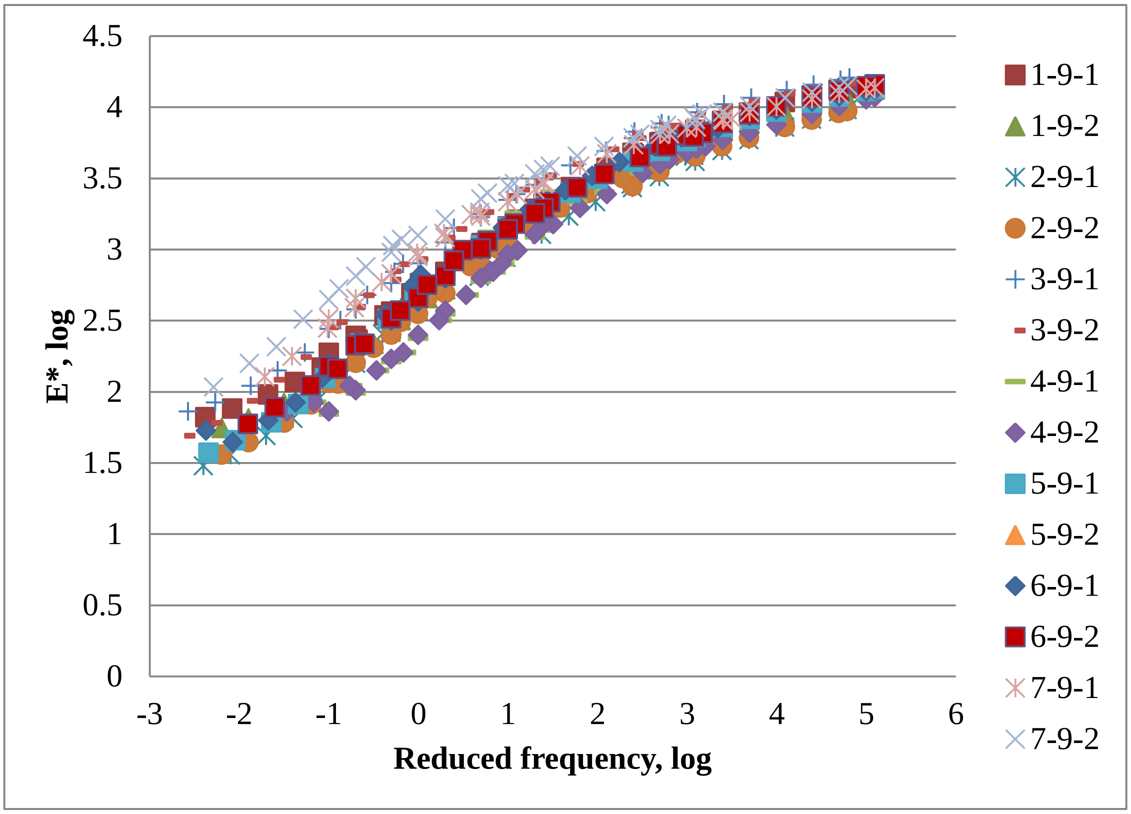
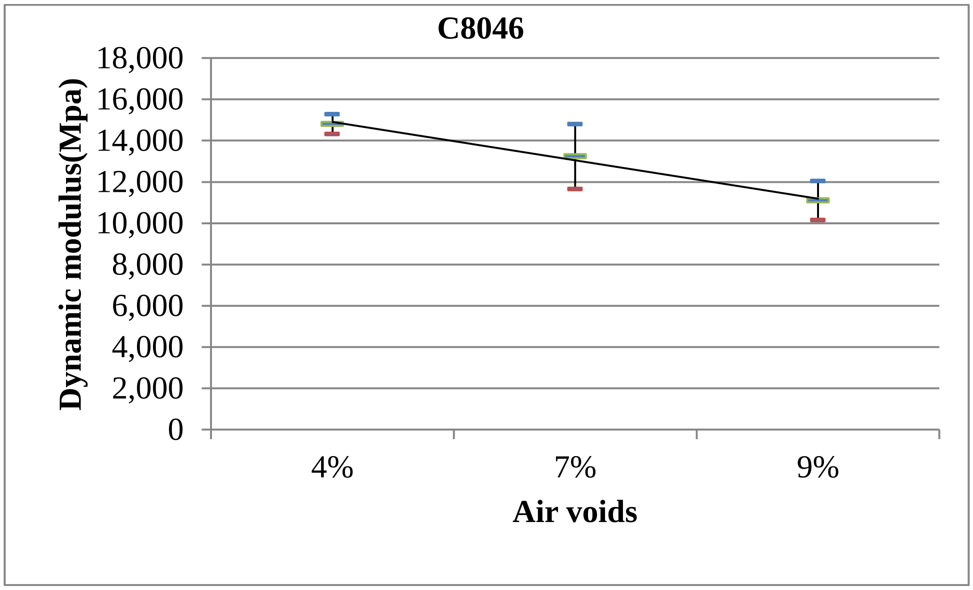
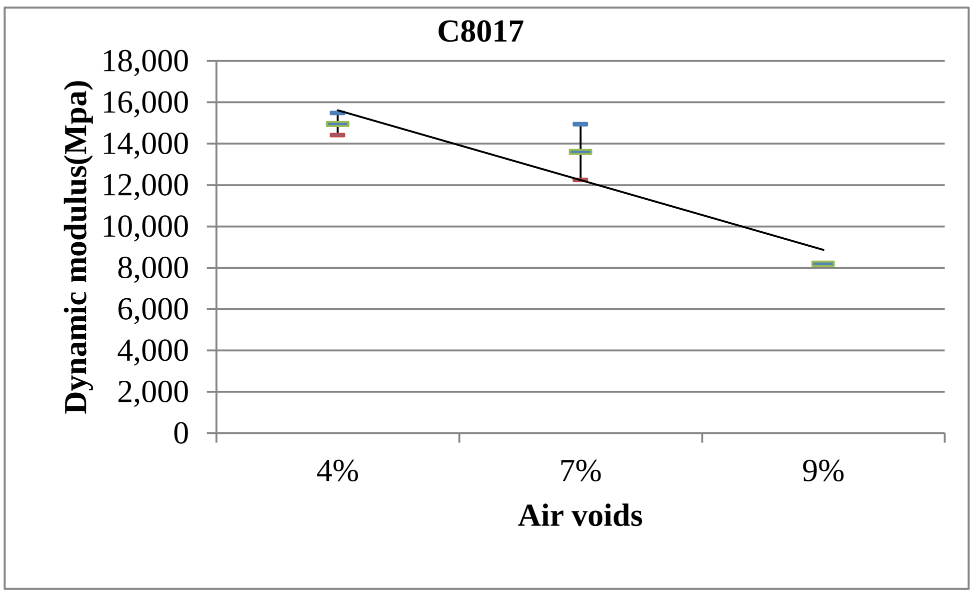


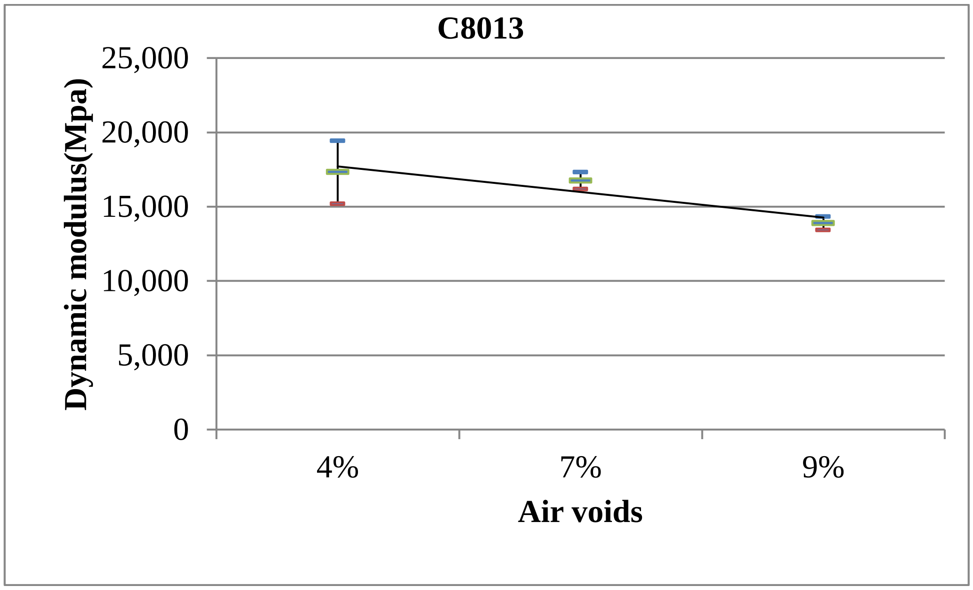
Figure 19. |E*| master curves with the same air voids levels

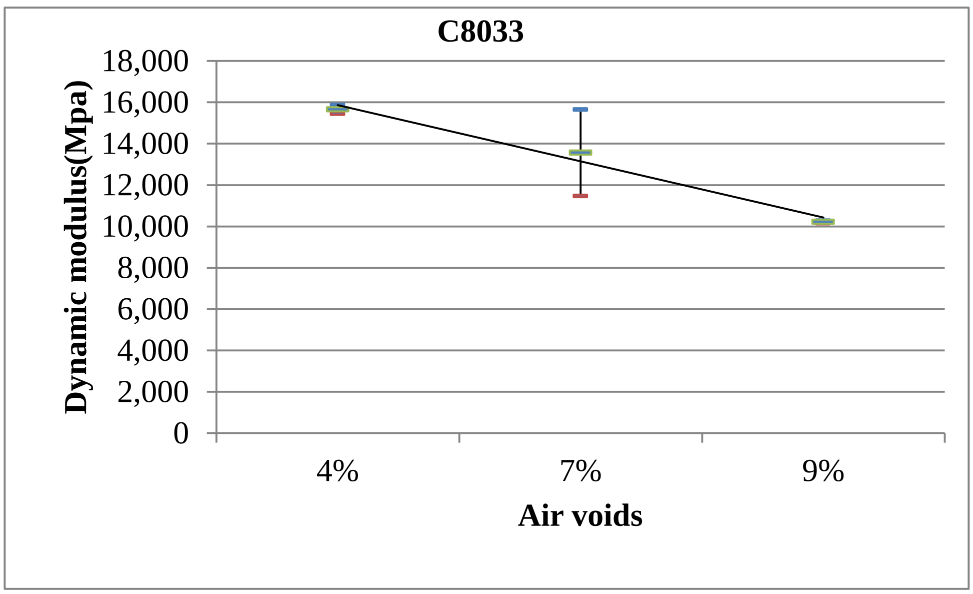
4.2 Effect of Air Voids on Dynamic Modulus

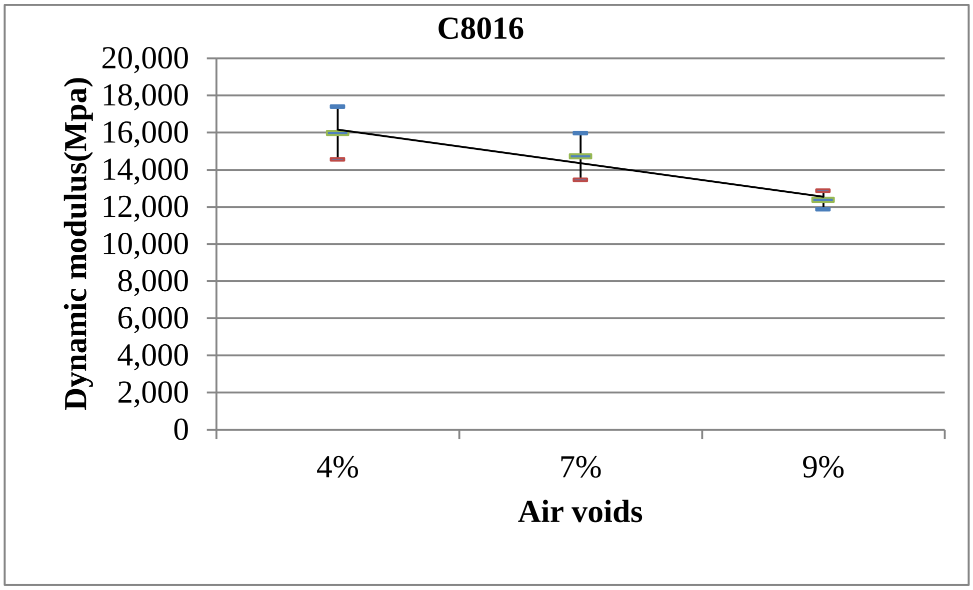
The air void property is a very important QA/QC control parameter for asphalt pavement. This study evaluated the effect of air voids on the dynamic modulus of asphalt mixture. Dynamic modulus at two levels is evaluated: (a) high E* level with temperature of 40^{o}F and loading frequency of 10Hz; and (b) low E* level with temperature of 130^{o}F and loading frequency of 0.1Hz. The results are shown in Figure 20 and Figure 21. As shown, in general, samples with higher air voids will have lower dynamic modulus. At low E* levels (high temperature and low frequency), more testing variation is observed.

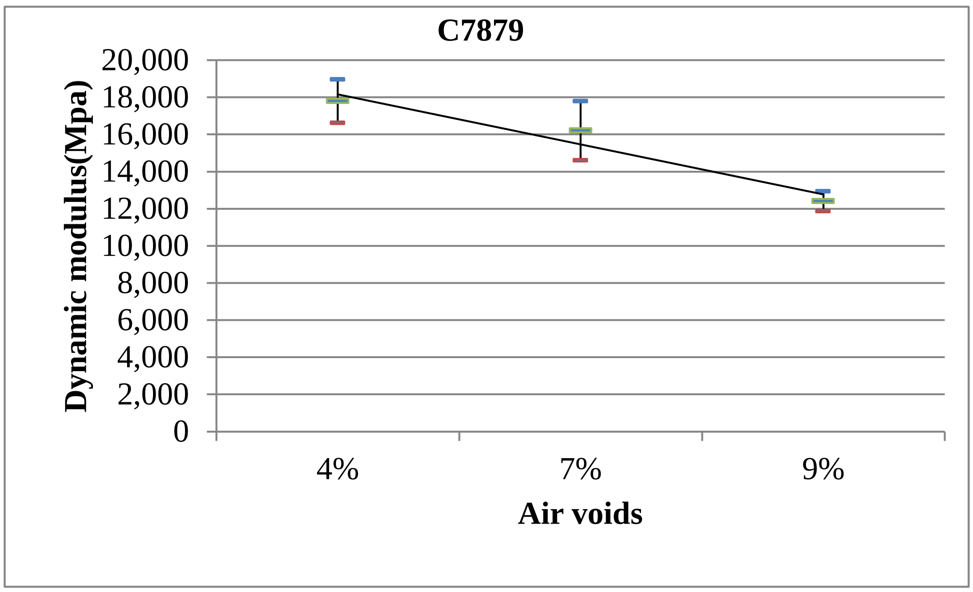

C8046
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Dynamic modulus(Mpa)
4%
7%
9%
Air voids


C8017
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Dynamic modulus(Mpa)
4%
7%
9%
Air voids


C8013
Dynamic modulus(Mpa)
25,000
20,000
15,000
10,000
5,000
0
4%
7%
9%
Air voids


C8033
Dynamic modulus(Mpa)
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
4%
7%
9%
Air voids


C8016
Dynamic modulus(Mpa)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
4%
7%
9%
Air voids


C7879
Dynamic modulus(Mpa)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
4%
7%
9%
Air voids

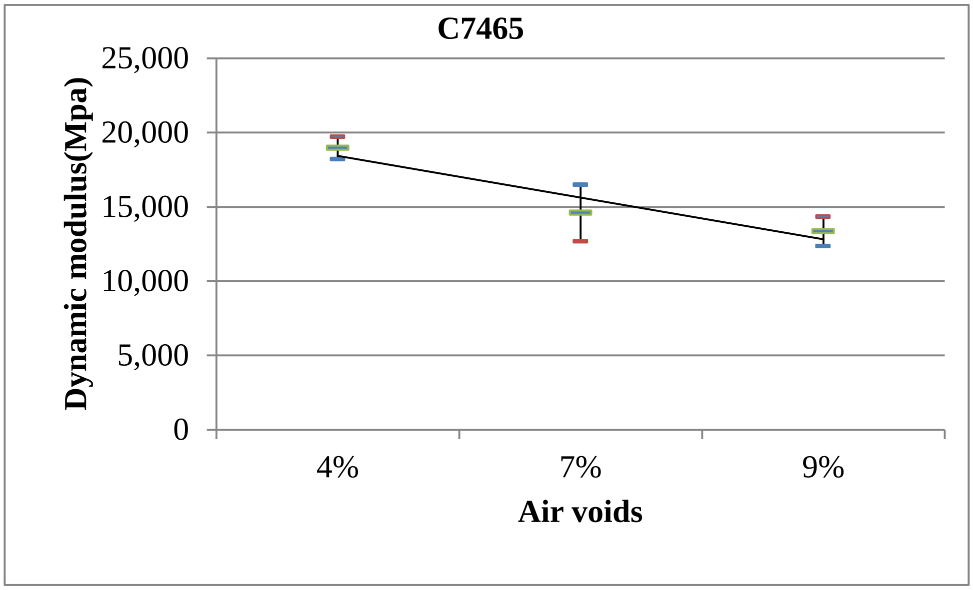
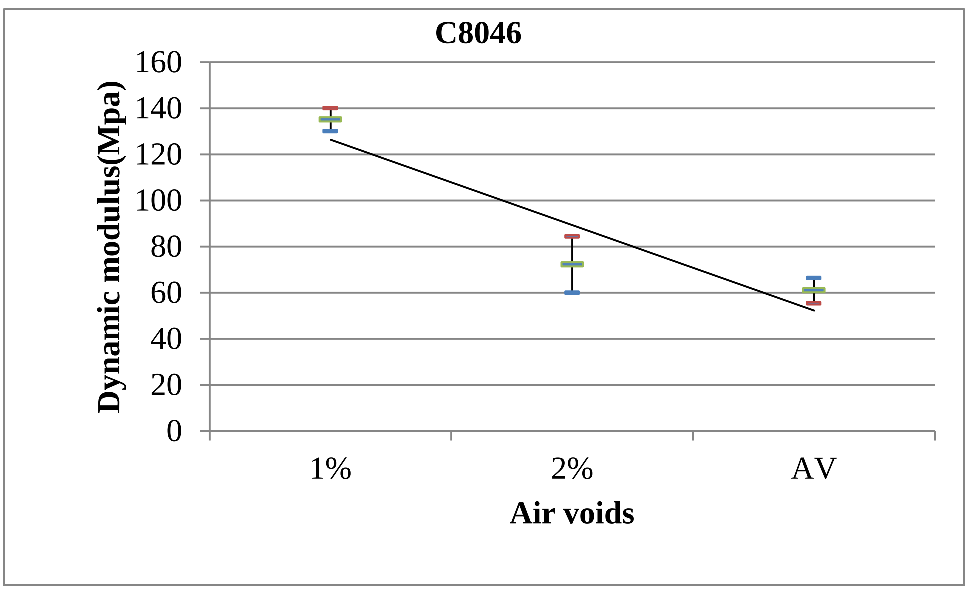
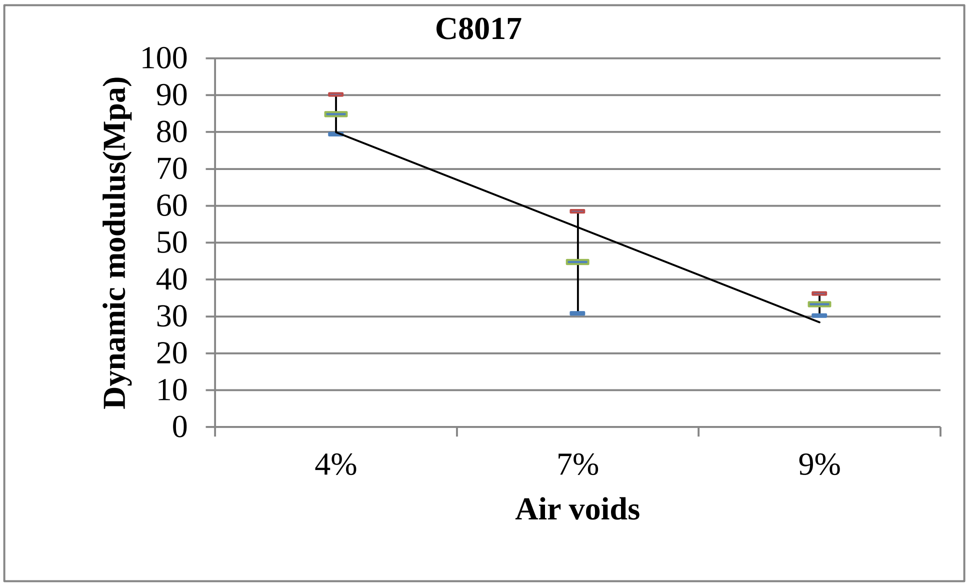
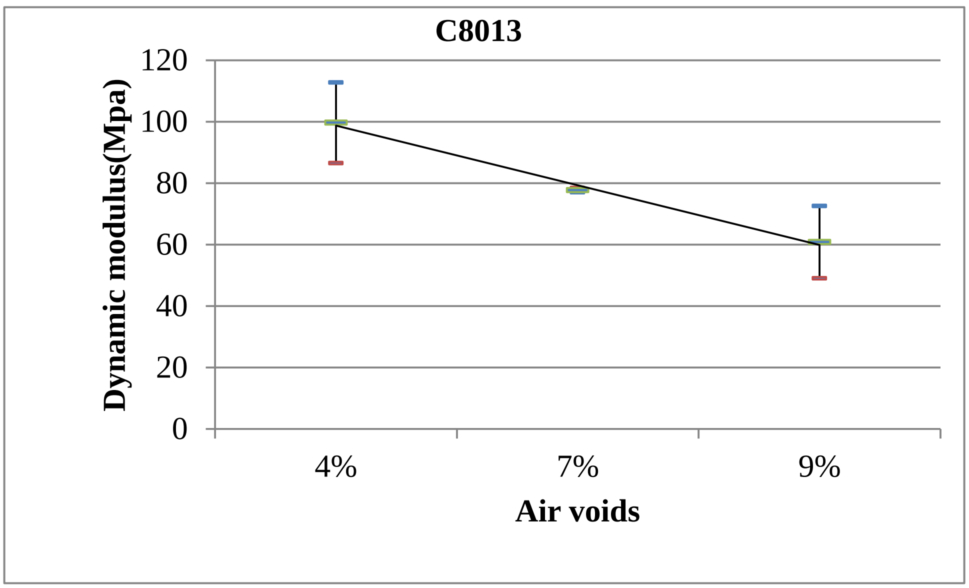
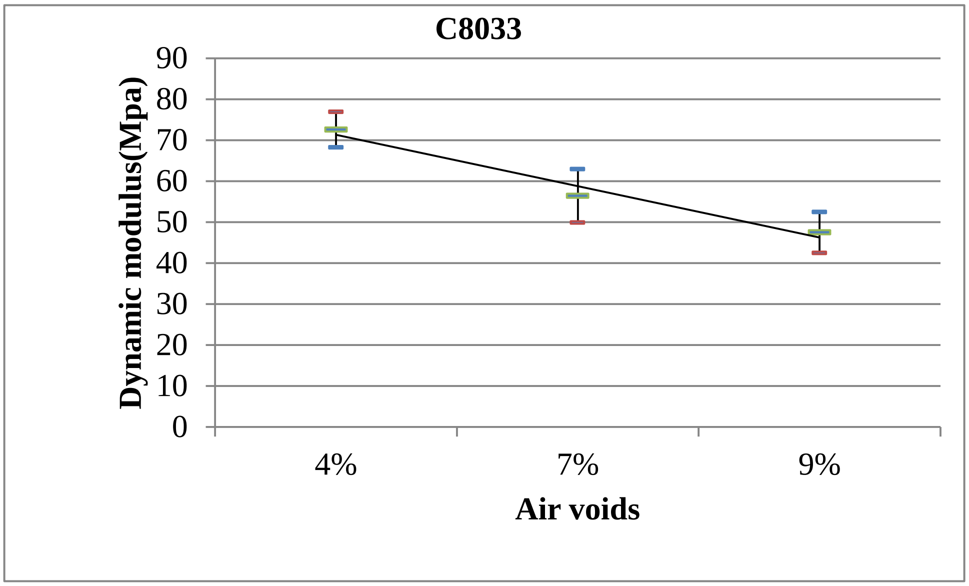


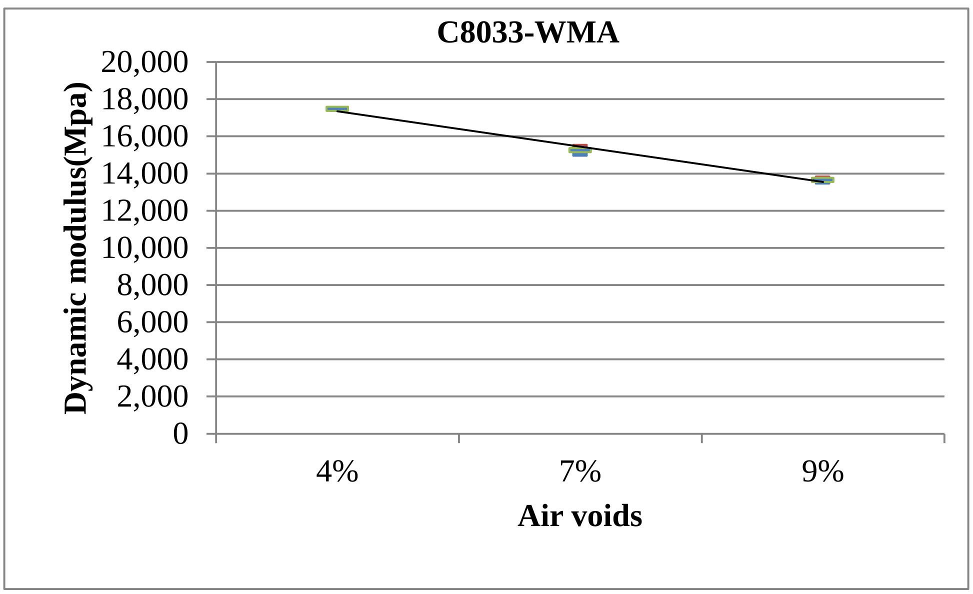
Figure 20. |E*| at temperature of 40°F and frequency of 10Hz

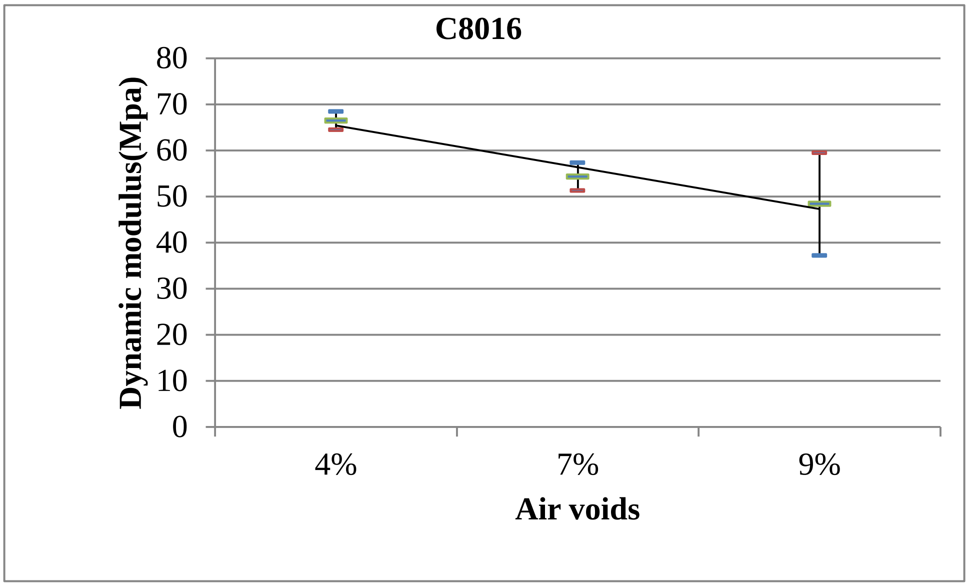


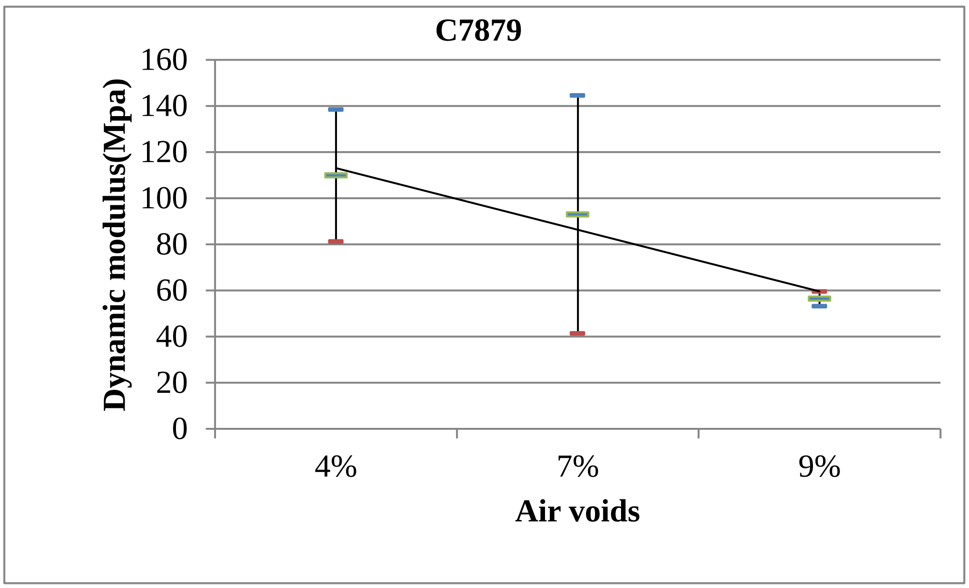

C8017
Dynamic modulus(Mpa)
100
90
80
70
60
50
40
30
20
10
0
4%
7%
9%
Air voids


C8013
Dynamic modulus(Mpa)
120
100
80
60
40
20
0
4%
7%
9%
Air voids


C8033
Dynamic modulus(Mpa)
90
80
70
60
50
40
30
20
10
0
4%
7%
9%
Air voids


C8033-WMA
Dynamic modulus(Mpa)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
4%
7%
9%
Air voids


C8016
Dynamic modulus(Mpa)
0
10
20
30
40
50
60
70
80
4%
7%
9%
Air voids


C7879
Dynamic modulus(Mpa)
0
20
40
60
80
100
120
140
160
4%
7%
9%
Air voids

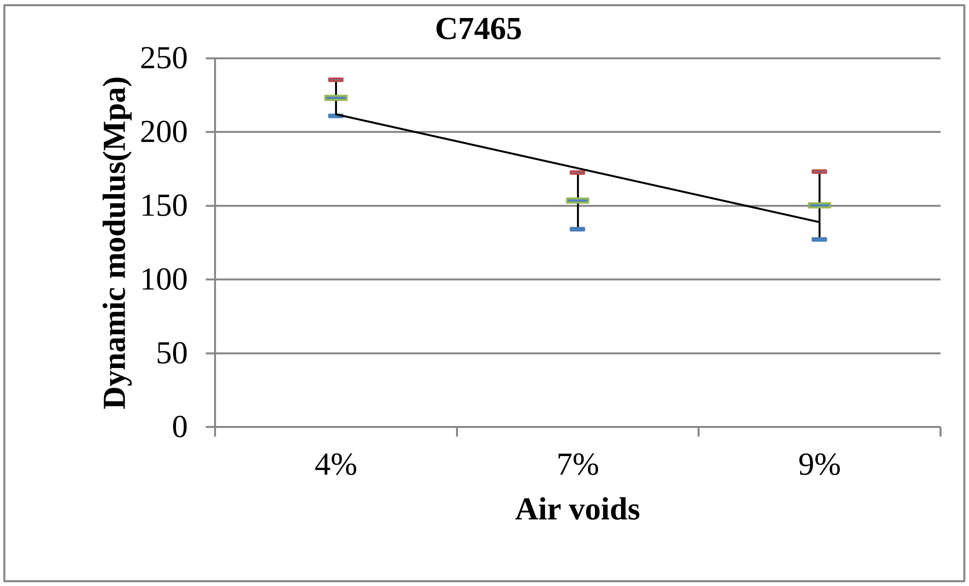


Figure 21. |E*| at temperature of 130^{o}F and frequency of 0.1Hz

4.3 EFFECT OF ASPHALT BINDER ON DYNAMIC MODULUS

The asphalt binder is an essential component of asphaltic mixtures. The performance of an asphaltic mixture is directly related to mechanical characteristics of the binder. Therefore, there is a need to evaluate the relationship between the properties of binders and asphaltic mixtures such that a proper understanding and selection of an asphalt binder can be made to improve the performance of an asphaltic mixture. In this study, the effects of asphalt binder properties on asphaltic mixtures at high temperatures low frequencies and low temperature high frequencies were evaluated based on experimental data.

Figure 22 shows the comparison of four types of binders at low E* level (high temperature and low frequency 130^{o}F/0.1Hz), which is associated with the rutting resistance of the asphalt mixture. The results show that the PG grade, especially the high PG grade, has a significant influence on the dynamic modulus at high temperature low frequency.

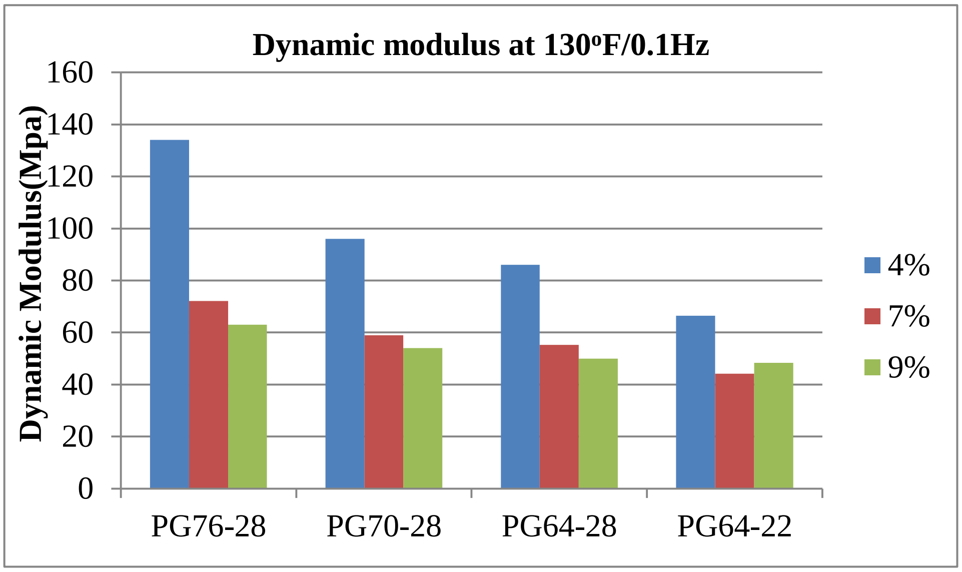


Figure 22. Effect of asphalt binder on dynamic modulus

Figure 23 shows the comparison of four types of binders at high E* level (low temperature and high frequency 40 ^{o}F/10Hz), which relates to the crack resistance of the asphalt mixtures. The results show that the binder type do not has a significant influence on the dynamic modulus at high E* level (low temperature and high frequency), partially due to the similar low PG grade all the mixes have.

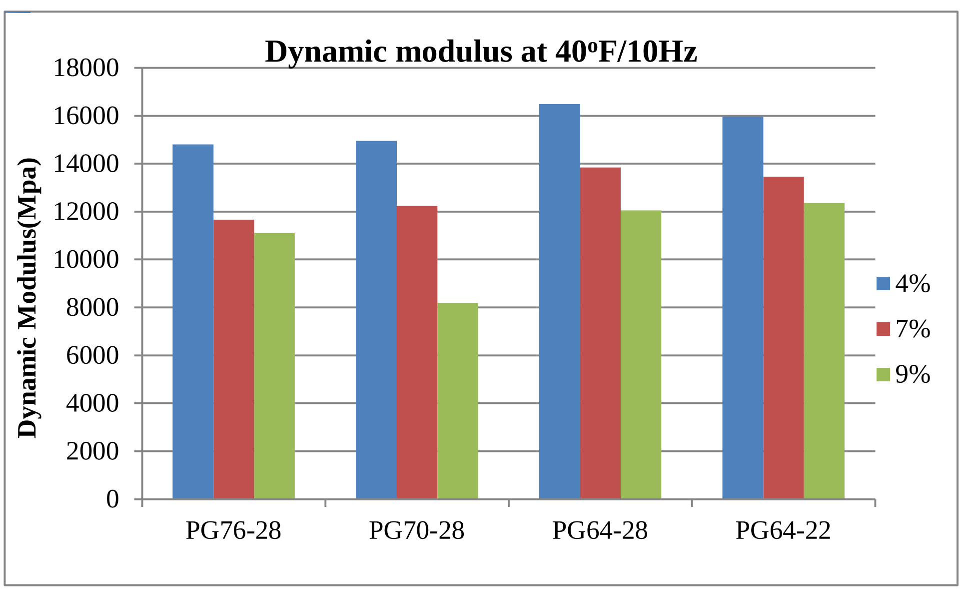
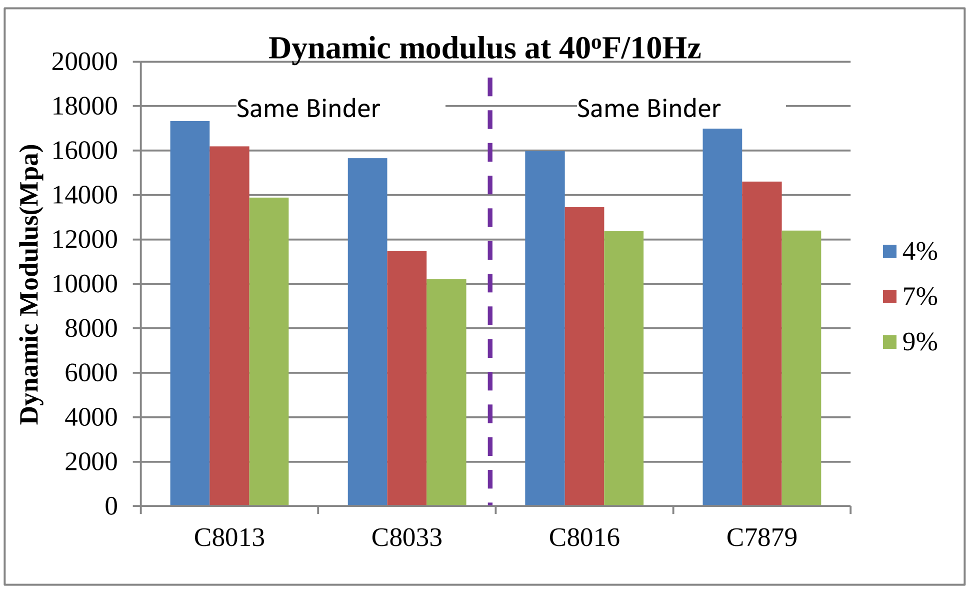


Figure 23. Effect of asphalt binder on dynamic modulus

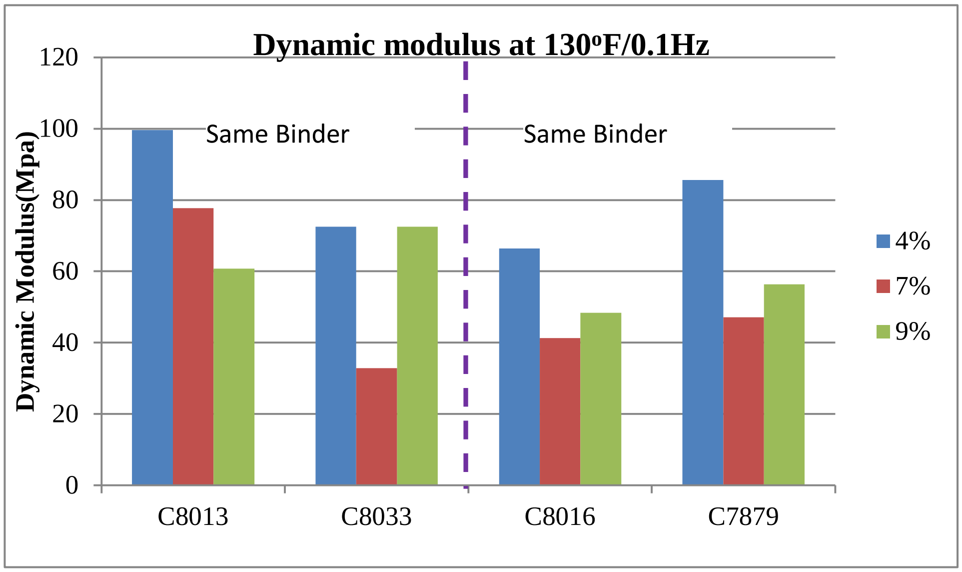
4.4 EFFECT OF AGGREGATE GRADATIONS ON DYNAMIC MODULUS

The majority of dense-graded asphalt mixture is made up of aggregate. As one of the key mix design components, the proper design of aggregate gradation has an influence on the resulting asphalt mixture performance. In this study, the effects of aggregate gradation on the dynamic modulus at both high and low E* levels are evaluated.

Figure 24 (a) shows the comparison of dynamic modulus at low E* level (high temperatures low frequencies) for four different asphalt mixtures types, and Figure 24 (b) shows the comparison of dynamic modulus at high E* level (low temperatures higher frequencies) for four different asphalt mixtures types. Contracts C 8013 and C8033 share the same asphalt binder, and contracts C8016 and C7879 share the same asphalt binder. The result shows that aggregate properties have an effect on dynamic modulus but the trend is not clear.



(a)

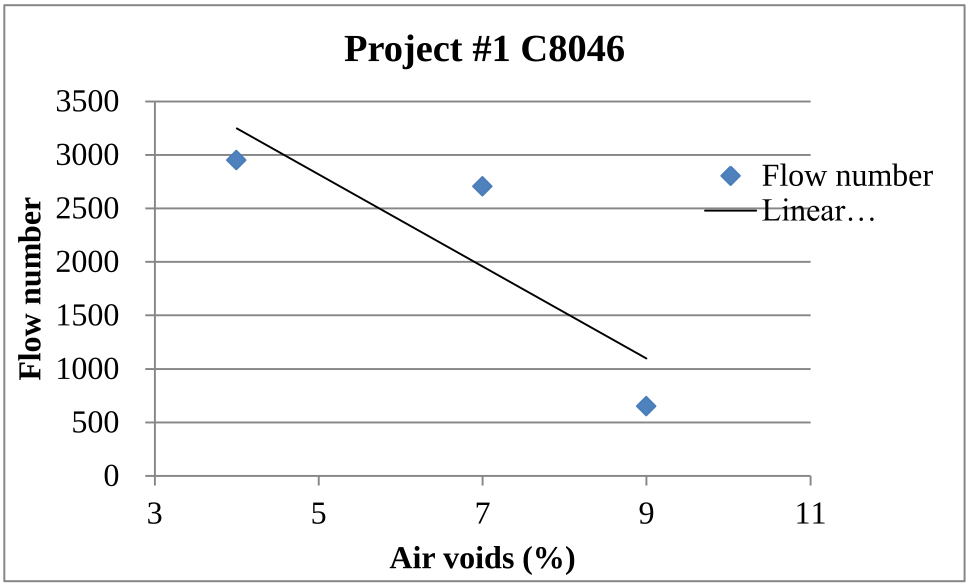


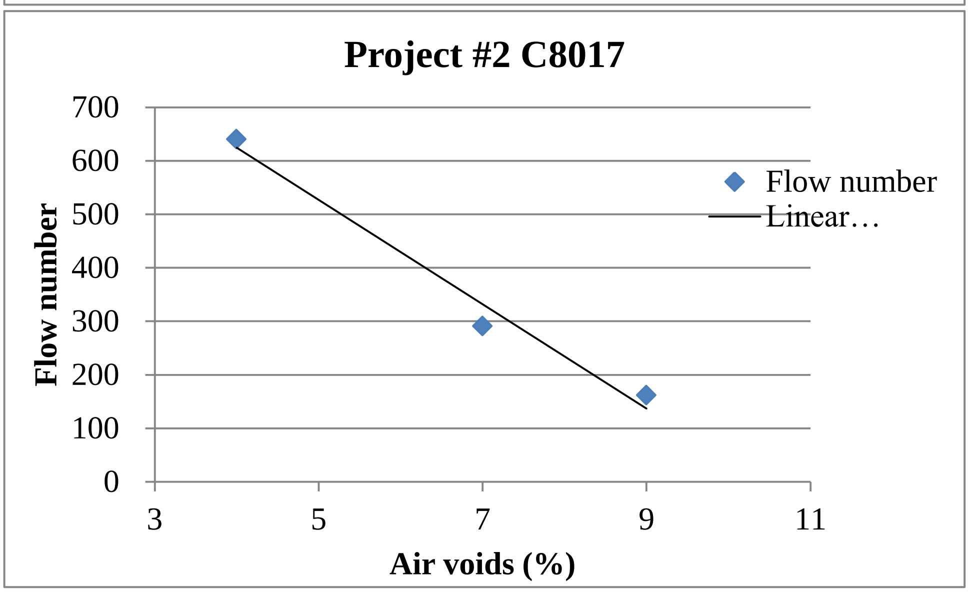
(b)

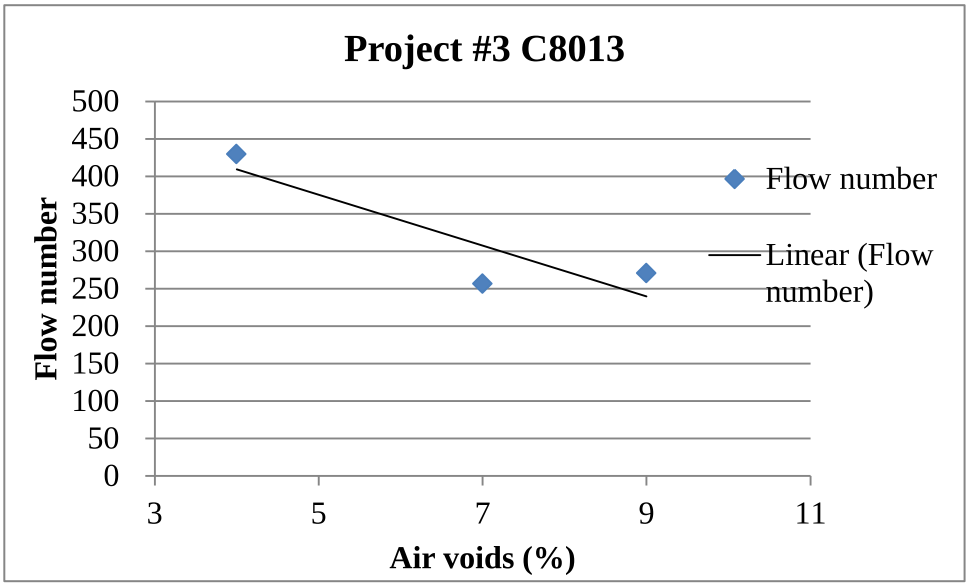
Figure 24. Effect of aggregate gradation on dynamic modulus

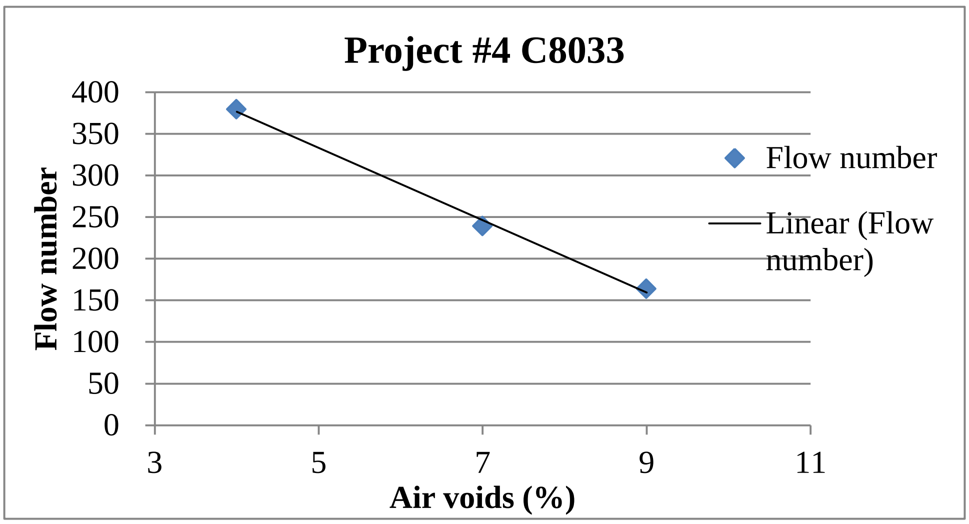
4.5 Flow Number Tests

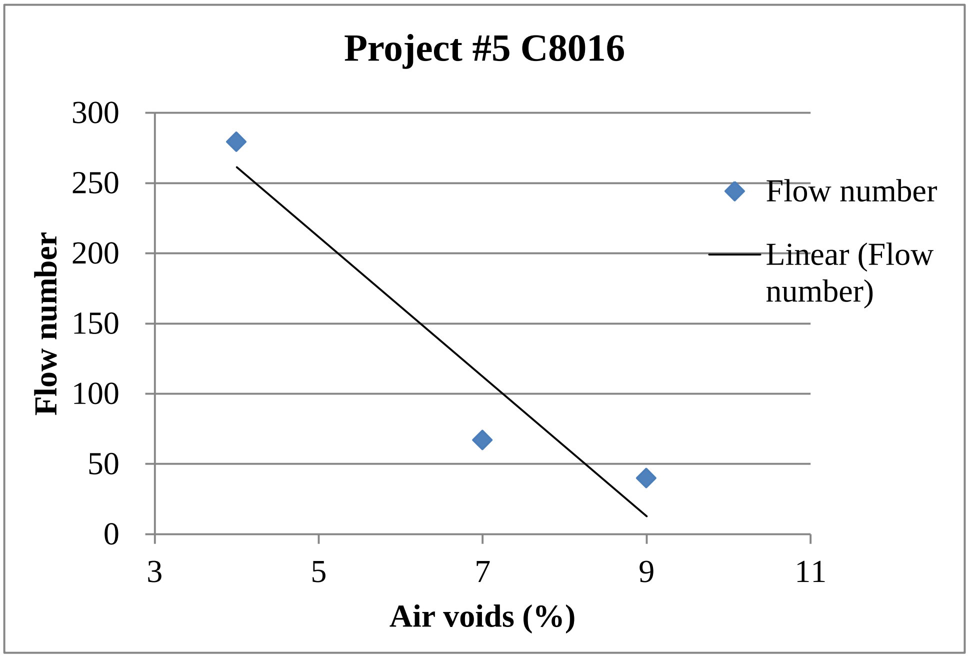
The relation between the air voids and flow number are shown in Figure 25. As indicated from the experimental results, the flow number decreases with the increase of air voids. Complete summary results of the average flow numbers for each mix at each air void levels are shown in Appendix E.

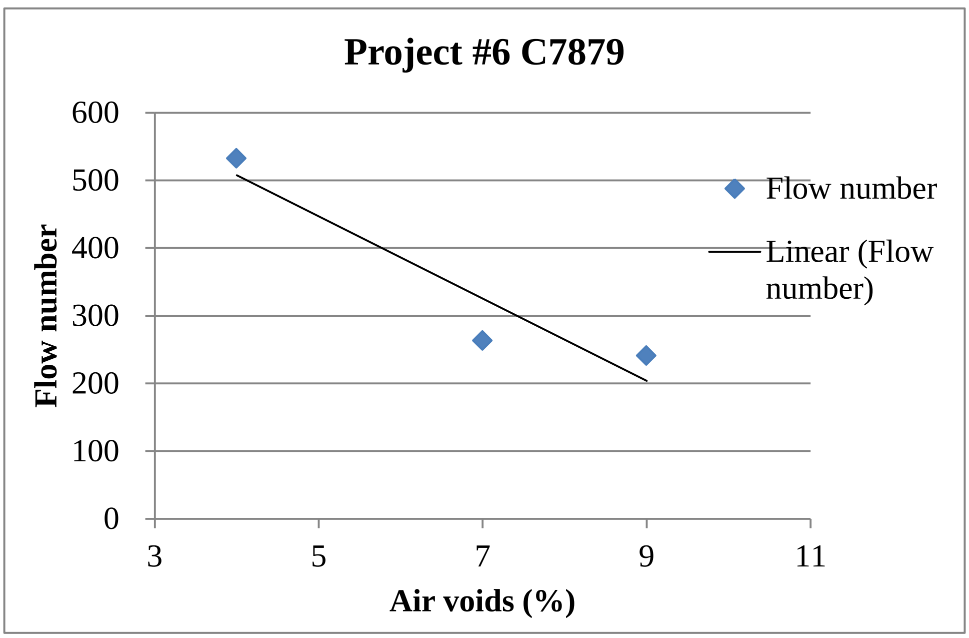

Project #1 C8046
3500
3000
2500
2000
1500
1000
500
0
3
5
7
9
11
Flow number
Air voids (%)
Flow number
Linear…

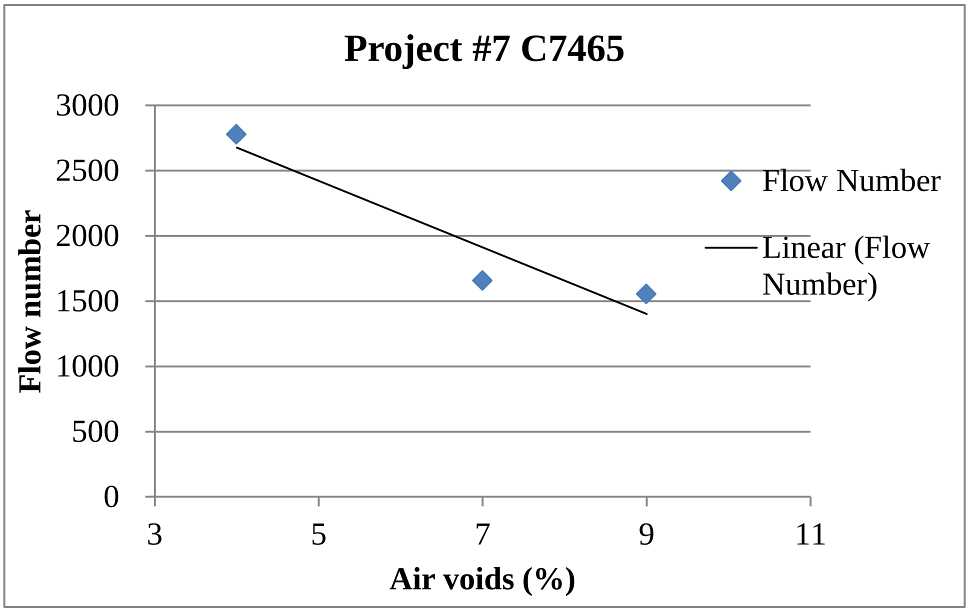

Project #2 C8017
700
600
500
400
300
200
100
0
3
5
7
9
11
Flow number
Air voids (%)
Flow number
Linear…


Project #3 C8013
Flow number
Air voids (%)
500
450
400
350
300
250
200
150
100
50
0
3
5
7
9
11
Flow number
Linear (Flow number)


Project #4 C8033
Flow number
Air voids (%)
400
350
300
250
200
150
100
50
0
3
5
7
9
11
Flow number
Linear (Flow number)


Project #5 C8016
300
250
200
150
100
50
0
Flow number
3
5
7
9
11
Air voids (%)
Flow number
Linear (Flow number)


Project #6 C7879
600
500
400
300
200
100
0
Flow number
3
5
7
9
11
Air voids (%)
Flow number
Linear (Flow number)



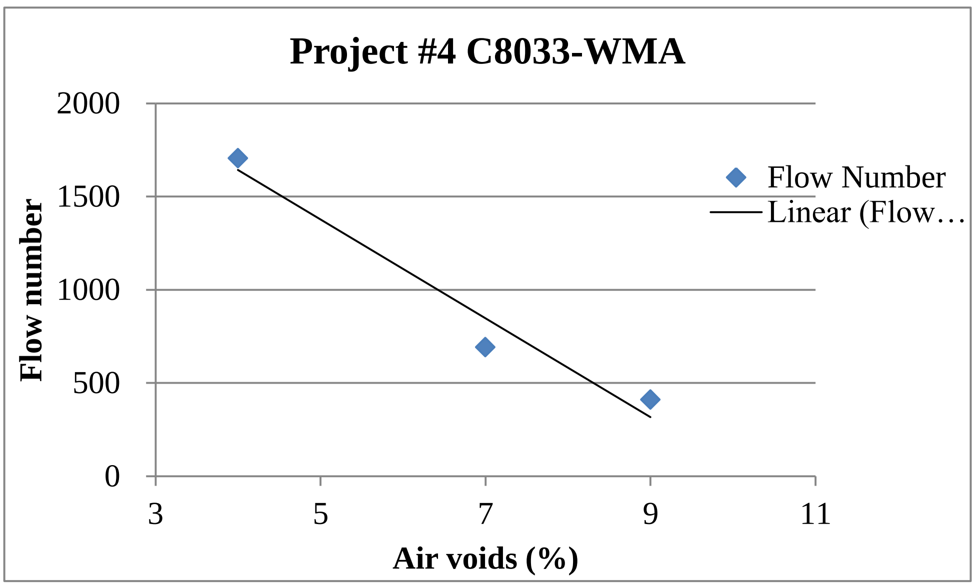


Figure 25. Flow number vs. air voids

4.6 Effect of Asphalt Binder on Flow Numbers

The effects of asphalt binder properties on the flow numbers were evaluated in this study. Figure 26 shows a comparison of the average flow numbers for mixtures with the same binder type. The results show that the PG binder has a direct influence on the flow numbers. Higher flow number values are obtained with high PG grade binder mixes. This finding agrees with the dynamic modulus test results that PG grade at high temperature have a directly influence on the rutting potential of asphalt mixture.

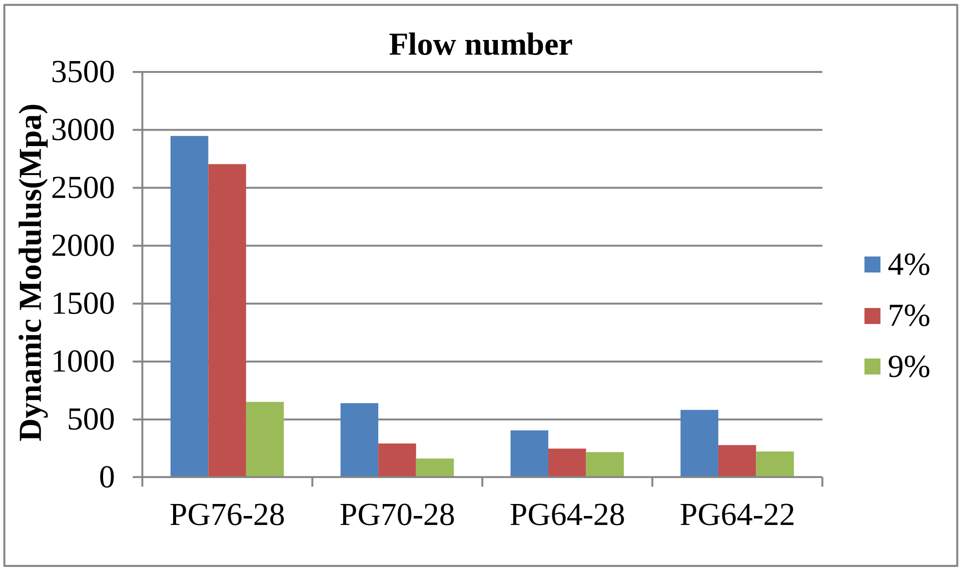


Figure 26. Effect of asphalt binder on flow number

4.7 Effect of Aggregate Gradations on Dynamic Modulus

The effect of aggregate properties on flow numbers was evaluated. Figure 27 shows the comparison of flow number for four different asphalt mixture types, Contracts C8013 and C8033 share the same asphalt binder type, and contracts C8016 and C7879 share the same asphalt binder type. It is observed that even though C8016 and C7879 share the same binder, the flow number varied a lot. Such difference could be attributed to the influence of aggregate gradation on the flow number. It is considered that at high temperatures, the asphalt binder is softer and less influential with respect to the load bearing capacity; instead, aggregate skeleton plays a more important role.

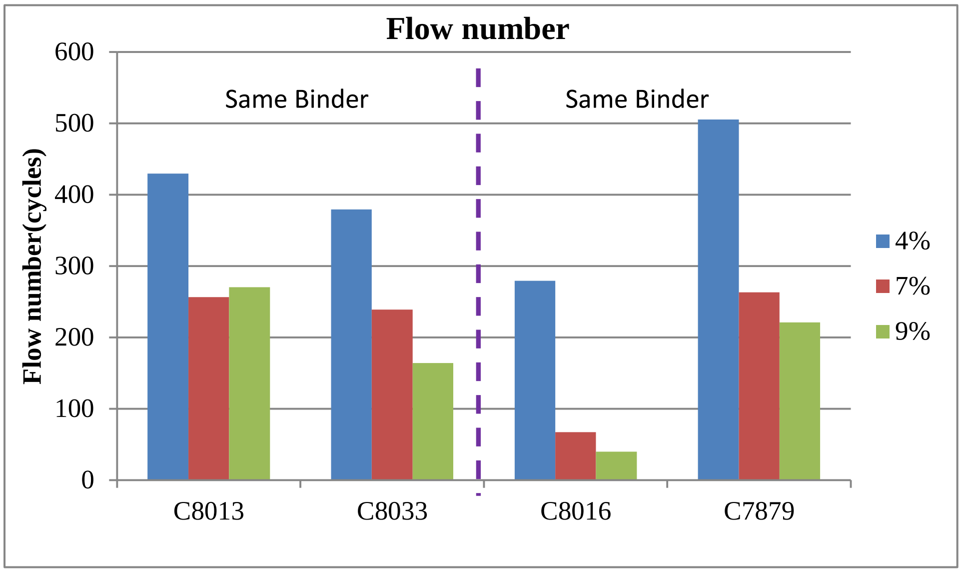


Figure 27. Effect of aggregate gradation on flow number

4.8 SUMMARY

This chapter summarized the experimental results of dynamic modulus tests and flow number tests for seven field projects. The influence of air voids, binder type, and aggregate gradation on dynamic modulus and flow number is shown. It is found that air voids have an important effect on E* and flow number. In general, higher air voids will result in lower E* and flow numbers. High PG grade has clear influence on E* and flow number; higher PG grade leads to higher E* and flow number. Aggregate gradation has some impact on E* and flow number but the trend of impact is not clear.

CHAPTER 5 DYNAMIC MODULUS AND FLOW NUMBER PREDICTION MODELS

Over the time, there have been significant efforts to establish prediction models of mechanical properties of asphalt mixture. Several models have been developed over the past decades to predict the dynamic modulus (E*) of HMA based on multivariate regression analysis of laboratory measurements. Among those models, the most widely used are the Witczak 1996 and 2006 predictive models and the Hirsch model. Besides, some researchers have proposed different prediction models of flow numbers to characterize the rutting potential of asphalt mixture. This chapter evaluated the accuracy of those models for predicting the dynamic modulus of Washington State asphalt mixtures. Based on the evaluation results, a revised Hirsch model for dynamic modulus prediction is established which significantly improved the predication quality and is recommended be used by the State of Washington for dynamic modulus prediction. In addition, a locally calibrated flow number prediction model for Washington State is provided.

5.1 EVALUATION OF EXISTING PREDICTION MODELS

As illustrated in Chapter 2 Literature Review, the most widely used dynamic modulus prediction models are the Witczak 1996 and 2006 predictive models and the Hirsch model. Although all provided reasonable accuracy as globally calibrated models, they were also reported by researchers not being able to capture the dynamic modulus behaviors for some local materials especially in high and low temperature extremes (Witczak 2002). In addition, these models were found to tend to overemphasize the influence of temperature and understate the influence of other factors or components (Ceylan et al. 2009). Therefore, it is necessary to modify existing prediction models or develop new models based on local field mixtures.

5.1.1 Prediction of dynamic modulus based on 1996 Witczak Model

The input variables for the Witczak 1996 E* predictive model include aggregate gradation, mixture volumetric properties, viscosity of the asphalt binder, and loading frequency *f*. The aggregate gradation variables are the percent passing the #200 sieve, percent retained on the #4, percent retained on the 9.5 mm sieve, and percent retained on the 19 mm sieve. The mixture volumetric properties are the air void percentage (Va) and effective binder percentage by volume (Vbeff). The aggregate and volumetric properties were determined from experiments following AASHTO specifications. The asphalt binder was short-term aged using the rolling thin film oven method and its dynamic shear modulus (G*) was measured using dynamic shear rheometer (DSR) following AASHTO T-240. A complete result of the dynamic shear modulus (G*) of asphaltic materials, including both binder and asphalt mastics, are shown in Appendix F.

Figure 28 presented a comparison between the measured and the predicted E* values. As shown, the Witczak model under predicts the dynamic modulus at lower temperature and over predicts the dynamic modulus at higher temperature. The total prediction results did not followed well with the line of equality indicating that those results cannot reasonably represent the dynamic modulus properties of Washington mix.

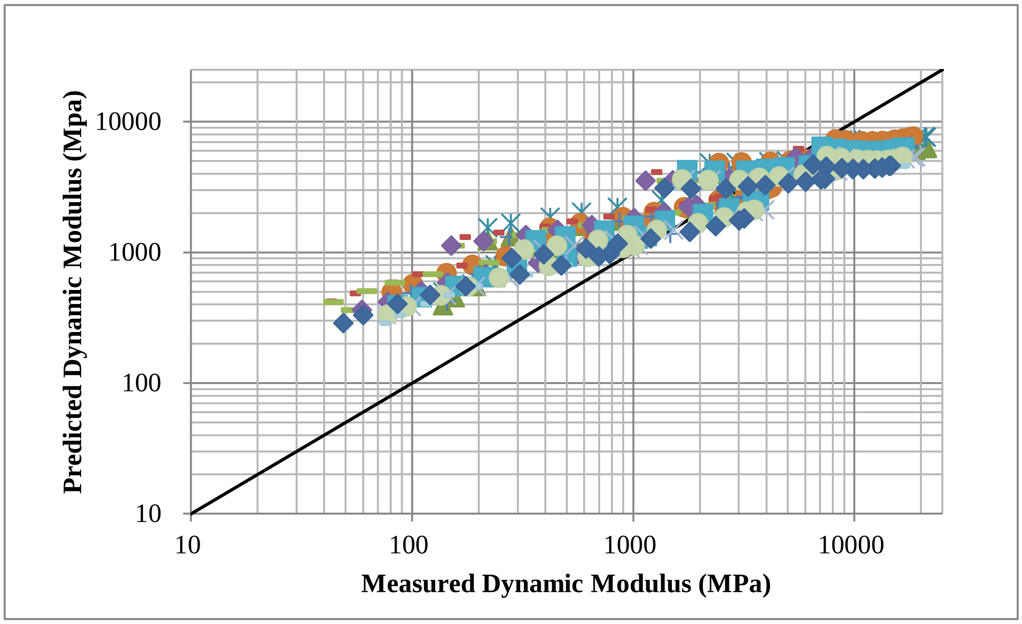


Figure 28. Dynamic modulus results based on 1996 Witczak model

5.1.2 Prediction of dynamic modulus based on New Witczak Model

This new Witczak Model was developed using a database (Bari 2005) of 7,400 measured E* values obtained from 346 different HMA mixes. This expanded database also included the data used to develop the earlier 1996 version of the model. In addition to the expanded database, the Witczak 2006 model replaced the binder's viscosity (η) and loading frequency (f) with dynamic shear modulus (G*) and phase angle (δ).

Figure 29 presented a comparison between the measured and the predicted E* values. As shown, the New Witczak model has a better prediction of dynamic modulus at higher (54.4^{o}C) and lower temperature (4.4^{o}C) compared to the 1996 Witczak model. However, it under predicts the dynamic modulus at medium temperatures (21.1^{o}C and 37.8^{o}C). Overall, the prediction results did not followed well with the line of equality, which means the New Witczak model is not a good prediction model for Washington mixes.

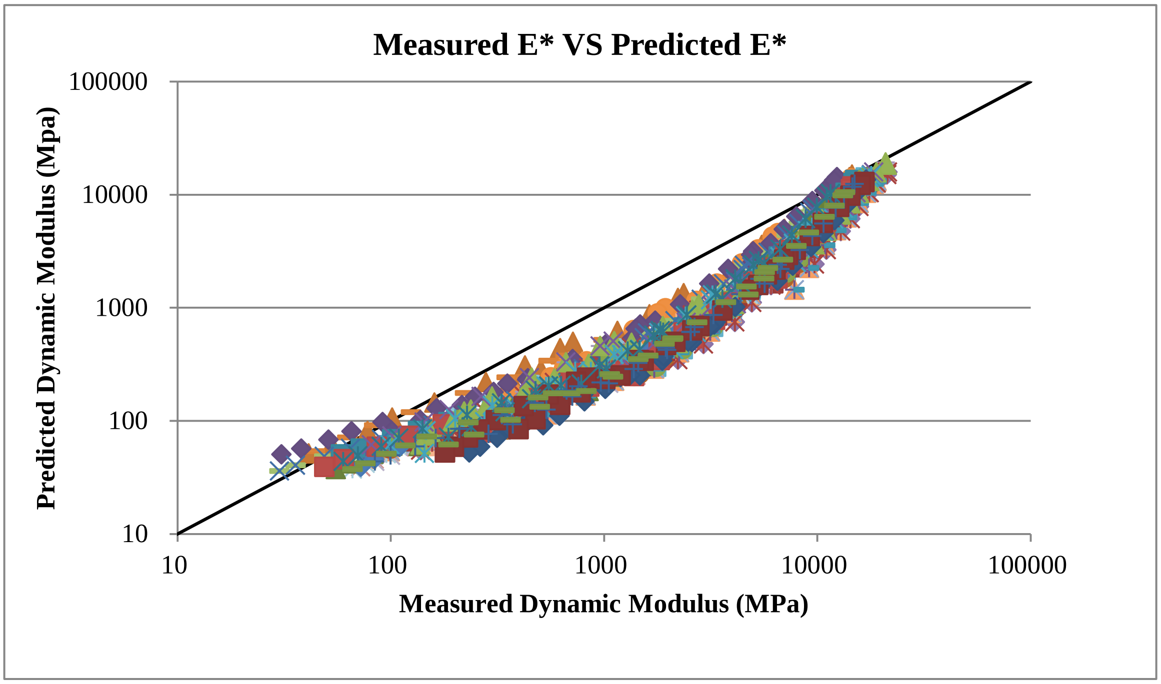


Figure 29. Laboratory measured E* and New Witczak model predicted E*

5.1.3 Prediction of dynamic modulus based on Hirsch Model

The Hirsch model for HMA dynamic modulus was developed based on data regression of 206 data points, indicated in Equation 35.

$$|E^*|_{mix} = Pc\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_b\left(\frac{VFA\times VMA}{10{,}000}\right)\right]+ (1-Pc)\left[\frac{1-(VMA/100)}{4{,}200{,}000}+\frac{VMA}{3VFA|G^*|_b}\right]^{-1} \quad (35)$$

Where;

$$Pc=\frac{\left(20+\dfrac{VFA\times 3|G^*|_b}{VMA}\right)^{0.58}}{650+\left(\dfrac{VFA\times 3|G^*|_b}{VMA}\right)^{0.58}} \quad (36)$$

The measured dynamic modulus for all samples was compared with the predicted dynamic modulus based on the original Hirsch model. In Hirsch model, the aggregate and volumetric properties were determined from experiments following AASHTO specifications. The asphalt binder was short-term aged using the rolling thin film oven method and its dynamic shear modulus (G*) was measured using dynamic shear rheometer (DSR) following AASHTO T-240. Figure 30 shows a comparison between the measured and the predicted E* values. As shown, the prediction of Hirsch model is better than the prediction of Witczak model. The total prediction of Hirsch model at mid-range and low temperature follows the line of equality well. However, the prediction at higher temperature and low frequency is not good, which may affect the capability of capturing the rutting resistance of the mix. A modified Hirsch model calibrated by local materials is thus needed.

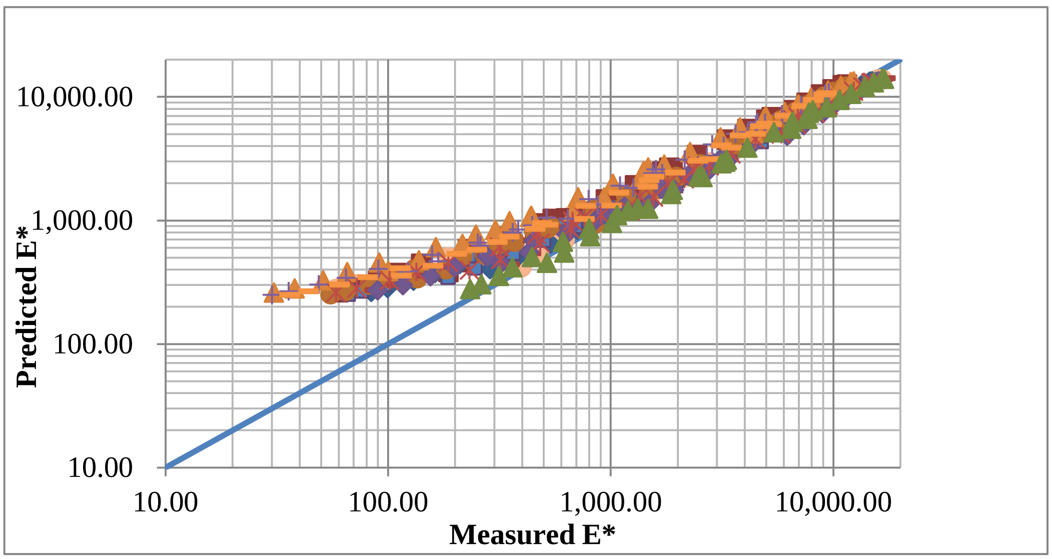


Figure 30. Laboratory measured E* and original Hirsch model predicted E*

5.1.4 Summary of previous prediction models

After reviewing all available models, the Hirsch model was selected in this study for several reasons listed below. It will be further modified based on local materials to achieve a better prediction.

(1) Unlike the Witczak models which are based on regression equations, the Hirsch model is based on the theory of composite materials.

(2) Unlike the Witczak models which consider the effect of aggregates for four individual sieve sizes, the Hirsch model considers the overall effect of aggregate gradations by relating the volumetric properties with the dynamic modulus.

(3) Compared with the Witczak models, the Hirsch model is simpler consisting of less parameter. This is particularly important for the purpose of obtaining a prediction model that can be used for estimating the dynamic modulus of asphalt mixtures at the early stage of the mix design with minimum requirement for the experimental testing.

(4) The initial evaluation of the experimental results for the Washington mixes tested in this study indicated that Hirsch model provided better prediction compared with the Witczak models.

5.2 MODIFICATION OF HIRSCH MODEL

5.2.1 **Theoretical background of Hirsch model**

Hirsch model (Christensen et al. 2003) considers that the composite material consists of different phases in series and/or in parallel arrangements. The asphalt material behaves as a serial arrangement composite at higher temperatures and as a parallel arrangement composite at lower temperatures. In addition, Hirsch model describes the visco-elastic asphalt material as time and temperature dependent material, and the aggregate contact proportion parameter Pc had a critical influence on the total behavior of the HMA. It was found that the HMA can be simulated with satisfactory accuracy with a simplified Hirsch model for which the general arrangements are in parallel rather than in series. The HMA was treated as a three-phase system which composed of aggregate, asphalt, and air voids. Based on such considerations, Equation 33 was proposed by Christensen et al. (2003) for regression process.

$$E_C = Pc \cdot (V_a \cdot E_a + V_b \cdot E_b) + (1 - Pc) \cdot \left[\frac{V_a}{E_a} + \frac{(V_b + V_v)}{V_b \cdot E_b} \right]^{-1} \tag{33}$$

Where

Va: true aggregate volume including volume of mineral filler,

V_b: effective binder volume,

E_a: aggregate response (for example modulus),

E_b: binder response (for example modulus),

V_v: air voids volume,

Pc: contact volume that represents the proportion of parallel to total phase volume and could be computed using the following expression:

$$Pc = \frac{\left(P_0 + \frac{VFA \cdot E_b}{VMA} \right)^{P_1}}{P_2 + \left(\frac{VFA \cdot E_b}{VMA} \right)^{P_1}} \tag{34}$$

Where

P_0, P_1, P_2: empirically determined constants,

VMA: voids in the mineral aggregate (voids + binder volume + mineral filler volume),

VFA: the percent of the VMA that is filled with the binder.

5.2.2 Modified Hirsch model based on local calibration for virgin binder

The original Hirsh model was calibrated in this study using the dynamic modulus testing results from 42 samples 7 asphalt mixtures at three different air voids) by minimizing square errors, and the modified Hirsch model was provided in Equation 35. Those equations are obtained from four different asphalt binder types.

$$|E^*| = Pc\left[4800000\left(1 - \frac{VMA}{100}\right) + 3|G_b^*|\left(\frac{VFA \cdot VMA}{10,000}\right)\right] + (1 - Pc)\left[\frac{1 - \frac{VMA}{100}}{4800000} + \frac{VMA}{VFA \cdot 3|G_b^*|}\right]^{-1} \tag{35}$$

Where,

$$Pc = \frac{\left(0.2 + \frac{VFA \cdot 3\left|G_b^*\right|}{VMA}\right)^{0.56}}{600 + \left(\frac{VFA \cdot 3\left|G_b^*\right|}{VMA}\right)^{0.56}} \tag{36}$$

Figure 31 compares the measured dynamic modulus with the predicted dynamic modulus based on the modified Hirsch model. It is clear that the prediction quality is improved and the prediction trend for high temperature is better than the original Hirsch model. However, results still shows that the revised Hirsch model over predicts the dynamic modulus at higher temperatures.

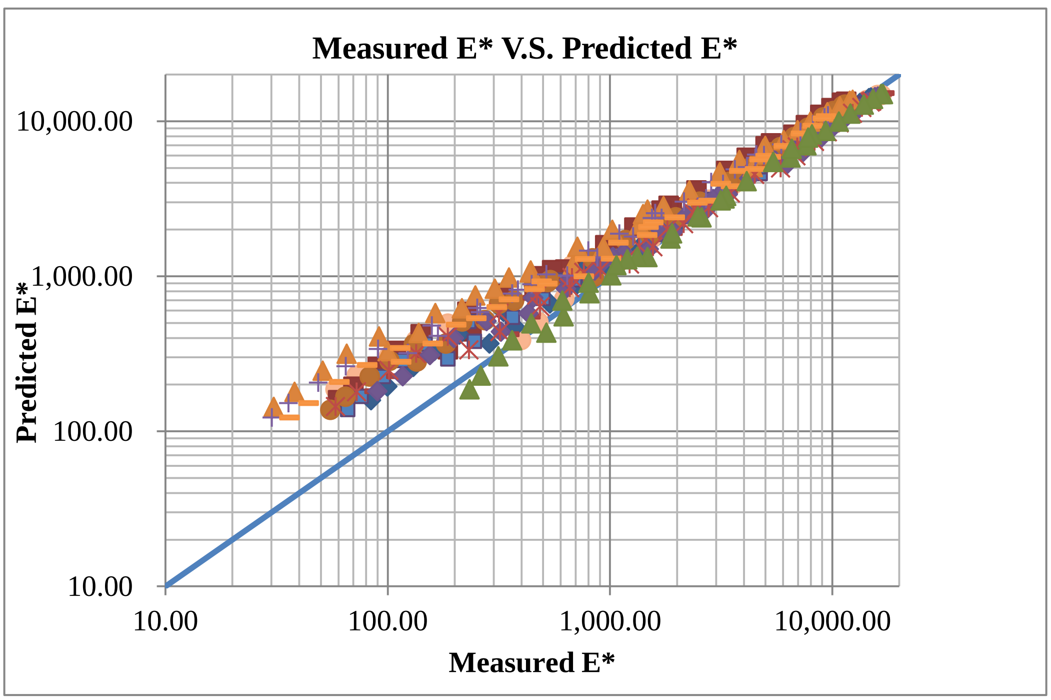


Figure 31. Measured E* and predicted E* based on modified Hirsch model

5.2.3 Modified Hirsch model based on local calibration for asphalt mastic

The addition of mineral fillers to asphalt binder as very fine materials improves the stiffness of the binder; this combination produces the asphalt mastic. Asphalt mastics play an important role in the compaction and performance of bituminous mixtures, and its influence should be taken into account as a combined material component rather than being treated separately as current predictive models did. Therefore, the shear complex modulus of mastics will be used in the Hirsch model to replace the binder's shear modulus term. The modified Hirsch model based on asphalt mastic is shown in Equation 37.

$$|E^*| = Pc\left[1.0E7\left(1-\frac{VMA}{100}\right)+3|G_b^*|\left(\frac{VFA\cdot VMA}{10,000}\right)\right] + (1-Pc)\left[\frac{1-\frac{VMA}{100}}{1E7}+\frac{VMA}{VFA\cdot 3|G_b^*|}\right]^{-1} \quad (37)$$

Where,

$$Pc = \frac{\left(20+\frac{VFA\cdot 3|G_b^*|}{VMA}\right)^{0.7}}{16,000+\left(\frac{VFA\cdot 3|G_b^*|}{VMA}\right)^{0.7}} \quad (38)$$

Where,

$|G_b^*|$ = mastic dynamic modulus, psi

Everything else is the same as Equation 4.

Figure 32 compares the measured dynamic modulus with the predicted dynamic modulus based on the modified Hirsch model with asphalt mastic. It is clear that the prediction quality is significantly improved and most of the data followed the line of equality very well. The prediction trend is good for a wide range of temperatures and frequencies. Although only based on limited data (limited gradation type and binder type for Washington mixes), this model is very promising as it changed the inherent prediction trend of the original Hirsch model (Figure 30) and improved the prediction especially at the high temperature of the dynamic modulus curves.

The modified Hirsch model provides a means to estimate the dynamic modulus based on only volumetric properties (VMA, VFA) and asphalt mastic dynamic shear modulus. It can be used for a quick check of the material properties at the early stage of the mix design.

When WSDOT is officially moving toward MEPDG design, this model can serve as the level 1 and level 2 material property prediction equations for state mixtures.

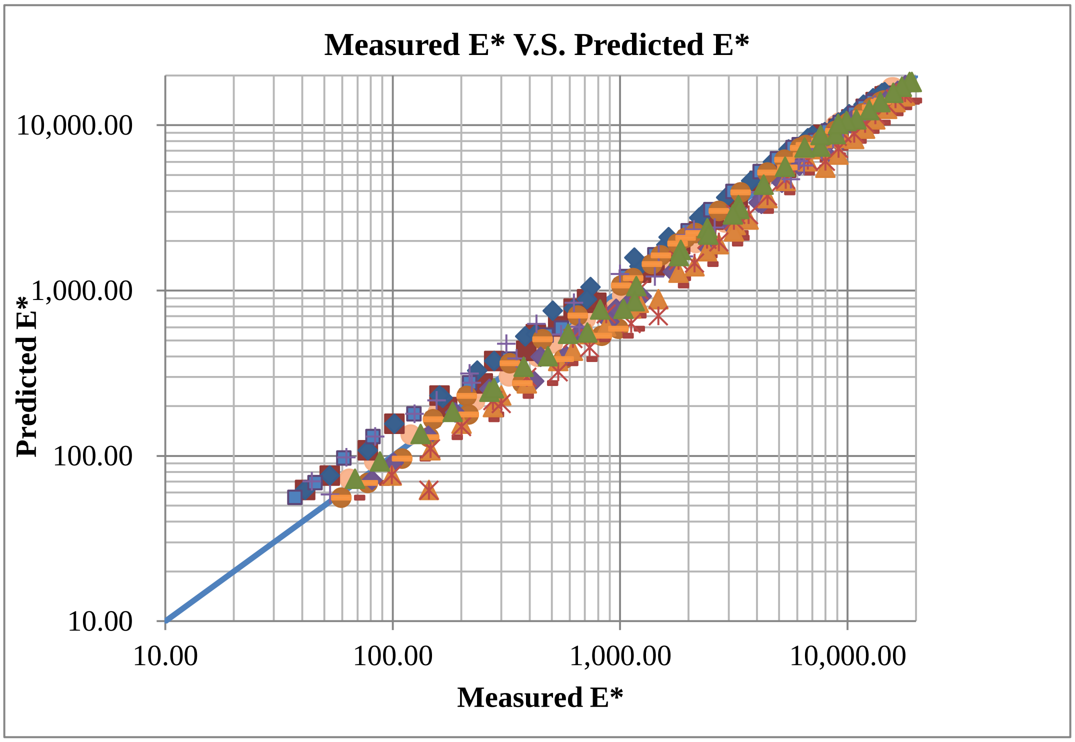


Figure 32. Measured E* and predicted E* based on modified Hirsch model of mastic

5.3 FLOW NUMBER PREDICTION MODELS

5.3.1 **Local calibration of flow number prediction model**

The previous effects on the prediction of mechanical properties of asphalt mixture have been put on the dynamic modulus, and there is no widely applied flow number prediction model available at this moment. A model capable of predicting or providing general guidance on the Flow Number characteristics of Washington State mix can be of great value. In this study, an effort was undertaken to develop a Flow Number predictive model for Washington State. The flow number prediction model was calibrated according to Kaloush (2001) flow number prediction model which was developed based on mixtures volumetric properties, binder type, and test temperature. The final calibrated model had fair statistical measures of accuracy and it covers the whole testing temperatures and frequencies. As more testing data become available, the model could be refined and re-calibrated for better accuracy.

The original Kaloush (2001) model used 135 unconfined laboratory FN tests and was presented as follows:

$$FN = (432367000)T^{-2.215}Visc^{0.312}V_{beff}^{-2.6604}V_a^{-0.1525} \tag{39}$$

Where,

FN = Flow Number

T = Test Temperature, °F

Visc = Binder Viscosity at 70°F, 106 poise

Vbeff = Effective Asphalt Content, % volume

Va = Air Voids, %

The local calibrated model is shown in equation (40),

$$FN = 2.865E10 \cdot T^{-2.83354}G^{0.462887}V_{beff}^{-4.98023}V_a^{-1.25751} \tag{40}$$

Where,

FN = Flow Number

T = Test Temperature, °F

G = Shear complex modulus of asphalt mastic, psi.

Vbeff = Effective Asphalt Content, % volume

Va = Air Voids, %

The comparison of prediction and measured results are shown in Figure 33.

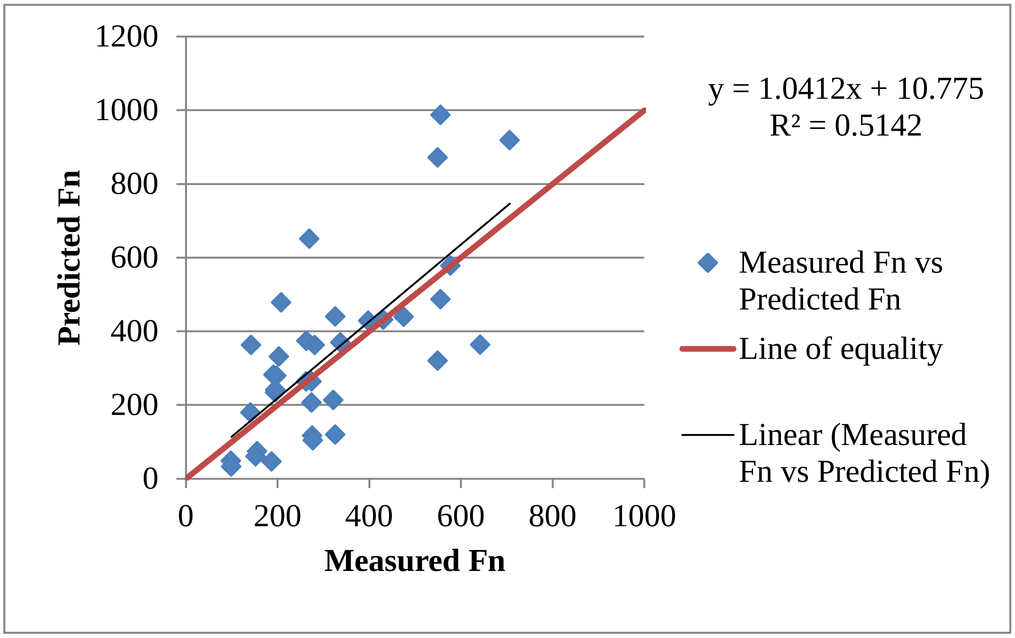


Figure 33. Measured E* and predicted E* based on modified Hirsch model of mastic

The data used for regression included mixtures from projects 2 to 7. The asphalt binders included PG 70-28, PG 64-28 and PG 64-22. Project 1 (C8046) used polymer modified asphalt binder, PG76-28, and produced significantly high flow number results. It is suggested that the presented flow number prediction model only be used for mixtures with conventional binders which have no high polymer modification involved.

5.3.2 Sensitivity analysis of flow number prediction model

Air voids is one of the most important control parameters for asphalt mixture design and field construction, which is also one of the parameters in the prediction model for determining the flow number of asphalt mixtures, this section studied the sensitivity of air voids on the flow numbers. Air voids levels from 3% to 7% are evaluated as shown in Figure 34, it can been seem that with the increase of air voids level, the flow number is decreasing which in consistent with the experimental results.

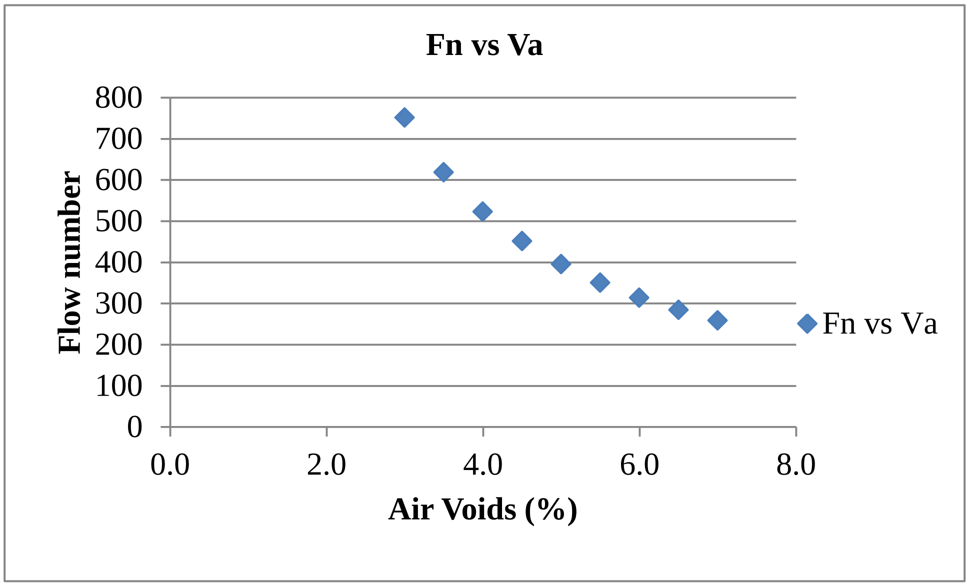


Figure 34. Measured E* and predicted E* based on modified Hirsch model of mastic

5.4 SUMMARY

This chapter compared the Hirsch model, 1996 Witczak model and New Witczak model using the dynamic modulus testing results conducted in this study. Based on the comparison results, the Hirsch model was selected as the basic model for further modification. A modified Hirsch model, based on the properties of asphalt mastic, was presented. It can reasonably predict the dynamic modulus properties of asphalt mixture in Washington State, considering a wide ranges of temperature, binder type, aggregate gradations, etc. The revised Hirsch can be used as both a designing tool and a screening tool to estimate the mixture's dynamic modulus at the early stage of the mix design.

A flow number prediction model was also developed based on experimental data on local mixes. The prediction model took into account the effects of volumetric properties, binder type, and test temperatures. The prediction results were reasonable for mixtures with conventional PG binder (PG 70-28, PG 64-28 and PG 64-22). It was however not recommended for highly polymer modified PG binder (i.e., PG76-28).

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY FINDINGS

This study measured the dynamic modulus and flow number of typical asphalt mixtures used in 2011 paving projects of Washington State. A material database including all material volumetric properties, dynamic modulus properties, and the flow number properties of the seven plant produced mixes were summarized and documented in this report. The effects of air voids, asphalt binder and aggregate gradation on the dynamic modulus and flow numbers were studied. Based on experimental results, both modified Hirsch model and a modified flow number prediction model were recommended for future usage of the conventional dense graded asphalt mixtures for Washington State. Other specific findings of the study included:

1. Air voids have significant impact on both dynamic modulus and flow numbers. The higher air voids, the lower dynamic modulus and flow number will be. The impact of air voids on dynamic modulus is more clear at high E* levels (low temperature and high frequency).
2. Binder properties, especially the high PG grade, has a significant influence on the dynamic modulus at low E* levels (high temperature and low frequency) and flow numbers.
3. Aggregate gradation has some impact on dynamic modulus and flow number of asphalt mixtures. However, the trend of gradation impact is not clear.
4. The properties of asphalt mastic have significant impact on the dynamic modulus of asphalt mixtures. If introducing such property into the modified Hirsch model, the prediction results of E* are greatly improved. Based on this finding, a modified Hirsch model is proposed for predicting the dynamic modulus of Washington mixes.

5. A flow number prediction model is locally calibrated for Washington State. It correlates the flow number with the volumetric properties, binder type, and test temperature of the mix. Reasonable prediction results have been achieved for conventional mixes (PG 70-28, PG 64-28 and PG 64-22 binder mixes). It however is not applicable for highly polymer modified mix such as PG76-28 mix.

6.2 RECOMMENDATIONS

This study tested seven plant produced asphalt mixtures typically used in the paving projects of Washington State. These results can be used as a basis of a material property database to help future pavement design and evaluation. More mixtures, including new types of mixes such as warm mix asphalt and mixtures with smaller nominal maximum sizes should be tested and added into the database. The field performance of these projects should be monitored to establish correlations between material properties and pavement performance, therefore, to calibrate the pavement performance models for Washington State. In addition, it is recommended that the proposed dynamic modulus prediction model and flow number prediction model be further validated and improved based on a larger database.

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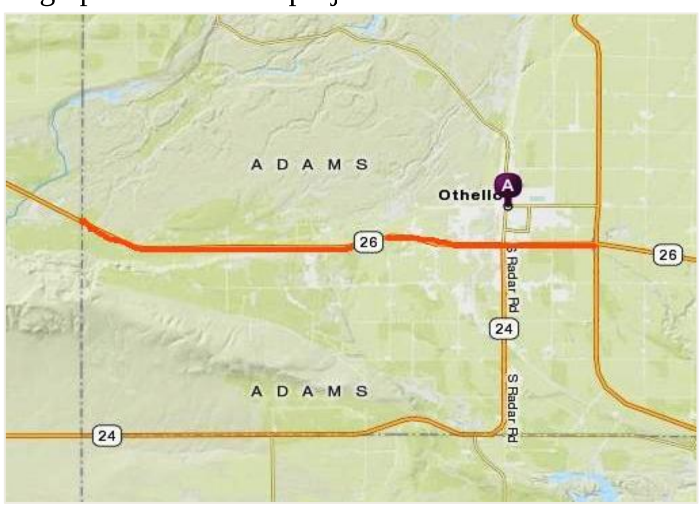
APPENDIX A: Geographic location of all projects

a): Geographic location of project #1 C8046 Ritzville to Tokio

b): Geographic location of project #2 C8017 Lee Rd to Vic I-90



c): Geographic location of project #3C8013 Grant County Line to SR 17

d): Geographic location of project #4 C8033 SR 124 Intersection

e): Geographic location of project #5 C8016 Joe Leary Slough to Nulle Rd. Vicinity

f): Geographic location of project #6 C7879 SR 510 - Yelm Loop (North Eastern)

g): Geographic location of project #7 C7465 Grand Mound to Maytown (North Eastern)

APPENDIX B: Mixture Design for all projects

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater WA 98512
BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL :	HMA Class 1/2"	WORK ORDER NO :	008046
DATE SAMPLED :	02/14/2011	SAMPLE ID :	00000109b37
DATE RECV'D :	03/07/2011	MIX ID NO :	MD110026
SR NO :	090	CONTRACTOR :	Poe Asphalt
SECTION :	Ritzville To Tokio - Paving of Outside Lanes Only		
PROJECT ENGINEER :	Hilmes, Bob	ORG CODE :	464310

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		4.9	5.4	5.9	
% Gmm @ Ninitial	8	83.3	85.9	87.5	≤ 89.0
% Va @ Ndesign	100	6.0	3.5	2.8	Approximate 3.5
% VMA @ Ndesign	100	17.4	16.3	16.7	≥ 14.0
% VFA @ Ndesign	100	66	78	83	68 - 80
% Gmm @ Nmax	160		97.1		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.4	1.2	1.2	0.6 - 1.6
Pbe		4.6	5.0	5.6	
Gmm		2.665	2.647	2.629	
Gmb		2.505	2.552	2.555	
Gb		1.033	1.033	1.033	
Gse		2.899	2.904	2.909	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		4.9	5.4	5.9		
% Gmm @ Ninitial	8	85.3	87.0	87.9	≤ 89.0	
% Va @ Ndesign	100	5.2	3.5	2.1	Approximate 3.5	
% VMA @ Ndesign	100	16.1	15.7	15.9	≥ 14.0	
% VFA @ Ndesign	100	68	78	87	68 - 80	
% Gmm @ Nmax	160		97.4		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.4	1.3	1.1	0.6 - 1.6	
Pbe		4.5	4.9	5.5		
Gmm		2.682	2.661	2.632		
Gmb		2.544	2.569	2.579		
Gb		1.033	1.033	1.033		
Gse		2.923	2.924	2.915		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.25%	0.50%	0.75%	1.0%
Visual Appearance :	NONE	NONE	NONE	NONE	NONE
% Retained Strength :	93	106	98	94	93

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**IDAHO ASPHALT**	
Asphalt Binder Grade	PG76-28	
Percent Binder (Pb) (By Wt. Total Mix)	5.4	
% Anti-Strip (By Wt. of Asphalt Binder)	0.25	
Type of Anti-Strip	SUPERBOND	
Mix ID Number	MD110026	
Sample Wt. (grams)	5050	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.38	(Informational Only)
Optimum Mixing Temperature (°F)	332	
Compaction Temperature (°F)	302	
Rice Density (lbs/ft³)	165.7	

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2" WORK ORDER NO : 008046
SAMPLE ID : 00000109b37 MIX ID NO : MD110026

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	5/8"-3/8"	7/16"-1/4"	1/4"-0	Combined	Specification	Tolerance
Source:	AD23	AD-23	AD-23			
Ratio:	21%	17%	62%			
3/4 in	100.0	100.0	100.0	100	100	99 - 100
1/2 in	80.0	100.0	100.0	96	90 - 100	90 - 100
3/8 in	17.0	90.0	100.0	81	90 Max	75 - 87
No. 4	1.0	3.0	84.0	53		48 - 58
No. 8	1.0	1.0	49.0	31	28 - 58	28 - 35
No. 16	1.0	1.0	31.0	20		
No. 30	1.0	1.0	22.0	14		
No. 50	1.0	1.0	17.0	11		
No. 100	1.0	1.0	13.0	8		
No. 200	0.5	0.5	9.9	6.3	2.0 - 7.0	4.3 - 7.0

Gsb Coarse	2.904	2.899			
Gsb Fine			2.878		
Gsb Blend	2.904	2.899	2.878	2.887	
Sand Equivalent (SE)			87	87	45 Min
% Uncompacted Voids			50	50	44 Min
% Fracture	100	100	100	100	90 Min Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.914	2.887	2.876		
Gsb Fine			2.872	2.872	
Gsb Blend	2.914	2.887	2.873	**2.884**	
Sand Equivalent (SE)			90	90	45 Min
% Uncompacted Voids				49	44 Min
% Fracture	99	100	100	100	90 Min Double Face Fracture

COMMENTS

Remarks:

Result Code:

Billing Code
T177 - 1
T185 - 16
T194 - 1

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 3/31/2011
Phone : (360) 709-5421

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater WA 98512
BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL :	HMA Class 1/2"	WORK ORDER NO :	008017
DATE SAMPLED :	03/03/2011	SAMPLE ID :	00000109bc6
DATE RECV'D :	03/07/2011	MIX ID NO :	MD110025
SR NO :	395	CONTRACTOR :	C.W.A.
SECTION :	US 395/LEE RD TO VIC JCT I-90 PAVING		
PROJECT ENGINEER :	Simonson, Chad	ORG CODE :	464307

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		5.2	5.7	6.2	
% Gmm @ Ninitial	8	84.0	86.0	87.0	≤ 89.0
% Va @ Ndesign	100	5.7	3.3	1.8	Approximate 3.5
% VMA @ Ndesign	100	14.8	14.2	14.2	≥ 14.0
% VFA @ Ndesign	100	61	77	87	68 - 80
% Gmm @ Nmax	160		98.0		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.6	1.4	1.2	0.6 - 1.6
Pbe		3.9	4.6	5.2	
Gmm		2.578	2.545	2.519	
Gmb		2.431	2.461	2.474	
Gb		1.032	1.032	1.032	
Gse		2.809	2.793	2.784	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		5.2	5.7	6.2		
% Gmm @ Ninitial	8	85.7	87.0	88.0	≤ 89.0	
% Va @ Ndesign	100	4.1	2.3	1.3	Approximate 3.5	
% VMA @ Ndesign	100	13.7	13.4	13.5	≥ 14.0	
% VFA @ Ndesign	100	71	83	91	68 - 80	
% Gmm @ Nmax	160		97.8		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.6	1.4	1.3	0.6 - 1.6	
Pbe		4.0	4.6	5.0		
Gmm		2.569	2.547	2.529		
Gmb		2.464	2.489	2.498		
Gb		1.032	1.032	1.032		
Gse		2.797	2.795	2.797		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.25%	0.50%	0.75%	1.0%
Visual Appearance :	NONE	NONE	NONE	NONE	NONE
% Retained Strength :	97	100	118	95	100

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**WSA**	
Asphalt Binder Grade	PG70-28	
Percent Binder (Pb) (By Wt. Total Mix)	5.7	
% Anti-Strip (By Wt. of Asphalt Binder)	0.50	
Type of Anti-Strip	POLARBOND	
Mix ID Number	MD110025	
Sample Wt. (grams)	4900	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.65	(Informational Only)
Optimum Mixing Temperature (°F)	323	
Compaction Temperature (°F)	300	
Rice Density (lbs/ft³)	158.6	

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater / WA 98512

BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2" — WORK ORDER NO : 008017

SAMPLE ID : 00000109bc6 — MIX ID NO : MD110025

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-#4	3/8"-0	Sand	Combined	Specification	Tolerance
Source:	AD74	AD74	GT154			
Ratio:	30%	65%	5%			
3/4 in	100.0	100.0	100.0	100	100	99 - 100
1/2 in	80.0	100.0	100.0	94	90 - 100	90 - 100
3/8 in	40.0	100.0	100.0	82	90 Max	76 - 88
No. 4	1.0	76.0	100.0	55		50 - 60
No. 8	1.0	47.0	100.0	36	28 - 58	32 - 40
No. 16	1.0	29.0	100.0	24		
No. 30	1.0	19.0	100.0	18		
No. 50	1.0	15.0	95.0	15		
No. 100	1.0	11.0	30.0	9		
No. 200	1.0	9.0	2.0	6.3	2.0 - 7.0	4.3 - 7.0

Gsb Coarse	2.797	2.808			
Gsb Fine		2.620	2.717		
Gsb Blend	2.797	2.663	2.717	2.705	
Sand Equivalent (SE)		87		87	45 Min
% Uncompacted Voids		50		49	44 Min
% Fracture	100			100	90 Min Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.741	2.738			
Gsb Fine		2.679	2.688	2.680	
Gsb Blend	2.741	2.693	2.688	**2.707**	
Sand Equivalent (SE)		84	63	82	45 Min
% Uncompacted Voids				49	44 Min
% Fracture	100	100		100	90 Min Double Face Fracture

COMMENTS

Remarks:

Result Code:

Billing Code

T177 - 1

T185 - 16

T194 - 1

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 3/31/2011
Phone : (360) 709-5421

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater WA 98512

BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL : HMA Class 1/2"
DATE SAMPLED : 03/28/2011
DATE RECV'D : 04/01/2011
SR NO : 026
SECTION : Grant County Line to SR 17 Paving
PROJECT ENGINEER : Waligorski, Kevin

WORK ORDER NO : 008013
SAMPLE ID : 0000010a005
MIX ID NO : MD110037
CONTRACTOR : C.W.A.
ORG CODE : 424301

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		5.0	5.2	6.0	
% Gmm @ Ninitial	8	85.2	85.2	87.5	≤ 89.0
% Va @ Ndesign	100	4.8	4.2	2.0	Approximate 4.0
% VMA @ Ndesign	100	14.4	14.4	14.4	≥ 14.0
% VFA @ Ndesign	100	67	71	86	65 - 75
% Gmm @ Nmax	160		97.1		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.4	1.3	1.1	0.6 - 1.6
Pbe		4.1	4.3	5.1	
Gmm		2.581	2.573	2.537	
Gmb		2.458	2.464	2.486	
Gb		1.034	1.034	1.034	
Gse		2.802	2.802	2.797	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		4.7	5.2	5.7		
% Gmm @ Ninitial	8	83.7	84.6	85.7	≤ 89.0	
% Va @ Ndesign	100	7.3	5.5	3.8	Approximate 4.0	
% VMA @ Ndesign	100	15.8	15.3	14.9	≥ 14.0	
% VFA @ Ndesign	100	54	64	75	65 - 75	
% Gmm @ Nmax	160		96.1		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.6	1.4	1.2	0.6 - 1.6	
Pbe		3.7	4.2	4.7		
Gmm		2.598	2.577	2.557		
Gmb		2.408	2.436	2.460		
Gb		1.034	1.034	1.034		
Gse		2.808	2.807	2.807		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.25%	0.50%	0.75%	1.0%
Visual Appearance :	NONE	NONE	NONE	NONE	NONE
% Retained Strength :	91	98	107	105	101

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**IDAHO ASPHALT**	
Asphalt Binder Grade	PG64-28	
Percent Binder (Pb) (By Wt. Total Mix)	5.2	
% Anti-Strip (By Wt. of Asphalt Binder)	0.50	
Type of Anti-Strip	SUPERBOND	
Mix ID Number	MD110037	
Sample Wt. (grams)	4820	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.70	(Informational Only)
Optimum Mixing Temperature (°F)	315	
Compaction Temperature (°F)	292	
Rice Density (lbs/ft³)	160.4	

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Washington State Department of Transportation - Materials Laboratory
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BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2"
SAMPLE ID : 0000010a005

WORK ORDER NO : 008013
MIX ID NO : MD110037

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-#4	3/8"-0	Sand	Combined	Specification	Tolerance
Source:	AD180	AD180	GT154			
Ratio:	29%	66%	5%			
3/4 in	100.0	100.0	100.0	100	100	99 - 100
1/2 in	82.0	100.0	100.0	95	90 - 100	90 - 100
3/8 in	42.0	100.0	100.0	83	90 Max	77 - 89
No. 4	1.0	73.0	100.0	53		48 - 58
No. 8	1.0	42.0	100.0	33	28 - 58	29 - 37
No. 16	1.0	27.0	100.0	23		
No. 30	1.0	19.0	100.0	18		
No. 50	1.0	13.0	95.0	14		
No. 100	1.0	10.0	30.0	8		
No. 200	1.0	8.0	2.0	5.7	2.0 - 7.0	3.7 - 7.0

Gsb Coarse	2.740	2.728			
Gsb Fine		2.725	2.700		
Gsb Blend	2.740	2.726	2.700	2.729	
Sand Equivalent (SE)		78	70	77	45 Min
% Uncompacted Voids		49		49	44 Min
% Fracture	99	99		99	Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.750	2.723			
Gsb Fine		2.711	2.743	2.714	
Gsb Blend	2.750	2.714	2.743	**2.726**	
Sand Equivalent (SE)		84	72	83	45 Min
% Uncompacted Voids				49	44 Min
% Fracture	100	100		100	Double Face Fracture

COMMENTS

Remarks:

Result Code:

Billing Code

T177 - 1
T185 - 18
T194 - 1

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 4/26/2011
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BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL :	HMA Class 1/2"	WORK ORDER NO :	008033
DATE SAMPLED :	06/16/2011	SAMPLE ID :	0000010b1fe
DATE RECV'D :	06/20/2011	MIX ID NO :	MD110071
SR NO :	012	CONTRACTOR :	Granite Northwest
SECTION :	SR 124 Intersection Build Interchange		
PROJECT ENGINEER :	Davari, Moe	ORG CODE :	454306

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		4.6	5.2	5.6	
% Gmm @ Ninitial	8	84.0	85.6	86.1	≤ 89.0
% Va @ Ndesign	100	6.4	4.0	2.3	Approximate 4.0
% VMA @ Ndesign	100	15.1	14.4	14.9	≥ 14.0
% VFA @ Ndesign	100	59	73	77	65 - 75
% Gmm @ Nmax	160		97.6		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.4	1.2	1.1	0.6 - 1.6
Pbe		3.8	4.4	4.8	
Gmm		2.565	2.541	2.526	
Gmb		2.406	2.440	2.438	
Gb		1.031	1.031	1.031	
Gse		2.763	2.763	2.764	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		4.7	5.2	5.7		
% Gmm @ Ninitial	8	83.8	85.0	86.4	≤ 89.0	
% Va @ Ndesign	100	7.3	5.5	3.8	Approximate 4.0	
% VMA @ Ndesign	100	16.4	16.0	15.5	≥ 14.0	
% VFA @ Ndesign	100	56	66	76	65 - 75	
% Gmm @ Nmax	160		96.1		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.4	1.2	1.1	0.6 - 1.6	
Pbe		3.9	4.5	5.0		
Gmm		2.558	2.536	2.517		
Gmb		2.372	2.396	2.423		
Gb		1.034	1.034	1.034		
Gse		2.759	2.756	2.756		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.25%	0.50%	0.75%	1.0%
Visual Appearance :	SLIGHT	NONE	NONE	NONE	NONE
% Retained Strength :	94	113	110	103	106

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**WSA**	
Asphalt Binder Grade	PG64-28	
Percent Binder (Pb) (By Wt. Total Mix)	5.2	
% Anti-Strip (By Wt. of Asphalt Binder)	0.25	
Type of Anti-Strip	POLARBOND	
Mix ID Number	MD110071	
Sample Wt. (grams)	4750	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.41	(Informational Only)
Optimum Mixing Temperature (°F)	309	
Compaction Temperature (°F)	286	
Rice Density (lbs/ft³)	157.9	

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BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2" WORK ORDER NO : 008033
SAMPLE ID : 0000010b1fe MIX ID NO : MD110071

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-3/8"	3/8"-0	Combined	Specification	Tolerance
Source:	R182	R182			
Ratio:	18%	82%			
3/4 in	100.0	100.0	100	100	99 - 100
1/2 in	62.0	100.0	93	90 - 100	90 - 99
3/8 in	34.0	96.0	85	90 Max	79 - 90
No. 4	3.0	64.0	53		48 - 58
No. 8	2.0	42.0	35	28 - 58	31 - 39
No. 16	2.0	29.0	24		
No. 30	1.0	19.0	16		
No. 50	1.0	13.0	11		
No. 100	1.0	9.0	8		
No. 200	1.0	6.5	5.5	2.0 - 7.0	3.5 - 7.0

Gsb Coarse	2.727	2.728		
Gsb Fine		2.683		
Gsb Blend	2.727	2.699	2.704	
Sand Equivalent (SE)		76	76	45 Min
% Uncompacted Voids		46	46	44 Min
% Fracture	96	94	94	90 Min Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.727	2.711		
Gsb Fine		2.687	2.687	
Gsb Blend	2.727	2.696	**2.702**	
Sand Equivalent (SE)		85	85	45 Min
% Uncompacted Voids			48	44 Min
% Fracture	100	100	100	90 Min Double Face Fracture

COMMENTS

Remarks:

Result Code:

Billing Code
T177 - 1
T185 - 12
T194 - 1

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 7/14/2011
Phone : (360) 709-5421

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater WA 98512
BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL :	HMA Class 1/2"	WORK ORDER NO : 008016
DATE SAMPLED :	05/11/2011	SAMPLE ID : 0000010a980
DATE RECV'D :	05/16/2011	MIX ID NO : MD110053
SR NO :	005	CONTRACTOR : Granite Construction
SECTION :	I-5, JOE LEARY SLOUGH TO NULLE ROAD VIC - PAVING DESIGN BUILD PROJECT	
PROJECT ENGINEER :	Boyd, Robyn	ORG CODE : 410011

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		4.7	5.3	5.7	
% Gmm @ Ninitial	8	88.2	88.3	89.7	≤ 89.0
% Va @ Ndesign	100	5.5	4.0	2.4	Approximate 4.0
% VMA @ Ndesign	100	14.0	14.0	13.4	≥ 14.0
% VFA @ Ndesign	100	61	72	82	65 - 75
% Gmm @ Nmax	160		97.6		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.4	1.2	1.1	0.6 - 1.6
Pbe		3.7	4.3	4.7	
Gmm		2.518	2.494	2.480	
Gmb		2.384	2.394	2.420	
Gb		1.034	1.034	1.034	
Gse		2.710	2.708	2.709	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		4.8	5.3	5.8		
% Gmm @ Ninitial	8	86.7	88.3	89.5	≤ 89.0	
% Va @ Ndesign	100	5.9	3.8	2.3	Approximate 4.0	
% VMA @ Ndesign	100	14.9	14.2	13.8	≥ 14.0	
% VFA @ Ndesign	100	60	74	84	65 - 75	
% Gmm @ Nmax	160		97.5		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.3	1.2	1.0	0.6 - 1.6	
Pbe		4.0	4.5	5.0		
Gmm		2.503	2.481	2.464		
Gmb		2.356	2.387	2.409		
Gb		1.034	1.034	1.034		
Gse		2.696	2.692	2.693		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.25%	0.50%	0.75%	1.0%
Visual Appearance :	SLIGHT	NONE	NONE	NONE	NONE
% Retained Strength :	91	97	105	103	97

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**HUSKY OIL**	
Asphalt Binder Grade	PG64-22	
Percent Binder (Pb) (By Wt. Total Mix)	5.3	
% Anti-Strip (By Wt. of Asphalt Binder)	0.50	
Type of Anti-Strip	ARR-MAZ 7700	
Mix ID Number	MD110053	
Sample Wt. (grams)	4750	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.95	(Informational Only)
Optimum Mixing Temperature (°F)	313	
Compaction Temperature (°F)	289	
Rice Density (lbs/ft³)	154.4	

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 S. 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2" WORK ORDER NO : 008016

SAMPLE ID : 0000010a980 MIX ID NO : MD110053

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-0	3/8"-0	#4-0	Sand	Combined	Specification	Tolerance
Source:	F160	F160	F160	F160			
Ratio:	18%	21%	34%	27%			
3/4 in	100.0	100.0	100.0	100.0	100	100	99 - 100
1/2 in	64.0	100.0	100.0	100.0	94	90 - 100	90 - 100
3/8 in	17.0	91.0	99.7	100.0	83	90 Max	77 - 89
No. 4	5.3	6.6	91.9	99.4	60		55 - 65
No. 8	1.3	1.7	63.0	87.8	46	28 - 58	42 - 50
No. 16	1.2	1.7	43.0	67.5	33		
No. 30	1.1	1.5	32.0	40.1	22		
No. 50	1.0	1.4	24.1	13.3	12		
No. 100	0.9	1.3	17.7	2.5	7		
No. 200	0.8	1.2	12.6	1.5	5.1	2.0 - 7.0	3.1 - 7.0

Gsb Coarse	2.696	2.690	2.673			
Gsb Fine			2.590	2.605		
Gsb Blend	2.696	2.690	2.597	2.605	2.636	
Sand Equivalent (SE)			80	65	73	45 Min
% Uncompacted Voids			47	42	45	44 Min
% Fracture	91	91	98		92	90 Min Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.694	2.667	2.643			
Gsb Fine			2.599	2.607	2.603	
Gsb Blend	2.694	2.667	2.603	2.607	**2.633**	
Sand Equivalent (SE)			56	88	67	45 Min
% Uncompacted Voids					44	44 Min
% Fracture	95	93	100		94	90 Min Double Face Fracture

COMMENTS

Remarks:

Result Code:

Billing Code

T177 - 1

T185 - 12

T194 - 1

Thomas E. Baker, P.E.
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Joseph R. DeVol
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Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION REFERENCE MIX DESIGN VERIFICATION REPORT

MATERIAL : HMA Class 1/2"
DATE RECV'D : 02/15/2011
REVIEWED BY : S. Davis
SR NO : 510
PROJECT ENGINEER : Uhlmeyer, Neal
SECTION : Yelm Loop Stage 1

WORK ORDER NO : 007879
REFERENCE NO : RD110018
MIX ID NO : MD100065
REFERENCED FROM WORK ORDER NO : 007879
ORG CODE : 434309
CONTRACTOR : Lakeside Industries

THIS REFERENCE MIX DESIGN FOR **8300 TONS** OF HMA IS BASED ON PREVIOUS USE OF AGGREGATES FROM THE SOURCE LISTED. THIS DESIGN IS IN LIEU OF AN EVALUATION OF CURRENT STOCKPILES AND PRODUCTION.

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		5.0	5.4	6.0	
% Gmm @ Ninitial	8	83.8	85.7	86.6	≤ 89.0
% Va @ Ndesign	100	5.3	4.0	2.2	Approximate 4.0
% VMA @ Ndesign	100	14.6	14.2	13.7	≥ 14.0
% VFA @ Ndesign	100	64	72	84	65 - 75
% Gmm @ Nmax	160		97.3		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.5	1.4	1.2	0.6 - 1.6
Pbe		4.1	4.4	4.9	
Gmm		2.499	2.487	2.472	
Gmb		2.366	2.388	2.418	
Gb		1.030	1.030	1.030	
Gse		2.702	2.705	2.715	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance
Pb		4.9	5.4	5.9		± 0.5%
% Gmm @ Ninitial	8	86.0	87.2	88.3	≤ 89.0	
% Va @ Ndesign	100	4.5	2.9	1.5	Approximate 4.0	
% VMA @ Ndesign	100	14.1	13.7	13.4	≥ 14.0	
% VFA @ Ndesign	100	68	80	89	65 - 75	
% Gmm @ Nmax	160		98.5		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.5	1.3	1.2	0.6 - 1.6	
Pbe		4.1	4.7	5.1		
Gmm		2.501	2.480	2.468		
Gmb		2.388	2.410	2.432		
Gb		1.030	1.030	1.030		
Gse		2.699	2.697	2.705		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.05%	0.10%	0.15%	0.20%
Visual Appearance :	SLIGHT	NONE	NONE	NONE	NONE
% Retained Strength :	97	97	103	97	94

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**SOUND**	
Asphalt Binder Grade	PG64-22	
Percent Binder (Pb) (By Wt. Total Mix)	5.4	
% Anti-Strip (By Wt. of Asphalt Binder)	0.10	
Type of Anti-Strip	ZYCOSOIL	
Mix ID Number	MD100065	
Sample Wt. (grams)	4750	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.59	(Informational Only)
Optimum Mixing Temperature (°F)	313	
Compaction Temperature (°F)	293	
Rice Density (lbs/ft³)	154.4	

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION REFERENCE MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2"
SAMPLE ID : 000001099e6

WORK ORDER NO : 007879
REFERENCE NO : RD110018
MIX ID NO : MD100065

SECTION : Yelm Loop Stage 1

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-3/8"	3/8"-0"	Combined	Specification	Tolerance
Source:	J9	J9			
Ratio:	32%	68%			
3/4 in	100.0	100.0	100	100	99 - 100
1/2 in	82.9	100.0	95	90 - 100	90 - 100
3/8 in	32.9	99.6	78	90 Max	72 - 84
No. 4	3.0	77.8	54		49 - 59
No. 8	2.8	51.5	36	28 - 58	32 - 40
No. 16	2.2	34.4	24		
No. 30	2.1	24.1	17		
No. 50	2.0	16.5	12		
No. 100	1.8	11.4	8		
No. 200	1.5	8.1	6.0	2.0 - 7.0	4.0 - 7.0

Gsb Coarse	2.675	2.669		
Gsb Fine		2.597		
Gsb Blend	2.675	2.613	**2.633**	
Sand Equivalent (SE)		62	62	45 Min
% Uncompacted Voids		45	45	44 Min
% Fracture	100	100	100	90 Min Single Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.684	2.656		
Gsb Fine		2.611	2.611	
Gsb Blend	2.684	2.621	**2.641**	
Sand Equivalent (SE)		78	78	45 Min
% Uncompacted Voids			48	44 Min
% Fracture	100	100	100	90 Min Single Face Fracture

COMMENTS

Remarks:

Result Code:

Remarks :

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 2/16/2011
Phone : (360) 709-5421

Billing Code
T162 - 1

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION REFERENCE MIX DESIGN VERIFICATION REPORT

MATERIAL :	HMA Class 1/2"	WORK ORDER NO :	007465
DATE RECV'D :	04/27/2011	REFERENCE NO :	RD110051
REVIEWED BY :	S. Davis	MIX ID NO :	MD100008
SR NO :	005	REFERENCED FROM WORK ORDER NO :	007465

PROJECT ENGINEER : Nebergall, MaryLou ORG CODE : 434304 CONTRACTOR : Lakeside

SECTION : Grand Mound to Maytown Stage One - Add Lanes

THIS REFERENCE MIX DESIGN FOR **13000 TONS** OF HMA IS BASED ON PREVIOUS USE OF AGGREGATES FROM THE SOURCE LISTED. THIS DESIGN IS IN LIEU OF AN EVALUATION OF CURRENT STOCKPILES AND PRODUCTION.

CONTRACTOR'S MIX DESIGN TEST DATA

					Specification
Pb		5.0	5.6	6.0	
% Gmm @ Ninitial	9	83.8	85.3	86.4	≤ 89.0
% Va @ Ndesign	125	5.6	4.0	3.0	Approximate 4.0
% VMA @ Ndesign	125	14.9	14.7	14.5	≥ 14.0
% VFA @ Ndesign	125	62	73	79	65 - 75
% Gmm @ Nmax	205		96.9		≤ 98.0
Dust to Asphalt Ratio (D/A)		1.2	1.1	1.0	0.6 - 1.6
Pbe		4.1	4.7	5.0	
Gmm		2.479	2.461	2.448	
Gmb		2.341	2.362	2.374	
Gb		1.036	1.036	1.036	
Gse		2.675	2.680	2.681	

STATE MATERIALS LABORATORY VERIFICATION TEST DATA

					Specification	Tolerance ± 0.5%
Pb		5.1	5.6	6.1		
% Gmm @ Ninitial	9	84.0	85.4	86.7	≤ 89.0	
% Va @ Ndesign	125	6.6	4.5	2.9	Approximate 4.0	2.5 - 5.5
% VMA @ Ndesign	125	15.4	14.7	14.1	≥ 14.0	≥ 12.5
% VFA @ Ndesign	125	57	70	80	65 - 75	
% Gmm @ Nmax	205		97.5		≤ 98.0	
Dust to Asphalt Ratio (D/A)		1.3	1.1	1.0	0.6 - 1.6	
Pbe		4.0	4.6	4.9		
Gmm		2.475	2.452	2.443		
Gmb		2.312	2.343	2.373		
Gb		1.036	1.036	1.036		
Gse		2.675	2.668	2.680		

STRIPPING EVALUATION

% Anti-Strip :	0.0%	0.08%	0.17%	0.33%	0.50%
Visual Appearance :	NONE	NONE	NONE	NONE	NONE
% Retained Strength :	87	93	88	90	89

STATE MATERIALS LABORATORY RECOMMENDATIONS

Asphalt Binder Supplier	**EXXON**	
Asphalt Binder Grade	PG64-22	
Percent Binder (Pb) (By Wt. Total Mix)	5.6	
% Anti-Strip (By Wt. of Asphalt Binder)	0.08	
Type of Anti-Strip	UP-5000	
Mix ID Number	MD100008	
Sample Wt. (grams)	4640	(Informational Only)
Sample Height @ Ndesign	115.0	(Informational Only)
Ignition Calibration Factor	0.61	(Informational Only)
Optimum Mixing Temperature (°F)	311	
Compaction Temperature (°F)	291	
Rice Density (lbs/ft³)	152.7	

Washington State Department of Transportation - Materials Laboratory
PO Box 47365 Olympia WA 98504 / 1655 2nd Ave. Tumwater / WA 98512
BITUMINOUS SECTION REFERENCE MIX DESIGN VERIFICATION REPORT

MATERIAL: HMA Class 1/2" WORK ORDER NO : 007465
SAMPLE ID : 0000010a5cd REFERENCE NO : RD110051
MIX ID NO : MD100008

SECTION : Grand Mound to Maytown Stage One - Add Lanes

CONTRACTOR'S DESIGN AGGREGATE STRUCTURE AND AGGREGATE TEST DATA

Material:	3/4"-3/8"	3/8"-0	Sand	Combined	Specification	Tolerance
Source:	L268	L268	L268			
Ratio:	31%	65%	4%			
3/4 in	100.0	100.0	100.0	100	100	99 - 100
1/2 in	85.0	100.0	100.0	95	90 - 100	90 - 100
3/8 in	43.0	100.0	100.0	82	90 Max	76 - 88
No. 4	4.0	76.0	100.0	55		50 - 60
No. 8	3.0	47.0	94.0	35	28 - 58	31 - 39
No. 16	1.8	30.0	77.0	23		
No. 30	1.6	20.0	52.0	16		
No. 50	1.4	14.0	19.0	10		
No. 100	1.3	10.0	4.0	7		
No. 200	1.1	7.0	1.2	4.9	2.0 - 7.0	2.9 - 6.9

Gsb Coarse	2.640	2.631			
Gsb Fine		2.581	2.579		
Gsb Blend	2.640	2.601	2.579	**2.612**	
Sand Equivalent (SE)		69	79	70	45 Min
% Uncompacted Voids		47		47	44 Min
% Fracture	93	100		95	90 Min Double Face Fracture

STATE MATERIALS LABORATORY AGGREGATE TEST DATA

Gsb Coarse	2.625	2.632			
Gsb Fine		2.565	2.528	2.562	
Gsb Blend	2.625	2.581	2.528	**2.592**	
Sand Equivalent (SE)		81	72	80	45 Min
% Uncompacted Voids				47	44 Min
% Fracture	97	99		98	

COMMENTS

Remarks:

Result Code:

Remarks :

Thomas E. Baker, P.E.
State Materials Engineer
Joseph R. DeVol
Bituminous Materials Engineer
Date : 4/28/2011
Phone : (360) 709-5421

Billing Code
T162 - 1

APPENDIX C: Specific gravity and volumetrics information

Sample ID	Gmm	Gsb	Pb	Gmb	Air Voids (%)	VMA	VFA
1-4-1	2.655	2.887	5.4	2.554	3.8	16.3	76.6
1-4-2	2.655	2.887	5.4	2.546	4.1	16.6	75.1
1-7-1	2.655	2.887	5.4	2.458	7.4	19.5	61.8
1-7-2	2.655	2.887	5.4	2.463	7.2	19.3	62.4
1-9-1	2.655	2.887	5.4	2.409	9.3	21.1	55.9
1-9-2	2.655	2.887	5.4	2.420	8.9	20.7	57.2
2-4-1	2.542	2.705	5.7	2.431	4.4	15.3	71.5
2-4-2	2.542	2.705	5.7	2.439	4.0	15.0	73.0
2-7-1	2.542	2.705	5.7	2.357	7.3	17.8	59.3
2-7-2	2.542	2.705	5.7	2.350	7.5	18.1	58.3
2-9-1	2.542	2.705	5.7	2.324	8.6	19.0	54.9
2-9-2	2.542	2.705	5.7	2.325	8.5	18.9	55.0
3-4-1	2.571	2.714	5.2	2.478	3.6	13.4	73.2
3-4-2	2.571	2.714	5.2	2.472	3.8	13.7	71.9
3-7-1	2.571	2.714	5.2	2.399	6.7	16.2	58.8
3-7-2	2.571	2.714	5.2	2.397	6.8	16.3	58.5
3-9-1	2.571	2.714	5.2	2.348	8.7	18.0	51.9
3-9-2	2.571	2.714	5.2	2.346	8.7	18.1	51.6
4-4-1	2.530	2.704	5.2	2.432	3.9	14.7	73.6
4-4-2	2.530	2.704	5.2	2.420	4.4	15.2	71.2
4-7-1	2.530	2.704	5.2	2.361	6.7	17.2	61.1
4-7-2	2.530	2.704	5.2	2.354	7.0	17.5	60.1
4-9-1	2.530	2.704	5.2	2.299	9.1	19.4	52.9
4-9-2	2.530	2.704	5.2	2.303	9.0	19.3	53.3
5-4-1	2.474	2.636	5.3	2.384	3.7	14.4	74.6
5-4-2	2.474	2.636	5.3	2.384	3.7	14.4	74.6
5-7-1	2.474	2.636	5.3	2.312	6.6	16.9	61.3
5-7-2	2.474	2.636	5.3	2.309	6.7	17.0	60.8
5-9-1	2.474	2.636	5.3	2.241	9.4	19.5	51.6
5-9-2	2.474	2.636	5.3	2.242	9.4	19.5	51.7
6-4-1	2.474	2.636	5.4	2.379	3.9	14.6	73.6

6-4-2	2.474	2.636	5.4	2.376	4.0	14.7	73.0
6-7-1	2.474	2.636	5.4	2.302	7.0	17.4	59.9
6-7-2	2.474	2.636	5.4	2.296	7.2	17.6	59.0
6-9-1	2.474	2.636	5.4	2.249	9.1	19.3	52.8
6-9-2	2.474	2.636	5.4	2.259	8.7	18.9	54.0
7-4-1	2.447	2.612	5.6	2.343	4.3	15.3	72.2
7-4-2	2.447	2.612	5.6	2.344	4.2	15.3	72.4
7-7-1	2.447	2.612	5.6	2.264	7.5	18.2	58.8
7-7-2	2.447	2.612	5.6	2.270	7.2	18.0	59.7
7-9-1	2.447	2.612	5.6	2.218	9.4	19.8	52.8
7-9-2	2.447	2.612	5.6	2.222	9.2	19.7	53.3
4-4-1W	2.530	2.704	5.2	2.434	3.8	14.7	74.0
4-4-2W	2.530	2.704	5.2	2.430	4.0	14.8	73.2
4-7-1W	2.530	2.704	5.2	2.344	7.4	17.8	58.7
4-7-2W	2.530	2.704	5.2	2.349	7.2	17.6	59.4
4-9-1W	2.530	2.704	5.2	2.311	8.7	19.0	54.3
4-9-2W	2.530	2.704	5.2	2.301	9.1	19.3	53.1

APPENDIX D: Experimental dynamic modulus data

Sample ID	δ	α	β	γ	4.4°C	21.1°C	37.8°C	54.4°C
1-4-1	1.8609	2.5580	0.1716	0.5611	3.3926	1.3893	0.0000	-1.3558
1-4-2	1.9286	2.4404	0.4003	0.6134	3.3927	1.4655	0.0000	-1.4792
1-7-1	0.9274	3.3705	-0.0773	0.5122	3.3927	1.5071	0.0000	-1.3638
1-7-2	1.1663	3.1968	-0.1263	0.5490	3.3928	1.3282	0.0000	-1.4318
1-9-1	1.1658	3.1386	0.0352	0.5866	3.3927	1.4050	0.0000	-1.3770
1-9-2	0.9078	3.3500	-0.0141	0.5653	3.3928	1.5859	0.0000	-1.1961
2-4-1	0.8481	3.6025	-0.3049	0.5118	3.3927	1.4814	0.0000	-1.3752
2-4-2	0.9532	3.4521	-0.3065	0.5141	3.3928	1.5140	0.0000	-1.3367
2-7-1	0.5238	3.8125	-0.0738	0.5427	3.3927	1.5401	0.0000	-1.2091
2-7-2	0.6734	3.7418	-0.3028	0.5028	3.3928	1.4845	0.0000	-1.3908
2-9-1	-0.7354	5.1360	-0.5832	0.3812	3.3927	1.6795	0.0000	-1.3979
2-9-2	0.5334	3.5847	-0.2568	0.5624	3.3928	1.6866	0.0000	-1.1787
3-4-1	1.3515	3.1270	-0.1299	0.5847	3.4771	1.6078	0.0000	-1.3922
3-4-2	0.7466	3.6299	-0.5162	0.5281	3.3979	1.4902	0.0000	-1.3844
3-7-1	0.3490	4.1514	-0.6283	0.4658	3.3980	1.4106	0.0000	-1.5456
3-7-2	0.8823	3.4964	-0.4102	0.5527	3.3980	1.4338	0.0000	-1.4629
3-9-1	0.8711	3.4962	-0.3947	0.5877	3.4150	1.3979	0.0000	-1.5686
3-9-2	0.8711	3.4962	-0.3947	0.5877	3.3980	1.4338	0.0000	-1.6021
4-4-1	1.2036	3.1532	0.0010	0.6170	3.6990	1.9209	0.0000	-1.2468
4-4-2	0.4078	4.0432	-0.3826	0.4862	3.6990	1.7740	0.0000	-1.1606
4-7-1	0.2952	3.9734	-0.2707	0.5650	3.6990	1.7741	0.0000	-1.1492
4-7-2	0.3185	3.9322	-0.1566	0.5599	3.6990	1.7743	0.0000	-0.9476
4-9-1	0.6969	3.5064	0.0758	0.6225	3.6990	1.7758	0.0000	-0.4372
4-9-2	0.3489	3.8654	-0.1273	0.5684	3.6990	1.8070	0.0000	-0.4662
5-4-1	-0.9276	5.4623	-0.8781	0.4222	3.6990	1.7537	0.0000	-1.1534
5-4-2	-0.1561	4.5369	-0.6966	0.4876	3.6990	1.8584	0.0000	-1.1178
5-7-1	0.3089	4.0052	-0.4546	0.5295	3.6990	1.7781	0.0000	-1.3013
5-7-2	-0.4826	4.9031	-0.6439	0.4381	3.6990	1.7597	0.0000	-1.2276
5-9-1	-0.0729	4.4224	-0.5006	0.4674	3.6990	1.6989	0.0000	-1.3417
5-9-2	0.4260	3.9477	-0.2751	0.5011	3.6990	1.7752	0.0000	-0.9015
6-4-1	1.8522	2.4938	0.5445	0.8420	3.6990	1.7973	0.0000	-0.8874

6-4-2	0.5898	3.8144	-0.6467	0.5139	3.4771	1.6783	0.0000	-1.5867
6-7-1	0.1424	4.2787	-0.6402	0.4906	3.6990	1.7779	0.0000	-1.1527
6-7-2	-0.4826	4.9031	-0.6439	0.4381	3.6990	1.7597	0.0000	-1.2276
6-9-1	0.3312	3.9476	-0.4031	0.5305	3.6990	1.9437	0.0000	-1.3708
6-9-2	0.4260	3.9477	-0.2751	0.5011	3.6990	1.7752	0.0000	-0.9015
7-4-1	0.9843	0.9843	0.9843	0.9843	3.6991	2.0742	0.0000	-0.8970
7-4-2	1.1243	1.1243	1.1243	1.1243	3.6991	2.1567	0.0000	-0.9758
7-7-1	-0.8172	-0.8172	-0.8172	-0.8172	3.6992	1.9833	0.0000	-1.1992
7-7-2	-0.7924	-0.7924	-0.7924	-0.7924	3.3979	1.7741	0.0000	-1.5844
7-9-1	-0.7848	-0.7848	-0.7848	-0.7848	3.6989	2.1068	0.0000	-0.7113
7-9-2	0.4215	0.4215	0.4215	0.4215	3.1761	1.2848	0.0000	-1.5200
4-4-1W	1.3369	3.0290	-0.0439	0.6349	3.6990	1.7735	0.0000	-1.2360
4-4-2W	1.0862	3.2768	-0.3139	0.6026	3.6990	1.6050	0.0000	-1.3813
4-7-1W	0.7962	3.5446	-0.1197	0.6118	3.6990	1.7978	0.0000	-1.0563
4-7-2W	0.5496	3.8550	-0.2834	0.5346	3.6990	1.7983	0.0000	-1.1916
4-9-1W	0.7873	3.5127	-0.1967	0.5801	3.6989	1.7296	0.0000	-1.2690
4-9-2W	0.3259	4.0137	-0.3420	0.5340	3.6990	1.7620	0.0000	-1.2919

APPENDIX E: Flow number test results

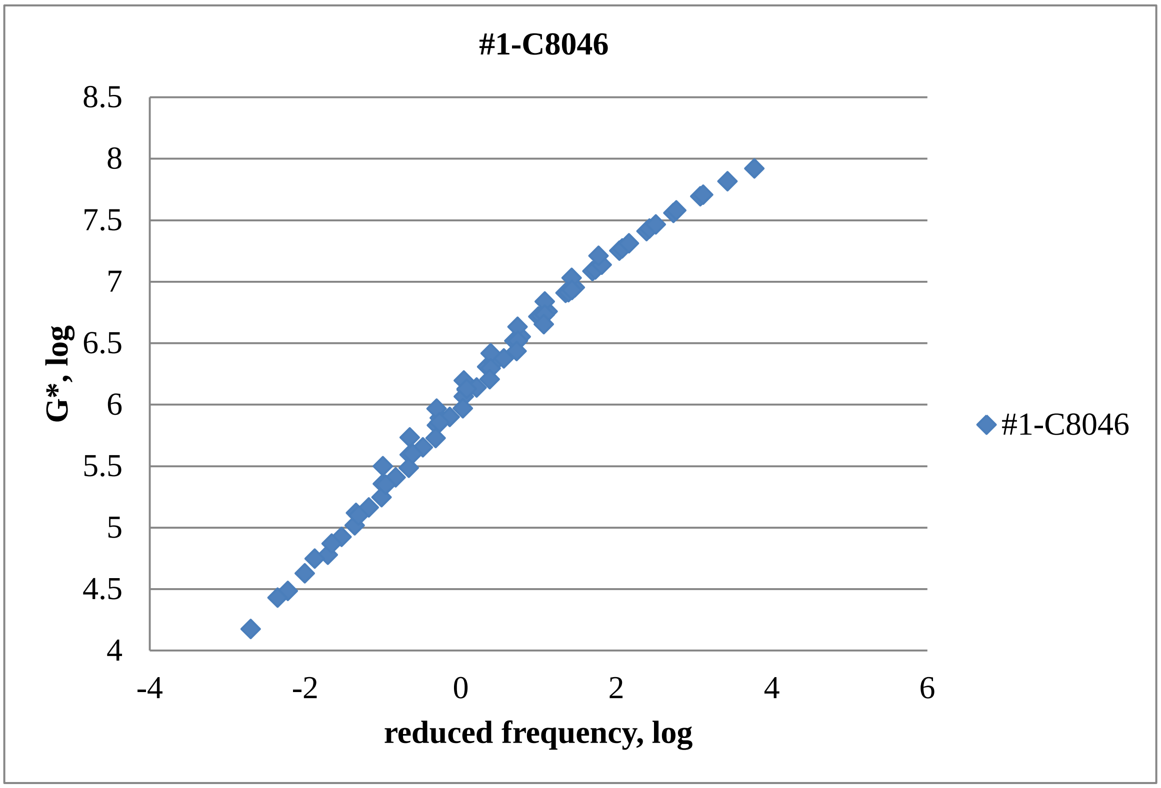
Sample ID	Target Temp.(degC)	Flow number (cycles)
1-4-1	53.5	2463
1-4-2	53.5	3435
1-7-1	53.5	2966
1-7-2	53.5	2445
1-9-1	53.5	681
1-9-2	53.5	620
2-4-1	55.1	363
2-4-2	55.1	918
2-7-1	55.1	369
2-7-2	55.1	213
2-9-1	55.1	206
2-9-2	55.1	117
3-4-1	55.5	431
3-4-2	55.5	428
3-7-1	55.5	279
3-7-2	55.5	234
3-9-1	55.5	362
3-9-2	55.5	179
4-4-1	45.4	320
4-4-2	45.4	439
4-7-1	45.4	104
4-7-2	45.4	374
4-9-1	45.4	46
4-9-2	45.4	282
5-4-1	56.9	440
5-4-2	56.9	119
5-7-1	56.9	74
5-7-2	56.9	60
5-9-1	56.9	48
5-9-2	56.9	32
6-4-1	48.5	578
6-4-2	48.5	487
6-7-1	48.5	263

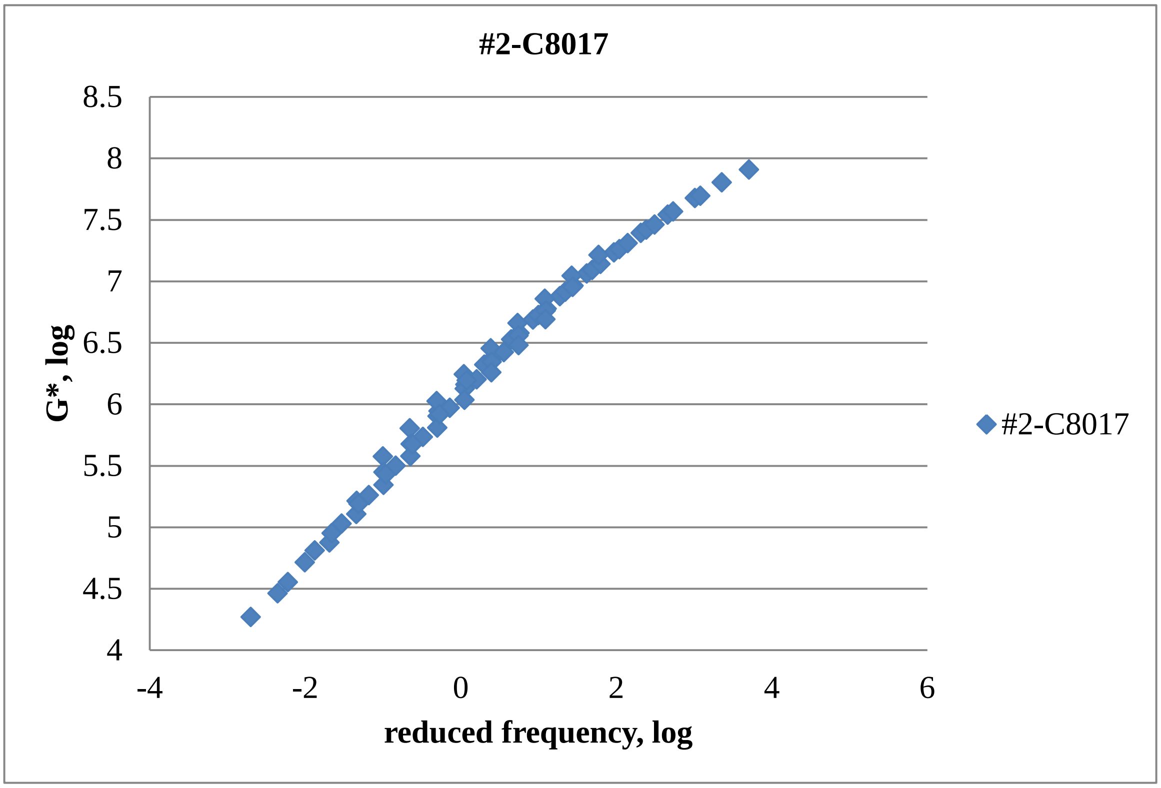
6-7-2	48.5	263
6-9-1	48.5	241
6-9-2	48.5	201
7-4-1	45.4	871
7-4-2	45.4	987
7-7-1	45.4	651
7-7-2	45.4	362
7-9-1	45.4	331
7-9-2	45.4	478
4-4-1W	45.4	1971
4-4-2W	45.4	1441
4-7-1W	45.4	751
4-7-2W	45.4	631
4-9-1W	45.4	391
4-9-2W	45.4	430

APPENDIX F: G* information for all binders

Three sections of information are included in Appendix D: (1) G* of Asphalt binders; (2) Summary of dust proportions of each mix design; and (3) G* of mastics.

D-1: G* of Asphalt Binders

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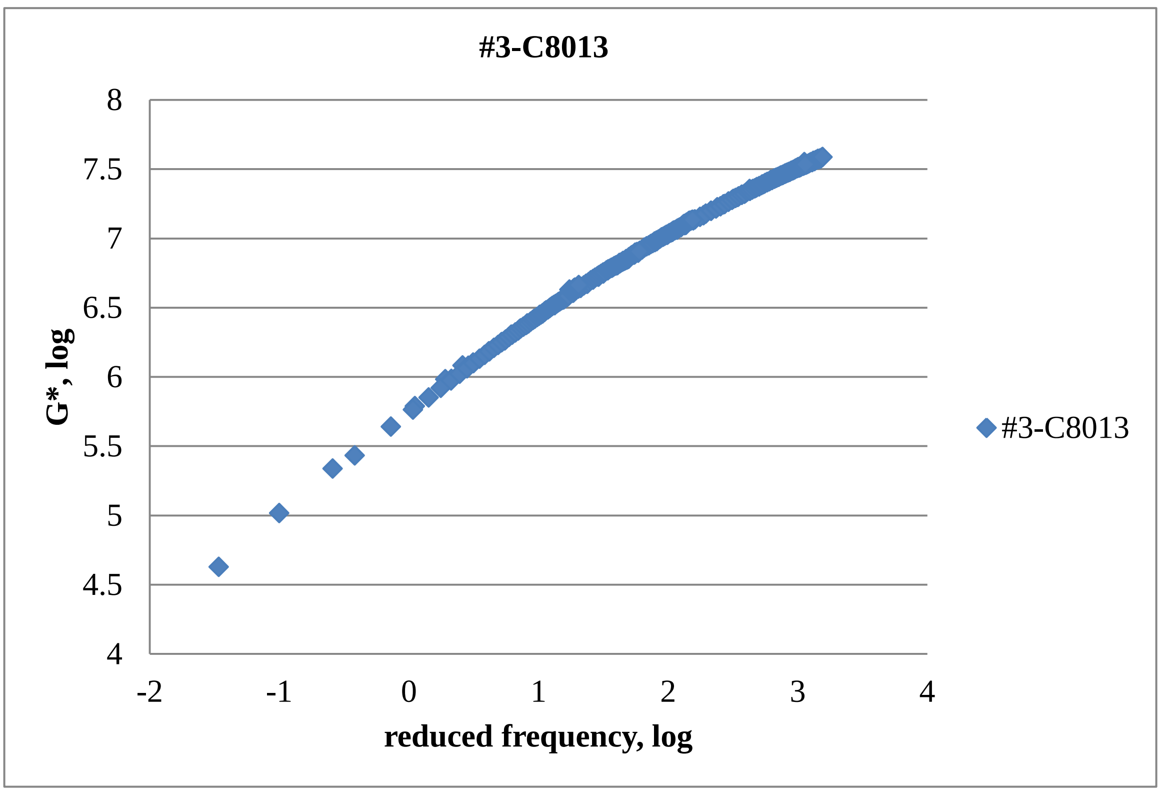
8
7.5
7
6.5
6
5.5
5
4.5
4
-4
-2
0
2
4
6
reduced frequency, log
#2-C8017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7.5
7
6.5
6
5.5
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4.5
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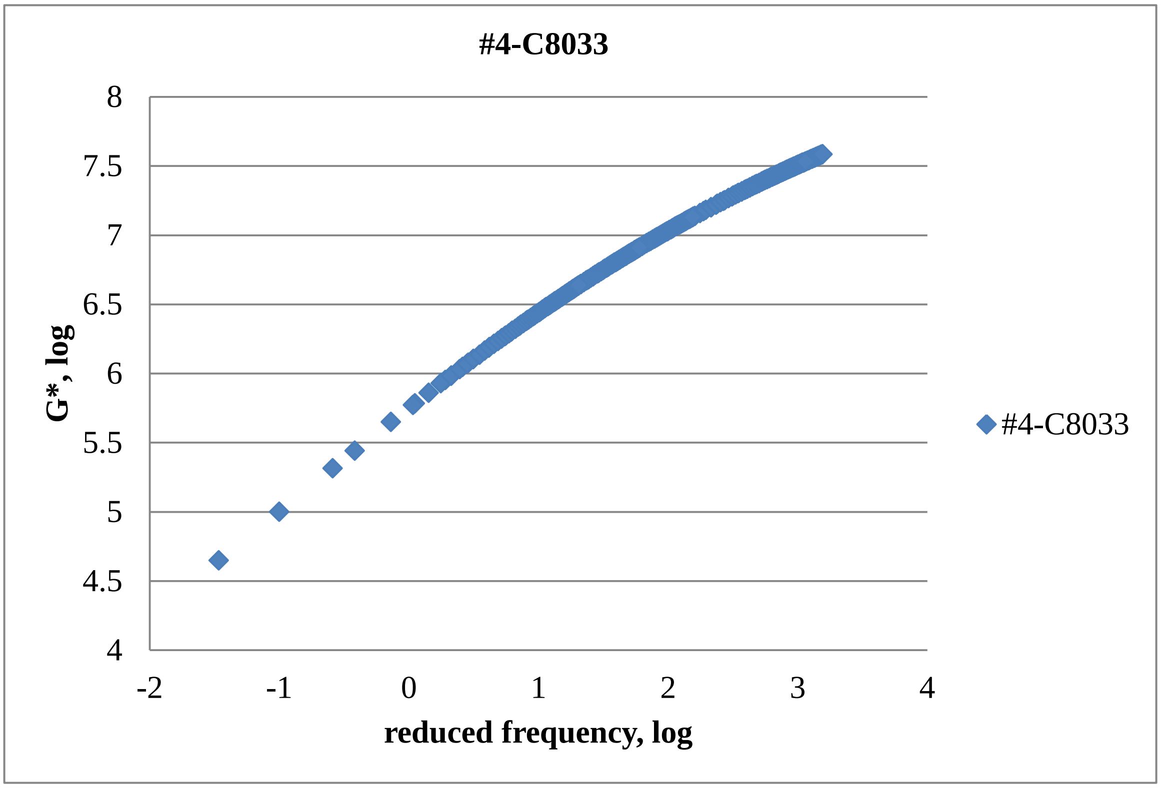
1
2
3
4
reduced frequency, log
#3-C8013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7.5
7
6.5
6
5.5
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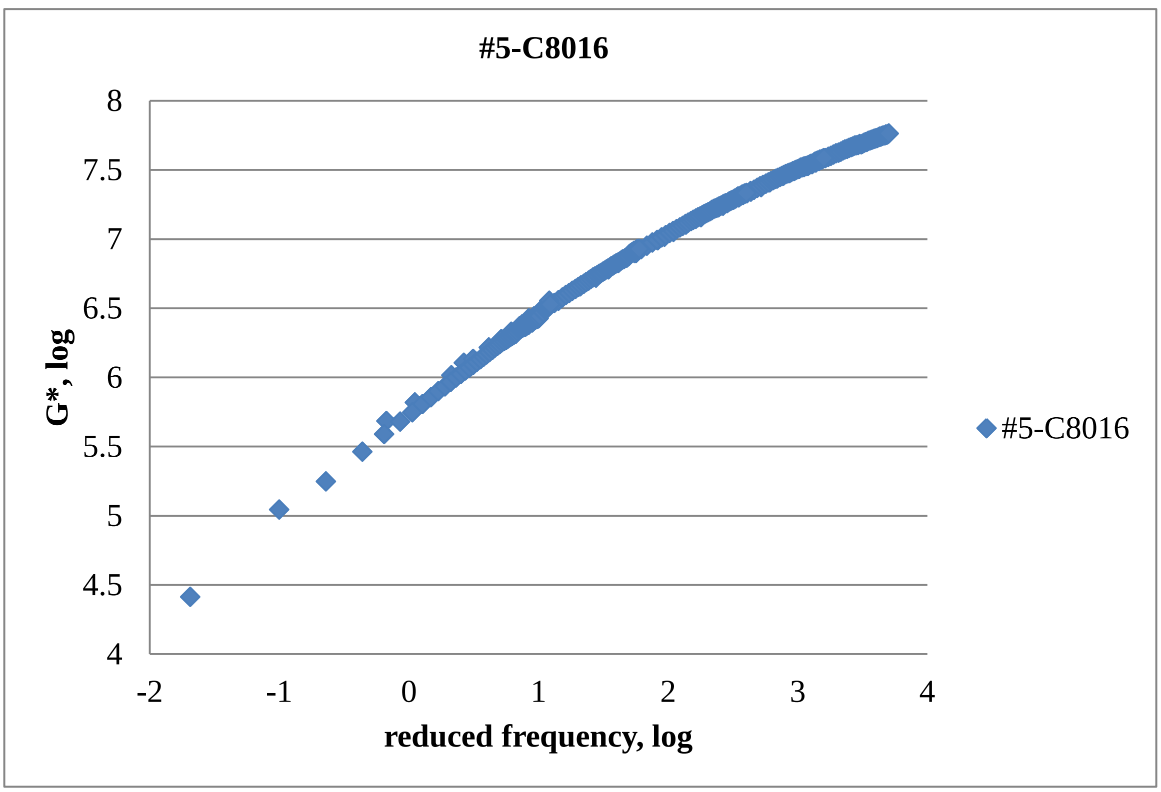
4.5
4
-2
-1
0
1
2
3
4
G*, log
reduced frequency, log
#4-C8033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7
6.5
6
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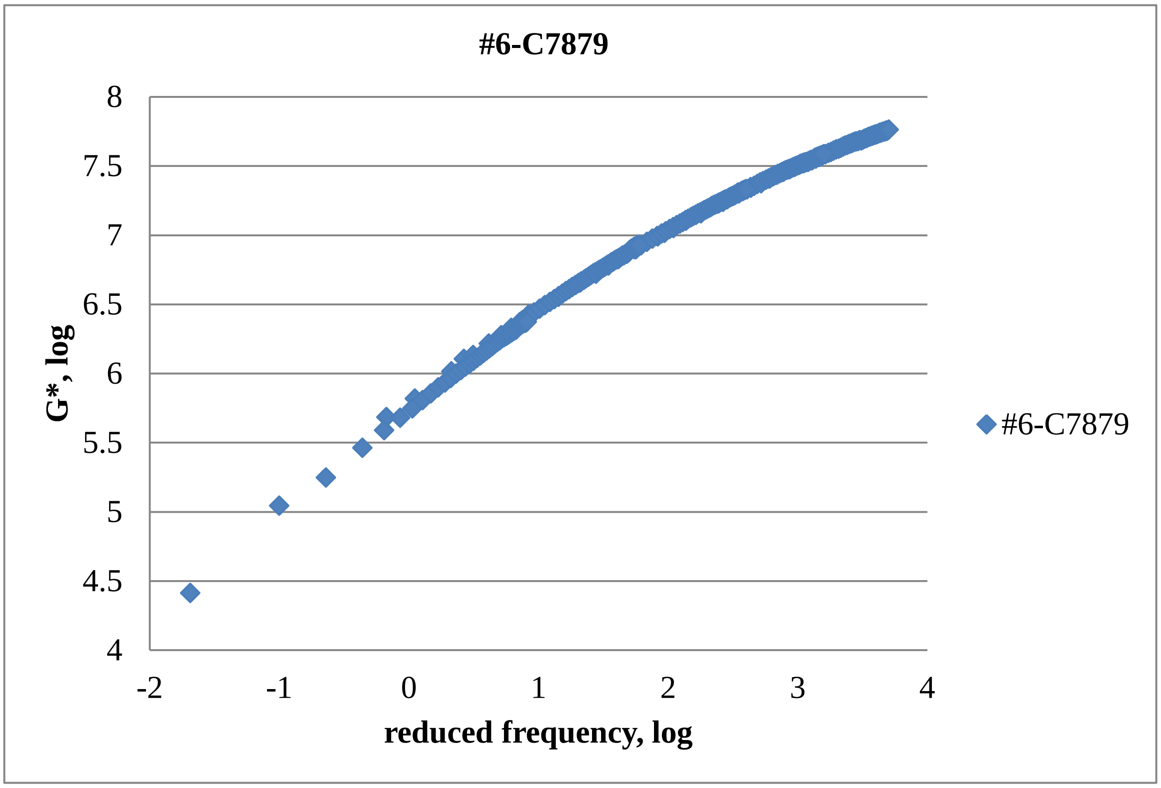
3
4
G*, log
reduced frequency, log
#5-C8016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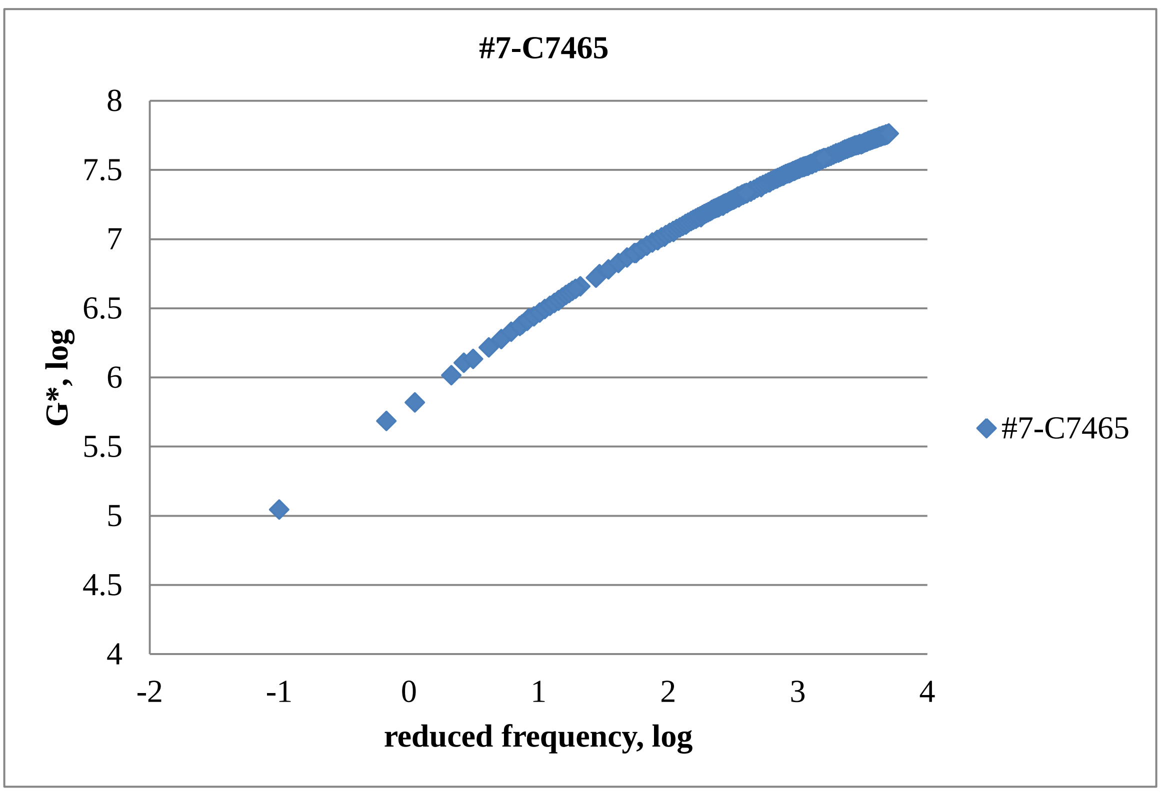
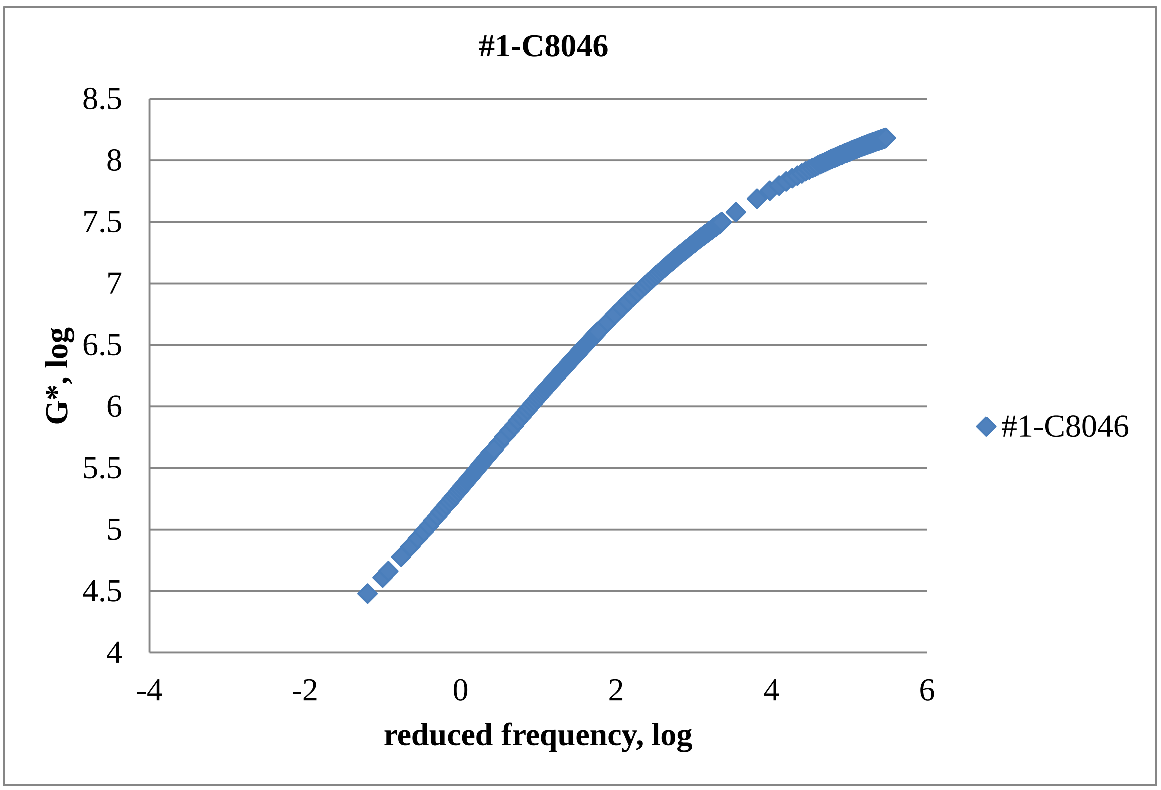
8
7.5
7
6.5
6
5.5
5
4.5
4
G*, log
-2
-1
0
1
2
3
4
reduced frequency, log
#6-C7879

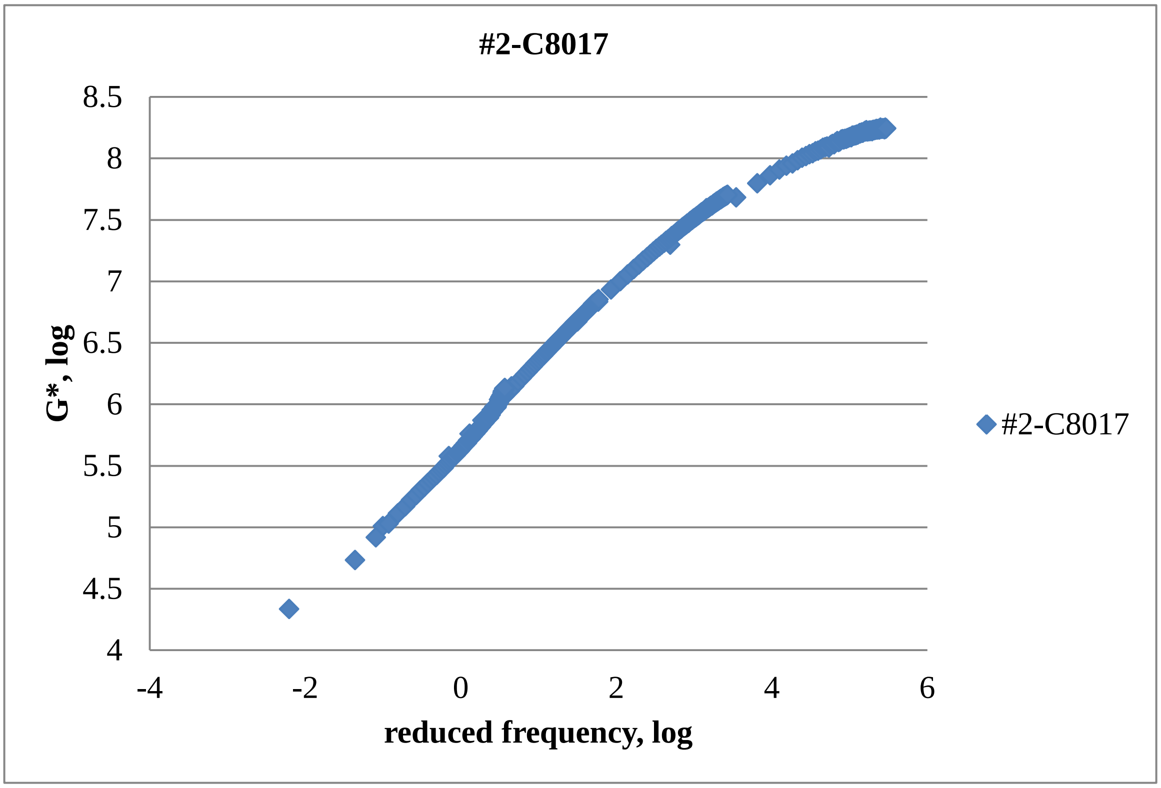

#7-C7465
8
7.5
7
6.5
6
5.5
5
4.5
4
G*, log
-2
-1
0
1
2
3
4
reduced frequency, log
#7-C7465

D-2: Dust Proportion

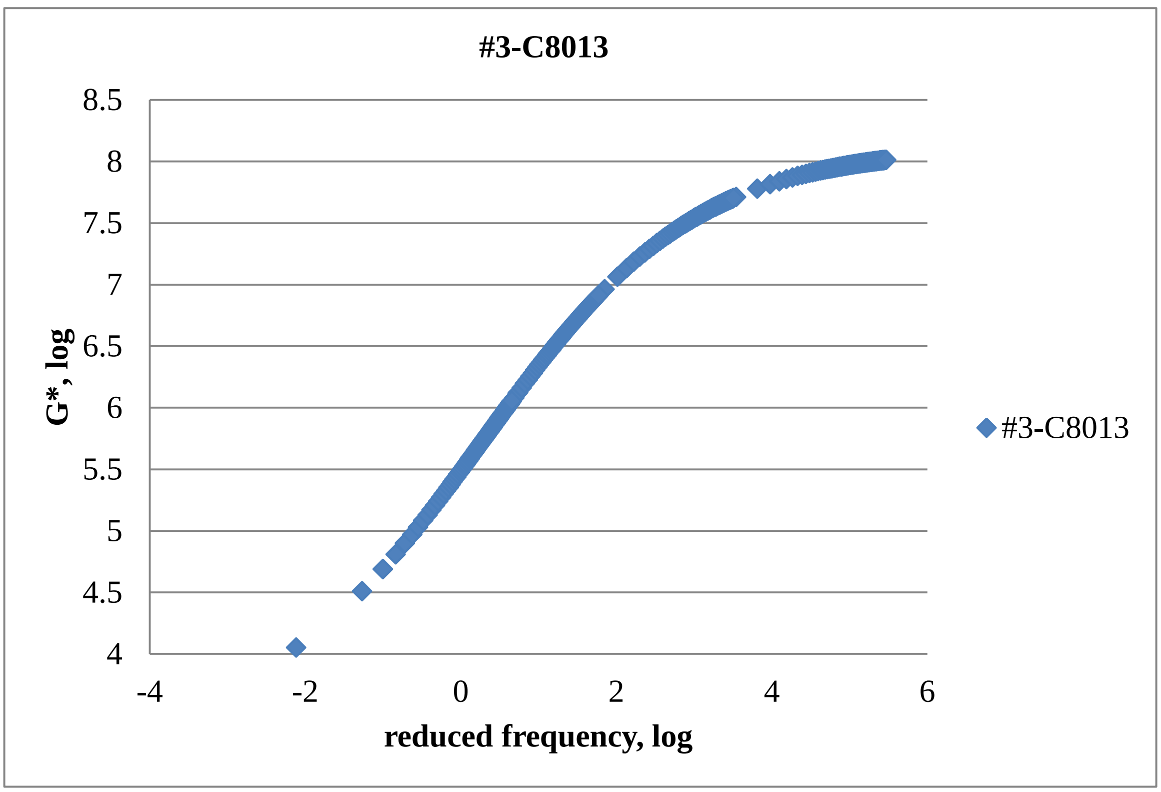
Project No.	Contract No.	Asphalt Content (%)	Pbe(%)	Dust(%)	A/D
#1	C8046	5.4	5.1	6.3	0.81
#2	C8017	5.7	4.6	6.3	0.73
#3	C8013	5.2	4.1	5.7	0.72
#4	C8033	5.2	4.6	5.5	0.84
#5	C8016	5.3	4.6	5.1	0.90
#6	C7879	5.4	4.7	6	0.78
#7	C7465	5.6	4.9	4.9	1.00

D-3: G* of Mastics

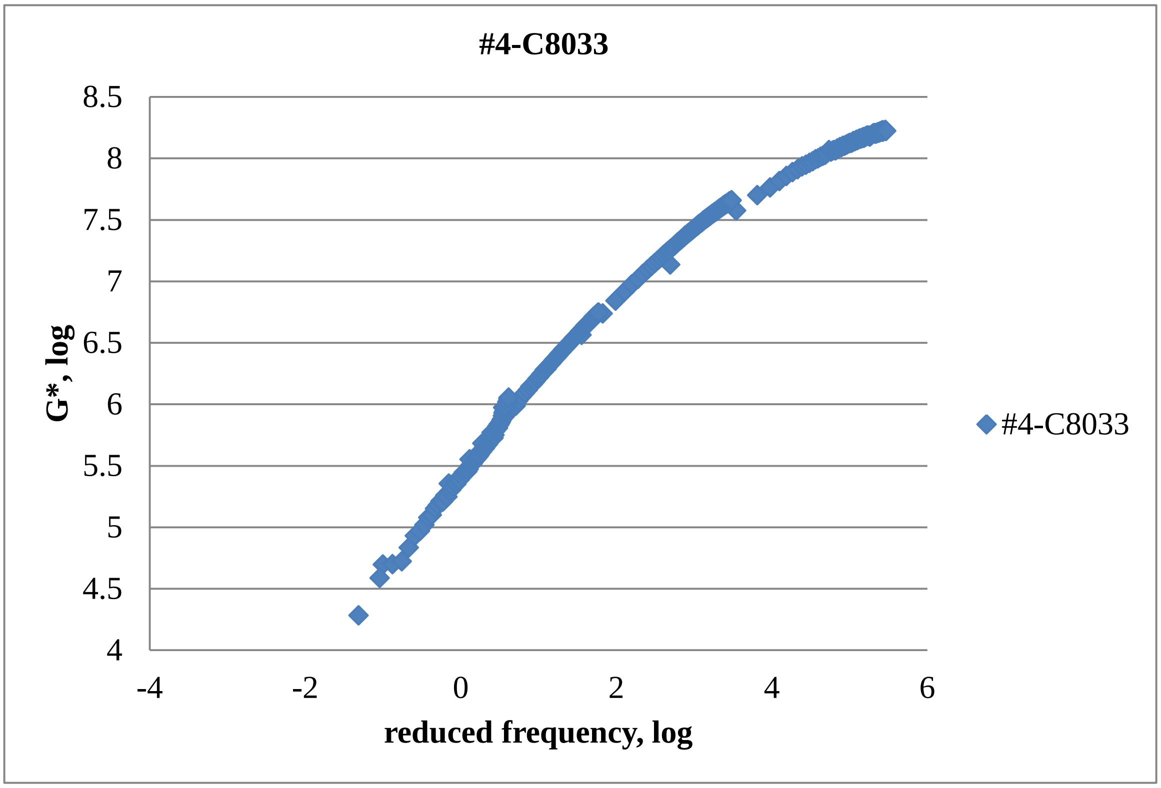


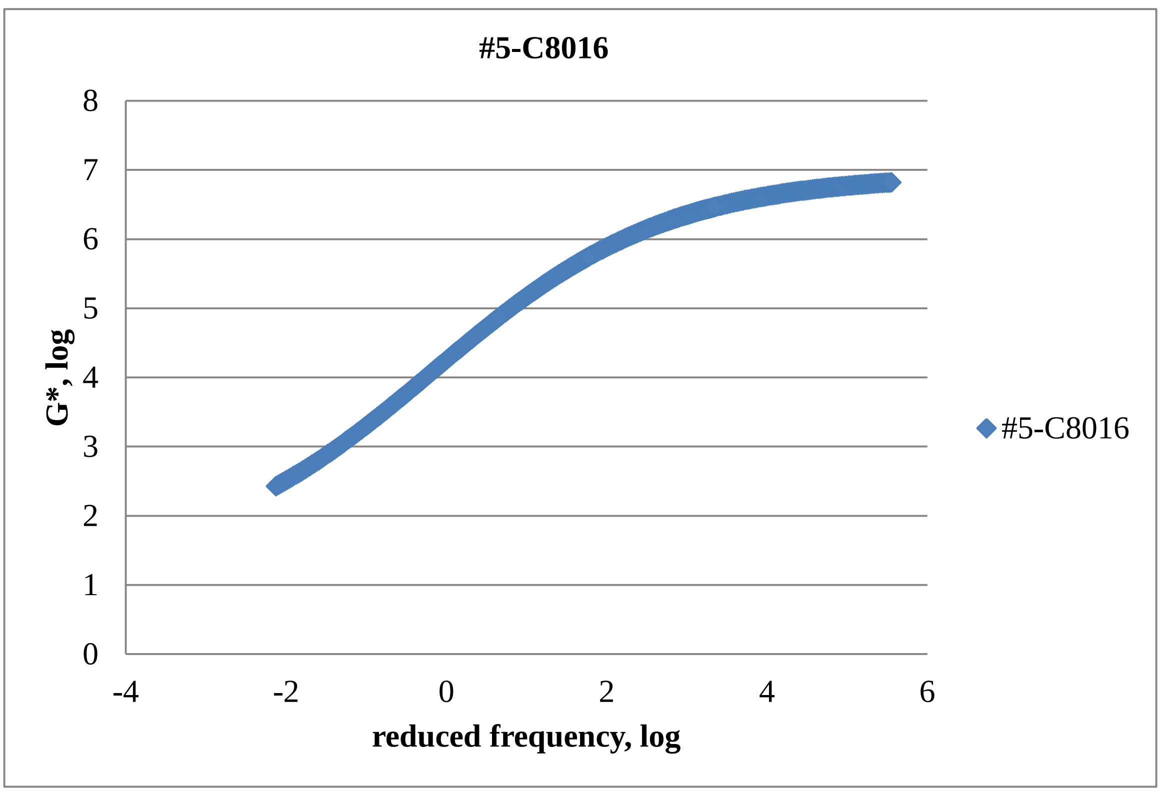


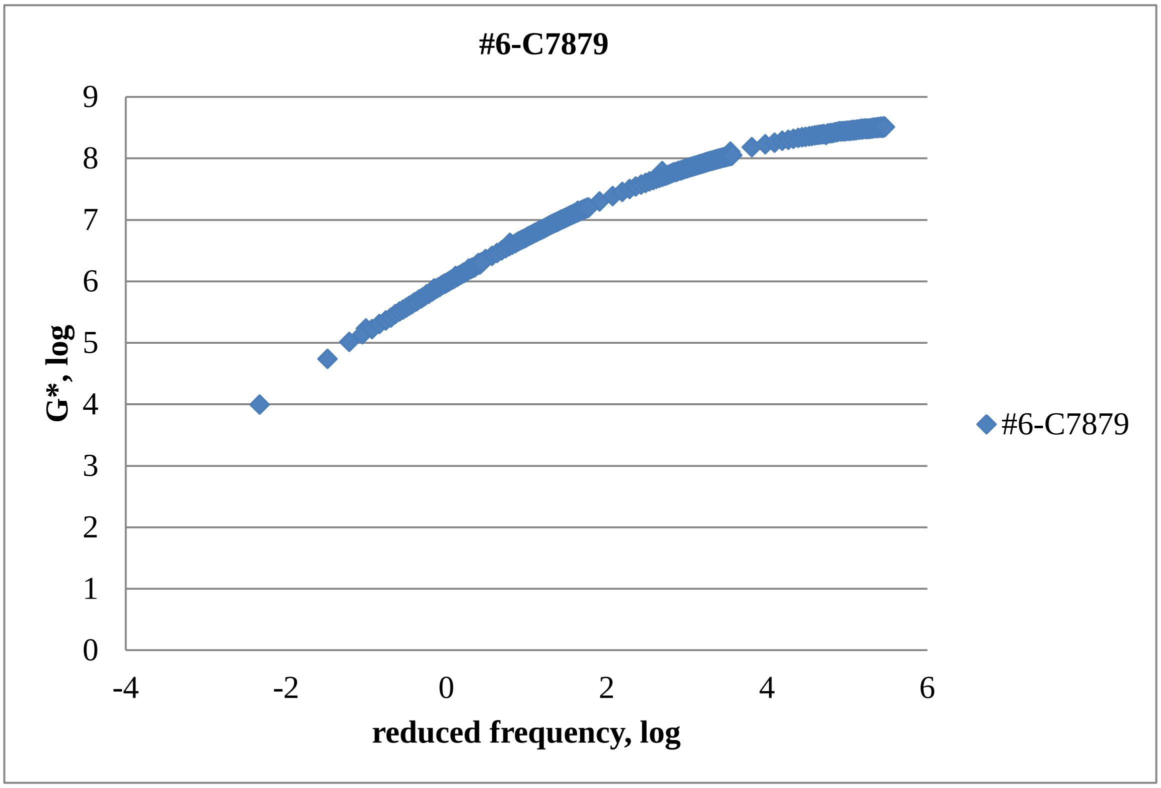
#2-C8017
G*, log
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
-4
-2
0
2
4
6
reduced frequency, log
#2-C8017

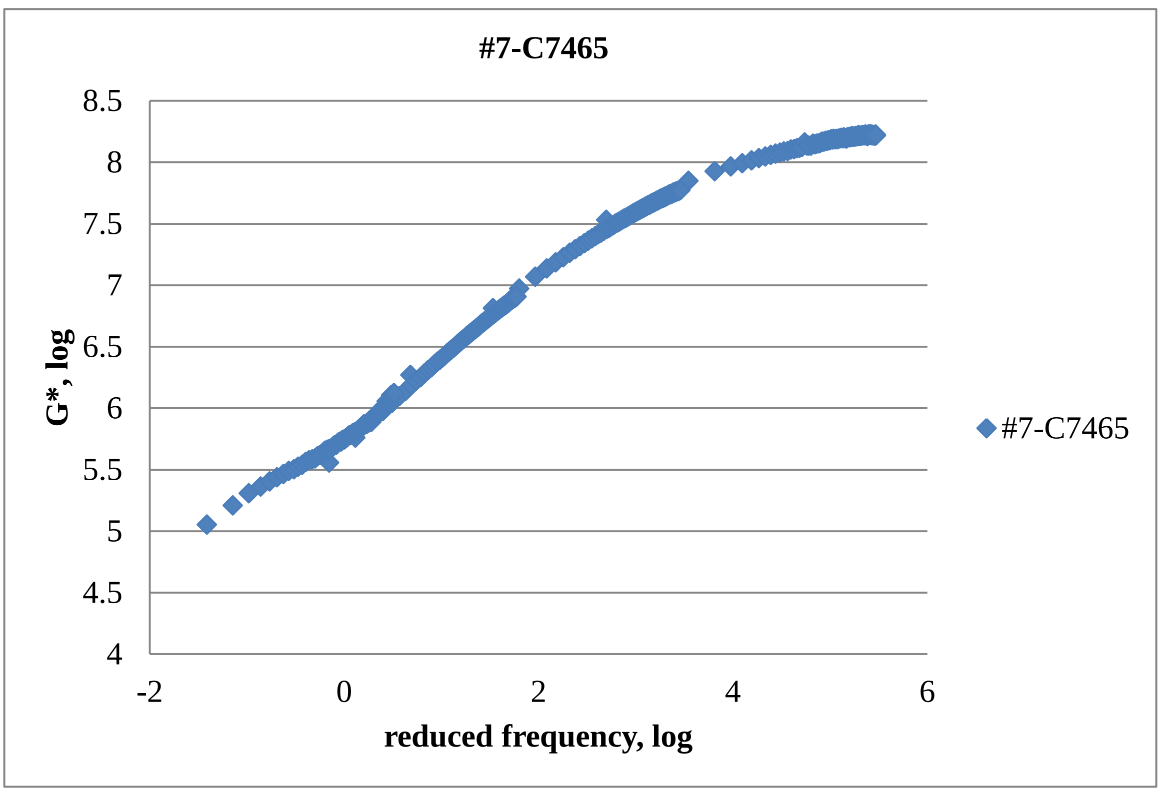


#3-C8013
G*, log
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
-4
-2
0
2
4
6
reduced frequency, log
#3-C8013


#4-C8033
G*, log
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
-4
-2
0
2
4
6
reduced frequency, log
#4-C8033


#5-C8016
G*, log
8
7
6
5
4
3
2
1
0
-4
-2
0
2
4
6
reduced frequency, log
#5-C8016


#6-C7879
G*, log
9
8
7
6
5
4
3
2
1
0
-4
-2
0
2
4
6
reduced frequency, log
#6-C7879


#7-C7465
G*, log
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
-2
0
2
4
6
reduced frequency, log
#7-C7465