

2009

Development of specifications for the superpave simple performance tests

Shu Wei Goh
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**DEVELOPMENT OF SPECIFICATIONS FOR THE SUPERPAVE
SIMPLE PERFORMANCE TESTS**

By
Shu Wei Goh

A Thesis

Submitted in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE IN CIVIL ENGINEERING

MICHIGAN TECHNOLOGICAL UNIVERSITY

2009

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This thesis, "Development of Specifications for the Superpave Simple Performance Tests," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN CIVIL ENGINEERING.

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ABSTRACT

This study describes the development and establishment of a proposed Simple Performance Test (SPT) specification in order to contribute to the asphalt materials technology in the state of Michigan. The properties and characteristic of materials, performance testing of specimens, and field analyses are used in developing draft SPT specifications. These advanced and more effective specifications should significantly improve the qualities of designed and constructed hot mix asphalt (HMA) leading to improvement in pavement life in Michigan. The objectives of this study include the following: 1) using the SPT, conduct a laboratory study to measure the parameters including the dynamic modulus terms ($E^*/\sin\phi$ and E^*) and the flow number (F_n) for typical Michigan HMA mixtures, 2) correlate the results of the laboratory study to field performance as they relate to flexible pavement performance (rutting, fatigue, and low temperature cracking), and 3) make recommendations for the SPT criteria at specific traffic levels (e.g. E3, E10, E30), including recommendations for a draft test specification for use in Michigan. The specification criteria of dynamic modulus were developed based upon field rutting performance and contractor warranty criteria.

ACKNOWLEDGMENTS

The author would like to thank Zhanping You for his continuous guidance for this study.

The author would like to thank the committee members Chris Williams, Jianping Dong and Jacob Hiller who make the defense of this thesis possible. The author would also like to thank Jim Vivian and Ed Tulppo who has been very helpful in keeping the asphalt lab busy. Also thanks to Kari Klaboe, Ryan Brennan, Joshua Marschke and Sarah Shann for their helps in mixing, compacting and testing the asphalt mixture samples.

The research work cannot be complete without the significant contribution of them.

The research work was partially sponsored by Federal Highway Administration through Michigan Department of Transportation. The author appreciates the guidance and involvement of John Barak from the Michigan Department of Transportation. The author also acknowledge the support from Curtis Bleech, Timothy R. Crook, John F. Staton, Michael Eacker, and Steve Palmer in Engineer of Materials Construction and Technology Division; David R. Schade from traffic monitoring information system; and Pat Schafer from Pavement Management section of the Michigan Department of Transportation. The assistance in material collection in the plants of various contractors is highly appreciated.

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CHAPTER 1: INTRODUCTION

Background

The Michigan Department of Transportation (MDOT) has successfully implemented the Superpave volumetric mixture design procedure. Yet, a number of studies have shown that the Superpave volumetric mixture design method alone is insufficient to ensure reliable mixture performance over a wide range of traffic and climatic conditions [1]. Some research projects have been conducted at Michigan Tech through support of MDOT to evaluate the performance of mixtures designed using the volumetric design procedure. However, there has been a lack of a simple performance test (SPT) criteria to evaluate pavement rutting, fatigue cracking, and low temperature cracking of flexible pavements.

The development of an SPT performance criterion has been the focus of considerable research efforts in the past several years. In fact, some aspects of the tests have been available for decades, such as the dynamic modulus test of hot mix asphalt (HMA). Dynamic modulus test was introduced in asphalt pavement area for decades ago [2]. However, the term “dynamic modulus” was around even earlier to describe concrete behavior as described by Valore and Yates [3], Preece [4], and Linger [5].

A few recent research projects on the SPT are introduced here as part of the background information of this thesis. Carpenter and Vavrik (2001) reported on the application of a repeated triaxial test for performance characterization [6]. Goodman et al. (2002) studied the shear properties using SPT testing as an approach for the

characterization of permanent deformation of HMA in Canada [7]. Wen and Kim (2002) investigated SPT testing for fatigue cracking, with validation using WesTrack mixtures [8]. Shenoy and Romero (2002) focused on using the dynamic modulus $|E^*|$ data to predict asphalt pavement distresses [9], whereas Pellinen and Witczak (2002) reported the possibility of using the stiffness of HMA as the basis for the SPT performance criteria [10]. Martin and Park (2003) used the Asphalt Pavement Analyzer (APA) and the repeated simple shear test (SST) to assess rutting performance of mixtures [11]. McCann and Sebaaly (2003) evaluated the moisture sensitivity and performance of lime-modified HMA through use of the resilient modulus, tensile strength, and simple shear tests [12]. Zhou and Scullion (2003) preliminarily validated the SPT for permanent deformation in a field case study, finding that both the dynamic modulus test ($E^*/\sin \delta$) and the repeated-load test (F_n) can distinguish between good and poor performing mixtures [13]. Sotil et al. (2004) investigated the reduced confined dynamic modulus testing protocol for asphalt mixtures [14]. Tandon et al. (2004) investigated the results of integrating an SPT with an environmental conditioning system [15]. Galal et al. (2004) investigated in-service accelerated pavement testing in order to model permanent deformation. More recently, Bonaquist and Christensen (2005) reported a practical procedure for developing dynamic modulus master curves for pavement structural design [16]. Faheem and Bahia (2005) estimated mixture rutting using the rutting rate and the flow number (F_n) from the SPT test for different traffic levels [17]. Yet, even with all this research, an SPT specification that considers specific trafficking levels for engineering application is not available at this time.

As this summary of past research indicates, a considerable number of potential performance tests have been investigated to measure and assess fundamental engineering material properties that can link the advanced material characterization to the development of criteria for HMA mixture design [18]. A number of tests evaluated for the SPT include the dynamic modulus test, shear modulus test, triaxial repeated test, triaxial and uniaxial creep test, triaxial compressive strength test, asphalt pavement analyzer, gyratory shear stress test, indirect tensile strength and fatigue test, direct tensile strength test [18]. The evaluation of the SPT was based on the following criteria:

- Correlation of the HMA response characterization to actual field performance;
- Reliability;
- Ease of use; and
- Equipment cost.

Table 1 lists the experimental test method and relationship to performance (test types, equipment, and associated pavement performance) for selecting an SPT [18]. Based upon the results of a comprehensive testing program, the test-parameter combinations for permanent deformation include: (1) the dynamic modulus term, $E^*/\sin\phi$, which is determined from the triaxial dynamic modulus test, (2) the flow time, Ft , which is determined from the triaxial static creep test, and (3) the flow number, F_n , which is determined from the triaxial repeated load test. These laboratory parameters correlated very well with the pavement performance observed at MnRoad, WesTrack, and in the FHWA Accelerated Load Facility (ALF) experiments. In order to correlate the lab test to

field fatigue cracking performance, the NCHRP Project 9-19 recommended that the dynamic modulus, E^* , measured at low test temperatures, be used [18]. Creep compliance from the indirect tensile creep test at long loading times and low temperatures is recommended for low temperature cracking based on the work carried out for SHRP, C-SHRP, and NCHRP Project 1-37A (Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures) [19].

Table 1 Experimental test method factorial for selecting the Simple Performance Test

Test Method		Distress	
Type of Test / Load	Equipment / Test Geometry	Permanent Deformation	Fracture
Dynamic Modulus Tests	Uniaxial, Unconfined	✓	✓
	Triaxial, Confined	✓	✓
	SST, Constant Height	✓	
	FST	✓	
	Ultrasonic Wave Propagation	✓	✓
	Predictive Equations	✓	✓
Strength Tests	Triaxial Shear Strength	✓	
	Unconfined Compressive Strength	✓	
	Indirect Tensile Strength		✓
Creep Tests	Uniaxial, Unconfined	✓	
	Triaxial, Confined	✓	
	Indirect Tensile		✓
Repeated Load Tests	Uniaxial, Unconfined	✓	
	Triaxial, Confined	✓	
	SST, Constant Height	✓	
	FST	✓	
	Indirect Tensile		✓

Problem Statement

The Michigan Department of Transportation (MDOT) has successfully implemented the Superpave volumetric mixture design method. However, the Superpave volumetric mix design method alone is insufficient to ensure reliable mixture performance as a mixture that has passed the Superpave volumetric mix specification may still perform poorly in rutting, low temperature cracking, and/or fatigue cracking. In order to minimize poor mixture performance, many researchers and agencies have employed laboratory testing such as the dynamic modulus test, shear modulus test, triaxial repeated load test, triaxial and uniaxial creep test, triaxial compressive strength test, asphalt pavement analyzer (APA) rutting test, gyratory shear stress test, four point beam fatigue test, indirect tensile strength, fatigue test, direct tensile strength test, and many others. However, it is time consuming and costly to conduct all these tests and even if all these tests could be done, it is still difficult to conclude if a given mixture will resist rutting, low temperature cracking, and fatigue cracking. NCHRP Project 9-19 provided five parameters that should be obtained from the SPT to ensure mixture performance:

- 1) Dynamic modulus terms ($E^*/\sin\phi$);
- 2) Flow number (F_N);
- 3) Dynamic modulus (E^*); and
- 4) Creep compliance ($D(t)$).

In order to utilize the five parameters from the SPT, it is necessary to correlate these parameters to a specific mixture and pavement design. Of these five parameters, dynamic modulus terms ($E^*/\sin\phi$ and E^*) and the flow number (F_n) are used to reflect

pavement rutting and fatigue potential. Therefore, the question is, for a given traffic level (e.g. E1, E3, E10, or E30), what specification criteria (in terms of these parameters) is required to ensure adequate performance?

Objectives

The objectives of this study include the following: 1) using the SPT, conduct a laboratory study to measure the five parameters including the dynamic modulus terms ($E^*/\sin\phi$ and E^*) and the flow number (Fn) for typical Michigan HMA mixtures, 2) correlate the results of the laboratory study to field performance as they relate to flexible pavement performance (rutting, fatigue, and low temperature cracking), and 3) Make recommendations for the SPT criteria for specific traffic levels (e.g. E3, E10, E30), including recommendations for a draft test specification for use in Michigan. Additionally, this study involved both laboratory testing and field data collection.

CHAPTER 2: LITERATURE REVIEW

Introduction

An asphalt mixture is a composite material of graded aggregates bound with asphalt binder plus a certain amount of air voids. The physical properties and performance of asphalt mixture is governed by the properties of the aggregate (e.g. shape, surface texture, gradation, skeletal structure, modulus, etc.), properties of the asphalt binder (e.g., grade, complex modulus, relaxation characteristics, cohesion, etc.), and asphalt-aggregate interactions (e.g., adhesion, absorption, physio-chemical interactions, etc.). Therefore, the structure of an asphalt mixture is very complex, which makes properties (such as stiffness and tensile strength) for design and prediction of field performance very challenging.

Traditionally, Marshall and Hveem designs were used in designing the asphalt mixtures for pavements. The objective of these designs was to develop an economical blend of aggregates and asphalt binders that meet the design expectations as defined by various parameters. However, due to the increasing traffic loads and traffic volumes, the reliability and durability of these designs have been significantly affected. In the United States, asphalt pavements have experienced increased rutting and fatigue cracking leading to poorer ride quality and can become a major concern due to road safety. The U.S. government spends millions of dollars annually on highway pavement construction, maintenance and rehabilitation to provide a national transportation infrastructure system capable of maintaining and advancing the national economy. Providing a safe and

reliable transportation system requires continual maintenance. Therefore, higher quality asphalt pavements are necessary to build a more durable, safer, and more efficient transportation infrastructure.

From 1987 to 1993, the Strategic Highway Research Program (SHRP) examined new methods for specifying tests and design criteria to ensure a high quality asphalt material [20, 21]. The final product of the SHRP asphalt research program is a new system referred as Superpave, which stand for Superior Performing Asphalt Pavements [22-24]. Asphalt mixture performance is affected by two major factors: climate and traffic loading. The Superpave design system was first to collect the HMA responses from different climate and traffic load, analyze the responses, and provide recommendations and limitations based on the responses versus the severity of distress. It represents an improved system for specifying the components of asphalt concrete, asphalt mixture design and analysis, and asphalt pavement performance prediction [21, 23-26]. All these analysis and limitations of each test were to design an asphalt concrete to reduce the potential of three major distresses – rutting, thermal cracking, and fatigue cracking in asphalt pavements.

From a materials design aspect, the Superpave volumetric mixture design method has been a success in many states. However, results from WesTrack, NCHRP Project 9-7 claimed that the Superpave design alone was insufficient to ensure the reliability of mixture performance over a wide range of climate and traffic conditions [27]. In order to minimize poor mixture performance, researchers [28-33] and agencies have employed laboratory testing such as the dynamic modulus test, shear modulus test, triaxial repeated

load test, triaxial and uniaxial creep test, triaxial compressive strength test, asphalt pavement analyzer (APA), gyratory shear stress test, four point beam fatigue test, indirect tensile strength and fatigue tests, direct tensile strength test, and many others. However, conducting these tests is time consuming and costly to and even if all these tests could be done, it is still difficult to conclude if a given mixture will resist rutting, low temperature cracking, and fatigue cracking. Additionally, industry also expressed their needs for a more simple type of testing to be used in pavement design especially design-build or warranty type projects [27, 34]. The development of Simple Performance Test (SPT) is an example of industry's effort toward this objective.

The Federal Highway Administration (FHWA) opened a request for proposals for SPT development in 1996. In addition, this project was going to be used in conjunction with a new pavement design guide (e.g. the Mechanistic-Empirical Pavement Design Guide) [35]. The SPT primary focus was on identifying a fundamental property of asphalt mixtures that could be used in the pavement design guide. It was defined as “a test method(s) that accurately and reliably measures a mixture response characteristic or parameter that is highly correlated to the occurrence of pavement distress (e.g. cracking and rutting) over a diverse range of traffic and climate conditions” [27].

NCHRP Project 9-19 recommended several parameters that should be obtained from the Simple Performance Test (SPT) to ensure mixture performance: dynamic modulus terms ($E^*/\sin\phi$ and E^*) and the flow number (F_N). These tests were found to have a good correlation with field performance [36]. The dynamic modulus terms are the most critical with respect to the Mechanical-Empirical Pavement Design Guide (MEPDG)

[34, 37-39]. The MEPDG relies heavily on the E^* of asphalt mixtures for nearly all predictions of pavement deterioration. Therefore, the dynamic modulus must be measured or estimated. The assessment of these critical material properties is intended to provide the basis for better understanding of pavement response and performance.

In this project, $|E^*|$ and F_N were evaluated. The advantages and disadvantages of the $|E^*|$ and F_N tests are shown in Table 2 [27]. Over the past few years, researchers have also tried to develop different parameters used in $|E^*|$ and flow number F_N . In addition, different kind of analysis methods on $|E^*|$ and F_N were developed, such as master curve development, viscoelastic models, etc. The main purpose of the literature review is to collect information from laboratory experiment and previous research on the $|E^*|$ and F_N .

Table 2 Simple Performance Test's Advantages and Disadvantages

Test	Advantages	Disadvantages
Dynamic Modulus	<ul style="list-style-type: none"> - An important parameter in level 1 Mechanistic-Empirical Design Guide (Direct input) - Master curve is not necessary - Can be easily linked to established regression and this can provide a preliminary parameter for mix criteria - Non destructive Test 	<ul style="list-style-type: none"> - Sample fabrication (coring and sawing) - The possibility of minor error in measuring the mixture responses due to arrangement of LVDTs - Poor result obtained from confined testing and this need a further study on its reliability.
Repeated Loading (Flow Number)	<ul style="list-style-type: none"> - Easy to operate - Affordable (inexpensive) - Provide a better correlation in field rutting distress. 	<ul style="list-style-type: none"> - Specification is hard to establish - May not simulate traffic/ field condition (dynamic loading) - Sample fabrication (coring and sawing)

Dynamic Modulus

The dynamic modulus ($|E^*|$) is the ratio of stress to strain under haversine (or sinusoidal) loading conditions [40-42]. It is one of the parameters to characterize the stiffness of HMA [43] and is used as one of the material characterization inputs in the level 1 and 2 MEPDG to model pavement performance [42, 44, 45].

For viscoelastic materials (e.g. asphalt mixtures), dynamic modulus is often referred to as the magnitude or the absolute value of complex modulus. Scientifically, the complex modulus is a composite number including the elastic and viscous parts (viscoelastic component). It consists of elastic or storage component (E') and a viscous or loss component (E'') [46]. The E' represents energy store in the material, and the E'' represents the loss of the energy in the entire system [43, 46, 47]. Thus, the equation for the complex modulus (E^*) can be written as [43]:

$$E^* = E' + i \cdot E''$$

where,

E^* : Complex modulus;

E' : Storage modulus;

E'' : Loss modulus; and

i : $\sqrt{-1}$.

The E' and E'' were different at different rate of loadings (frequencies) and temperatures. As indicated previously, dynamic modulus is the magnitude of complex modulus. Thus, it can be express as [47]:

$$|E^*| = \sqrt{(E')^2 + (E'')^2}$$

The phase angle, which defined as the responded strain lags behind the applied stress, is expressed as:

$$\phi = \frac{E''}{E'}$$

The phase angle appears to be 0° for a pure elastic material and 90° for a pure viscous material. All these relationships are shown in Figure 1:

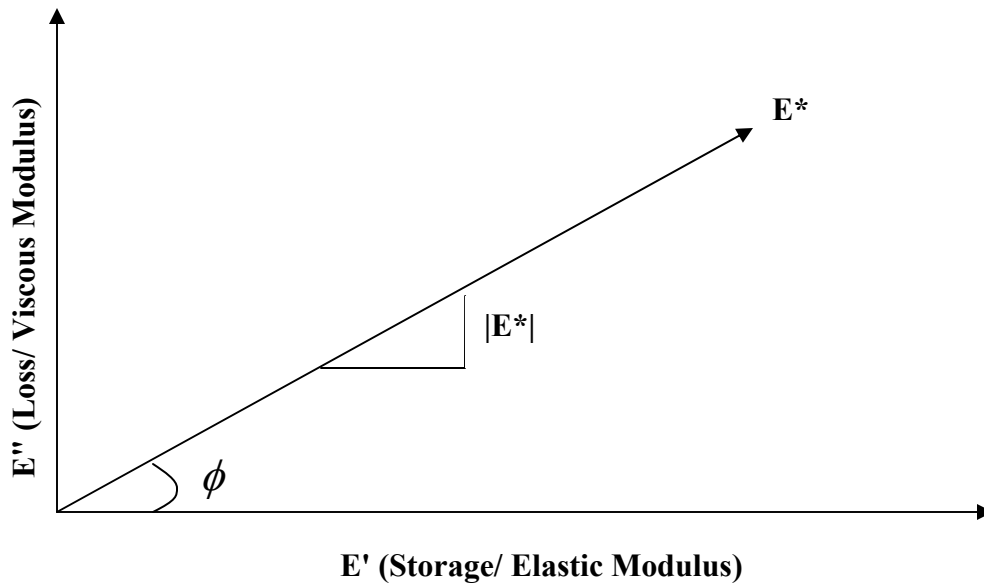


Figure 1 Relationships of Dynamic Modulus

Currently, there are two general approaches in determining the dynamic modulus, E^* : one is based upon experimental tests and the other is a prediction one. In the prediction approach, there are two major methods, one is the discrete and finite element methods [48-53]; the other method is using the empirical equations [31, 54] or micromechanical predictive equations [16].

Dynamic Modulus Literature Reviews

The dynamic modulus, $|E^*|$ is not a new concept in asphalt pavement area. The first dynamic modulus test procedure was developed by Papazian (1962) which described asphalt mixture as a viscoelastic material [2, 55]. Papazian applied a sinusoidal stress at different frequencies and found out that the responses of asphalt mixtures were lagged by an angle ϕ [2]. Thus, Papazian concluded that there is a complex relationship which is the function of loading rate between stress (applied) and strain (response) [2]. In 1964, Coffman et al (1964) performed $|E^*|$ testing using the mixture simulated from the AASHO Road Test [35, 56]. He found out the basic relationship of viscoelastic material that $|E^*|$ increased when temperature decreased, and when temperature increased, phase angle increased. In 1969, Shook and Kallas (1969) studied the factors that affected the $|E^*|$ measurement [57]. They conducted $|E^*|$ testing over various temperatures and frequencies on mixtures and varied the mixture components (e.g. asphalt content, air void, viscosity and compaction effort). Shook and Kallas determined $|E^*|$ increased with a decrease in air and asphalt content, and compaction effort [57]. Additionally, Shook and Kallas also found the $|E^*|$ increased when viscosity increased [57].

Witczak et al. (2002) indicated that $|E^*|$ testing has a good correlation with field performance based on the several rutting test results (i.e. WesTrack, FHWA's Accelerated Loading Facility (FHWA ALF) and MnRoad) [29, 30]. They also found that $E^*/(\sin\phi)$ tested at unconfined condition shows the strongest relationship with field performance. For $|E^*|$ tested at confined condition, poor relationship was found when compared to field performance [30]. For the relationship between $|E^*|$ test with fatigue

and thermal cracking, Witczak et al. indicated that none of the results showed a good relationship after running numerous $|E^*|$ tests at low temperatures with confined and unconfined condition [30]. However, they indicated that $|E^*|_{\max}/(\sin\phi)$ at unconfined condition were highly correlated with field fatigue distress.

A further field validation of SPT development in terms of $|E^*|$ was conducted by Zhou and Scullion (2003) [13]. A total of 20 test sections (known as Special Pavement Studies-1) were constructed using the same degree of traffic level on US-281 in Texas. The permanent deformation of these test sections was then measured by Zhou and Scullion using a trenching operation. Zhou and Scullion (2003) analyzed and compared results from the test sections with laboratory $|E^*|$ test results, and concluded that $|E^*|/(\sin\phi)$ can effectively distinguish the quality of the mixture in terms of rutting susceptibility. Similar relationship between $|E^*|$ and rutting from Witczak et al. (2002) was found by Zhou and Scullion (2003) that $|E^*|$ increased, the rutting depth decreased.

Clyne et al (2003) evaluated $|E^*|$ and phase angle of asphalt mixture from four different MnROAD test sections [55]. Six temperatures (range from -20°C to 54.4°C) and five frequencies (range from 0.01 to 25 Hz) were used. The results from Clyne et al (2003) indicated that phase angle increased as the temperature increased from -2 to 20°C . However, for high temperatures at 40°C to 50°C , the phase angle decreased when the temperature increased. The reason of decreased phase angle at high temperature is the aggregate interlock becomes the controlling factor at high temperatures. Mohammad et al. (2005) also performed an evaluation of $|E^*|$ [58]. The testing included both field and laboratory prepared samples. The main results obtained from the testing included [58]:

1. When asphalt content in the mixture decreased, the $|E^*|$ increased and the ϕ decreased.
2. The ϕ decreased with an increase in frequency at 25°C. At high temperature (i.e. 45°C and 54°C), the phase angle increased with frequency increased up to approximately 10hz, and ϕ began to decrease.
3. No statistical difference was identified for the test results from multiple days of production.

Dynamic Modulus Test Setup

The dynamic modulus test was conducted according to AASHTO TP62-03 [59]. A sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt mixture at a given temperature and loading frequency. Figure 2 shows the test set up, where the sample of an asphalt mix specimen is loaded under the compressive test. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle. The dynamic modulus is defined as the ratio of the amplitude stress (σ) and amplitude of the sinusoidal strain (ϵ) that results in a steady state response at same time and frequency as shown in Figure 3:

$$E^* = \frac{\sigma}{\epsilon} = \frac{\sigma_0 e^{i\omega t}}{\epsilon_0 e^{i(\omega t - \phi)}} = \frac{\sigma_0 \sin(\omega t)}{\epsilon_0 \sin(\omega t - \phi)}$$

where,

σ_0 : peak (maximum) stress;

ϵ_0 : peak (maximum) strain;

ϕ : phase angle, degrees;

ω : angular velocity; and

t: time, seconds.



Figure 2 Dynamic Modulus Test Setup

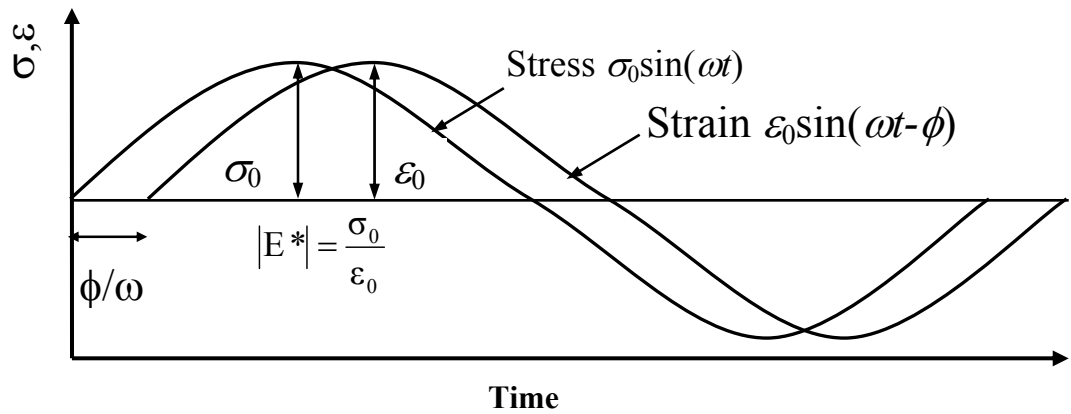


Figure 3 E^* as a Function of Temperature, Rate of Loading (Frequencies), Aging, and Volumetric Properties

Strain Level for Dynamic Modulus Test

The SPT suggested strain level used in dynamic modulus test should be adjusted between 50 to 150 micro-strains. However, this range may be too large and would affect the variability and the accuracy of the result [60]. In addition, a large recoverable axial micro-strain (e.g. 150 micro-strain) might exceed the viscoelastic range of an asphalt mixture [60]. Figure 4 shows the comparison of $|E^*|$ between 50-100 micro-strains and 100-150 micro-strains. Observation from Figure 4 indicates that results tested within the range of 50-100 micro-strains have lower $|E^*|$. Tran and Hall suggested the strain level be controlled between 50 to 100 micro-strains so it would not affect the material's viscoelastic behavior [60].

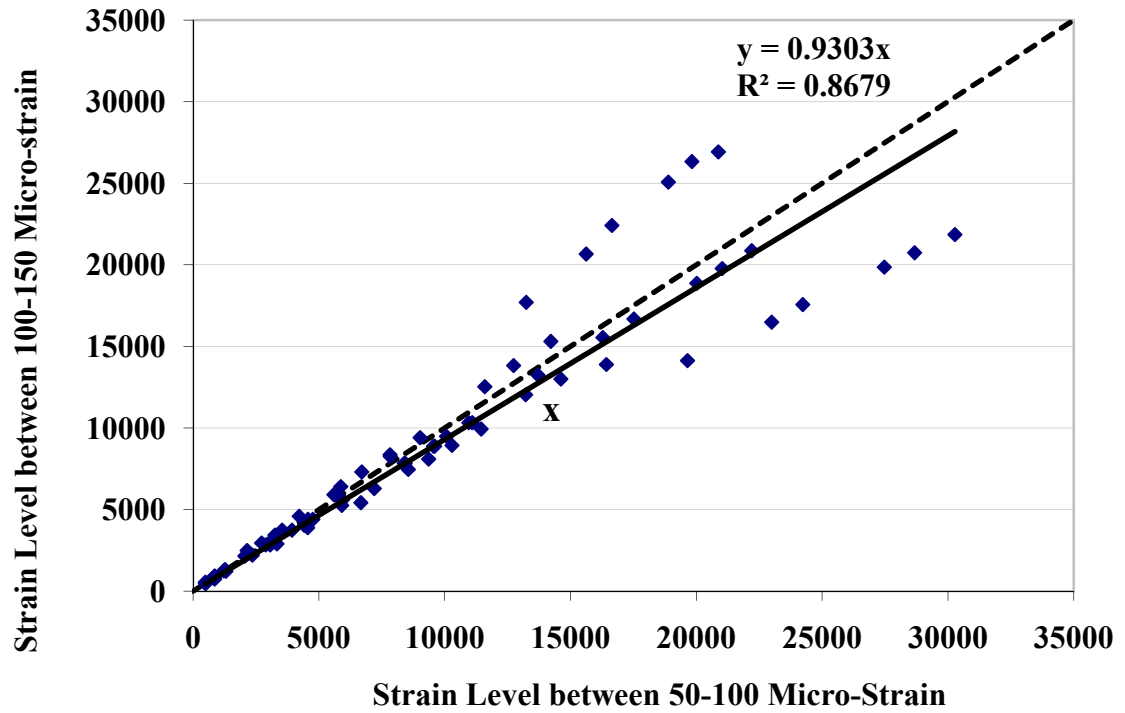


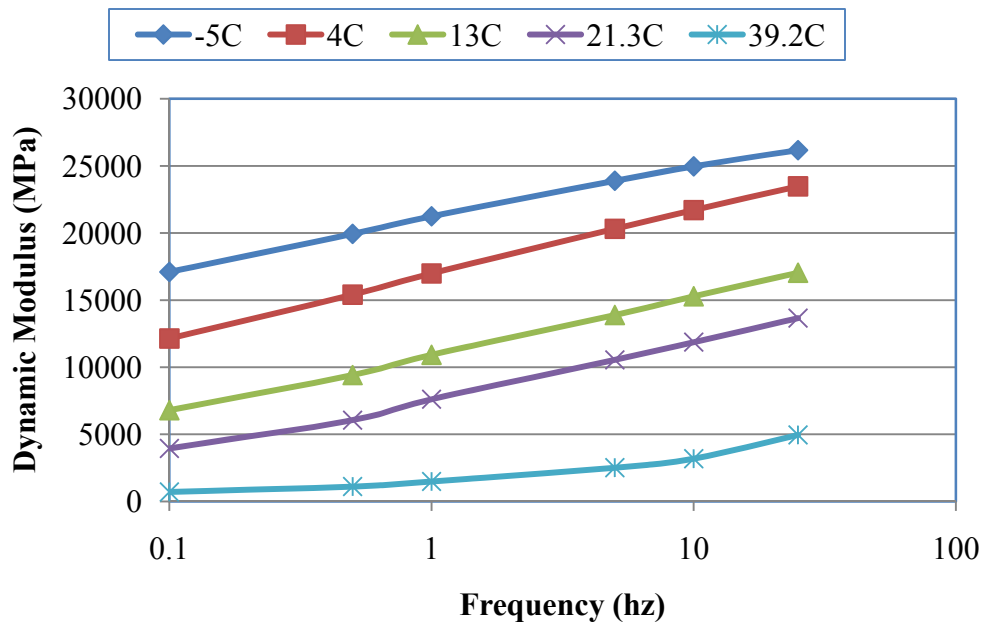
Figure 4 Comparison of $|E^*|$ at Strain Level between 50-100 micro-strains and 100-150 micro-strains

Dynamic Modulus Master Curve

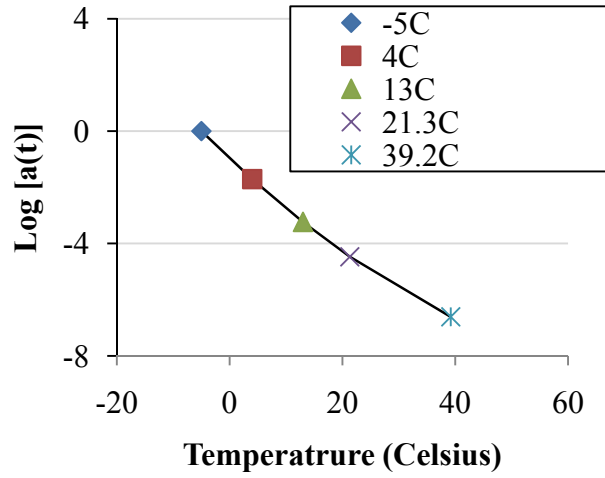
In the latest MEPDG design, all levels of temperature and rate of loading (frequency) is determined from a master curve constructed at a reference temperature [32, 43]. Master curves are constructed using the principal of time-temperature superposition or time-temperature equivalence [48]. The time-temperature superposition reflected the viscoelastic behavior of asphalt mixtures or that it showed the movement or flow of an asphalt could be same either at high temperature and shorter time of loading, or low

temperature at longer loading time [61, 62]. The behavior of this kind of material was often referred to as thermorheologically simple (TRS) [43, 63].

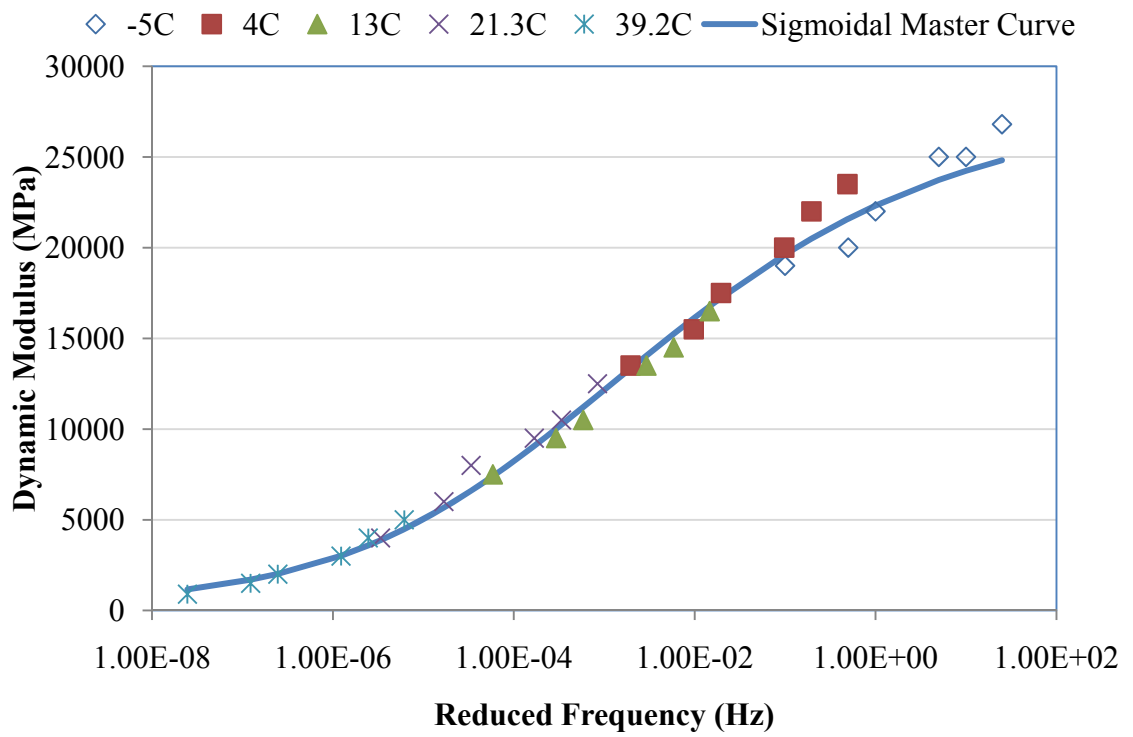
Figure 5 shows a sample of dynamic modulus data obtained from the lab test [64]. As expected, the dynamic modulus increases when the temperature decreases and the loading frequency increases [65]. These data at various temperatures can be simplified and superimposed to form a single curve called a master curve. A physical observation from Figure 5(c) supports the use of a sigmoidal function to describe the behavior of asphalt mixtures. At the upper end of the function, the mixture's stiffness is bound by the limiting of the binder stiffness. At the lower end function, the mixture's stiffness is governed by aggregate influences.



(a)



(b)



(c)

Figure 5 Typical data (a) Before Shifting, (b) Shift Factor vs. Temperature and (c) After Shifting

The master curve of the modulus, as a function of time formed in this manner describes the time dependency of the material [66]. The relationships between the amount of horizontal shift, temperature, loading frequency, and the reduced frequency are initially defined as follows [66-68]:

$$a_T = \frac{f_{T_0}}{f_T}$$

where,

a_T : Frequency-temperature shift factor for temperature T;

f_{T_0} : Reduced frequency at the reference temperature (T_0); and

f_T : Frequency at temperature T.

After years of testing by researchers, a second order polynomial relationship between the logarithm of the shift factor [$\log(a_T)$] and the temperature in Fahrenheit (T_i) show more precise results [65]. The relationship can be expressed as follows [66, 68, 69]:

$$\log[a(t)] = a \cdot t^2 + b \cdot t + c$$

where,

t: Temperature of interest; and

a, b, c: Regression coefficients.

The amount of shifting at each temperature required to form the master curve describe the temperature dependency of the material. In general, the master modulus curve can be mathematically modeled by a sigmoidal function describe as the equation below:

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

where,

δ : The minimum value of all Log(E*measure);

α : Maximum value of all Log(E*measure) – δ ;

β, γ : Regression Coefficients; and

t_r : Reduced time of loading at reference temperature.

In order to minimize the error between predicted E* from master curve and lab measured E*, an error minimization technique was used. This technique was accomplished by using the Solver module in Microsoft's Excel to find out all the regression coefficients.

Dynamic Modulus Predictive Model

Dynamic modulus of asphalt mixtures is dependent upon the properties of the individual components and volumetric composition of the mixes. Dynamic modulus of the asphalt mixes is predictable if the properties of components are known. An asphalt mixture shows viscoelastic phenomena due to viscous characteristics of the binder [70, 71]. There are some empirical relationships available for predicting dynamic modulus for mixtures.

Several predictive models were developed for |E*| including the Witczak and Hirsch Models. In 1985, Akhter and Witczak (1985) were trying to identify variables that would affect the |E*| [72]. They evaluated more than 130 mixtures and determined temperature and frequency were the most significant factors in the |E*| predictive model

[35, 72]. In addition, they also found that coarse aggregate and gap-graded mixtures have higher $|E^*|$, resulted in a longer pavement life [72].

In this recent report, two predictive models (Witczak and Hirsch models) were discussed. The Witczak and Hirsch models were developed using aggregate properties, gradation and asphalt binder properties (e.g. dynamic shear modulus of asphalt binder at various temperatures and frequencies) [73]. Typically, properties of short-term aged (Rolling-Thin Film Oven aging) asphalt binder was used [64]. The following section discussed a more detail of Witczak's prediction equation and Hirsch's model.

Witczak's Predictive Equation

In the current MEPDG (NCHRP I-37A) [74], the stiffness of asphalt mixtures is determined from a sigmoidal E^* master curve using one of three alternate input levels. The master curve for input Level 1 design is developed using numerical optimization to shift the laboratory mixture E^* test data into a master curve [32, 33, 54]. Before shifting the $|E^*|$ data, the relationship between binder viscosity and temperature is established by:

$$\eta = \frac{|G_b^*|}{10} \left(\frac{1}{\sin \delta_b} \right)^{4.8628}$$

$$\log \log \eta = A + VTS \log T_R$$

where,

- η : Binder viscosity, cP;
- $|G_b^*|$: Binder complex shear modulus, Pa;
- δ_b : Binder phase angle, degrees;

A, VTS: Regression parameter; and

T_R: Temperature, °Rankine.

The master curve for the Level 2 input is directly determined from the “Witczak |E*| Predictive Equation”, using specific laboratory binder test and mixture data. The Level 3 input is developed using this predictive equation and certain (typical) properties of the binder and mix. The current version of the Witczak |E*| Predictive Equation is as follows:

$$\log_{10} |E^*| = -0.349 + 0.754 \left(|G_b^*|^{-0.0052} \right) \times \left(6.65 - 0.032\rho_{200} + 0.0027\rho_{200}^2 - 0.011\rho_4 - 0.0001\rho_4^2 + 0.006\rho_{38} - 0.00014\rho_{38}^2 - 0.08V_a - 1.06 \left(\frac{V_{beff}}{V_a + V_{beff}} \right) \right) + \frac{2.56 + 0.03V_a + 0.71 \left(\frac{V_{beff}}{V_a + V_{beff}} \right) + 0.012\rho_{38} - 0.0001\rho_{38}^2 - 0.01\rho_{34}}{1 + e^{(-0.7814 - 0.5785 \log |G_b^*| + 0.8834 \log \delta_b)}}$$

where,

|E*|: Dynamic modulus, psi;

ρ₂₀₀: Percent of aggregate (by weight of the total aggregate) passing through no. 200 sieve, %;

ρ₄: Percent of aggregate (by weight of the total aggregate) retained on no. 4 sieve, %;

- ρ_{38} : Percent of aggregate (by weight of the total aggregate) retained on the 3/8 inch sieve, %;
- ρ_{34} : Percent of aggregate (by weight of the total aggregate) retained on the 3/4 inch sieve, %;
- V_a : Air voids (by volume of the mix), %;
- V_{beff} : Effective binder content (by volume of the mix), %;
- $|G_b^*|$: Dynamic shear modulus of binder, psi; and
- δ_b : Phase angle of binder associated with $|G_b^*|$, degrees.

The relation of the predicted and measured dynamic modulus is as follow:

$$|E^*|_{measured} = \Delta \cdot |E^*|_{Predicted}$$

where,

$|E^*|_{measured}$: Dynamic Modulus from laboratory measurement;

Δ : Calibration factor, constant; and

$|E^*|_{Predicted}$: Dynamic Modulus from Witczak's equation.

Hirsch Model

The Hirsch Model was developed by Christensen et al. (2003) to estimate the dynamic modulus of asphalt concrete using the binder dynamic modulus and volumetric properties of the mixture (VMA and VFA). The equation was expressed as following equation.

$$|E^*|_{mix} = P_C \left[4200000 \left(1 - \frac{VMA}{100} \right) + 3 |G^*|_b \left(\frac{VFA * VMA}{1000} \right) \right] + (1 - P_C) \left[\frac{1 - \frac{VMA}{100}}{4200000} + \frac{VMA}{3VFA * |G^*|_b} \right]^{-1}$$

where,

- $|E^*|_{mix}$: Complex modulus for mixture, lb/in²;
 $|G^*|_b$: Complex modulus for binder, lb/in²; and
 P_C : The contact factor.

The contact factor was expressed as following equation:

$$P_C = \frac{\left(20 + \frac{VFA * 3 |G^*|_b}{VMA} \right)^{0.58}}{650 + \left(\frac{VFA * 3 |G^*|_b}{VMA} \right)^{0.58}}$$

where,

- VFA : Voids filled with asphalt, %;
VMA : Voids in mineral aggregate, %; and
 $|G^*|_b$: Dynamic shear modulus of binder, lb/in².

Similar to Witczak's model, the relation of the predicted and measured dynamic modulus is as follow.

$$|E^*|_{measured} = \Delta \cdot |E^*|_{Predicted}$$

where,

- $|E^*|_{measured}$: Dynamic Modulus from laboratory measurement;
 Δ : Calibration factor, constant; and
 $|E^*|_{Predicted}$: Dynamic Modulus from the Hirsch Model.

Potential Uses of Dynamic Modulus in Pavement Rutting Performance

Witczak (2007) indicated that $|E^*|$ could be used as the specification and guideline to control the pavement rutting performance [32, 34, 75]. The relationship of $|E^*|$ and rutting can be established by graphing $|E^*|$ versus rutting depth. This graph can be generated for various traffic levels, climatic and structural conditions, and any combination of them [75]. As mentioned previously, $|E^*|$ is a measurement of mixture stiffness. Mixtures that have higher $|E^*|$ tend to have a better rutting resistance (stiffer). Figure 6 shows a typical chart of using $|E^*|$ as the specification in rutting performance's quality control [75]. There are two zones/ phases in Figure 6, which are "Accepted" and "Rejected". "Accepted" indicated allowed rutting depth used in the design and "Rejected" is the rut depth exceeds the design limit. Additionally, the "rutting failure criteria" is the minimum allowed rut depth for the design. The benefits of using this graph is that engineers can evaluate different types of asphalt mixtures based on $|E^*|$ test results by comparing the rutting depth with $|E^*|$ [75]. Thus, engineers can design an appropriate pavement with rutting resistance using a specific $|E^*|$.

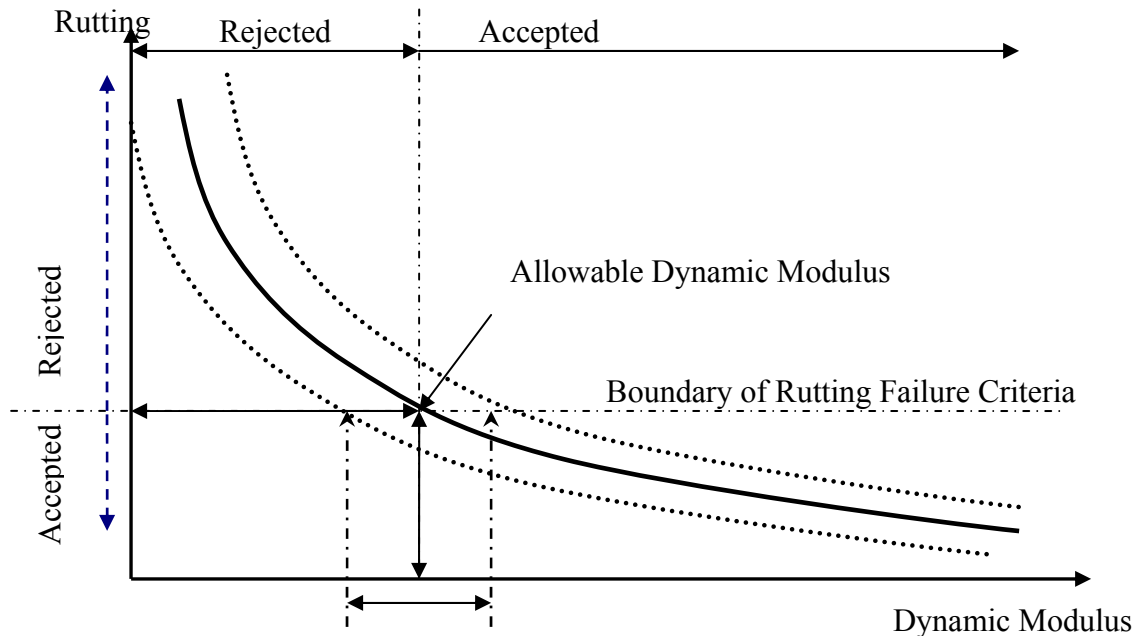


Figure 6 Quality Control using Dynamic Modulus for Rutting Distress

Mechanistic Empirical Pavement Design Guide for Asphalt Pavements

The Mechanistic-Empirical Pavement Design Guide (MEPDG) was used to assess the pavement distress level. It is combination of mechanistic and empirical approaches. The MEPDG was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A and is designed to be adopted by the American Association of State Highway and Transportation Officials (AASHTO) for use as the future pavement design guide for the public and private sectors [45, 76]. Mechanistic design means purely scientific design and based on theoretical formula of structural loading. Empirical design is based on experience or experiments and linked to the performance. The development of the MEPDG is based on the collective experience of pavement experts, data from road

tests, calculation of pavement response, and mechanistic and empirical pavement performance models [76, 77]. It is directly involved with using climate, materials and traffic data to estimate pavement distress. Users enter trial design with repeated traffic, climate and materials input. The user inputs the design life and acceptable performance in terms of key distresses. The software shows performance vs. time in graphical and tabular formats. A user can either retain or modify the design based upon the estimated distress levels. The M-E design allows a wide range of pavement structure like new construction, reconstruction, rehabilitation and overlays. Figure 7 illustrates the NCHRP asphalt pavement M-E design process. It allows for traffic volume adjustment factors like monthly and hourly distribution, vehicle class distribution and axle load distribution. It also uses the Enhanced Integrated Climatic Model (EICM) to understand how a developed pavement design will perform due to varying climatic conditions. The EICM uses specific and detailed inputs of asphalt and concrete pavement like modulus and thermal conductivity, heat capacity, absorption and drainage. The software provides multiple performance indicators like rutting, fatigue cracking, thermal cracking and smoothness (IRI).

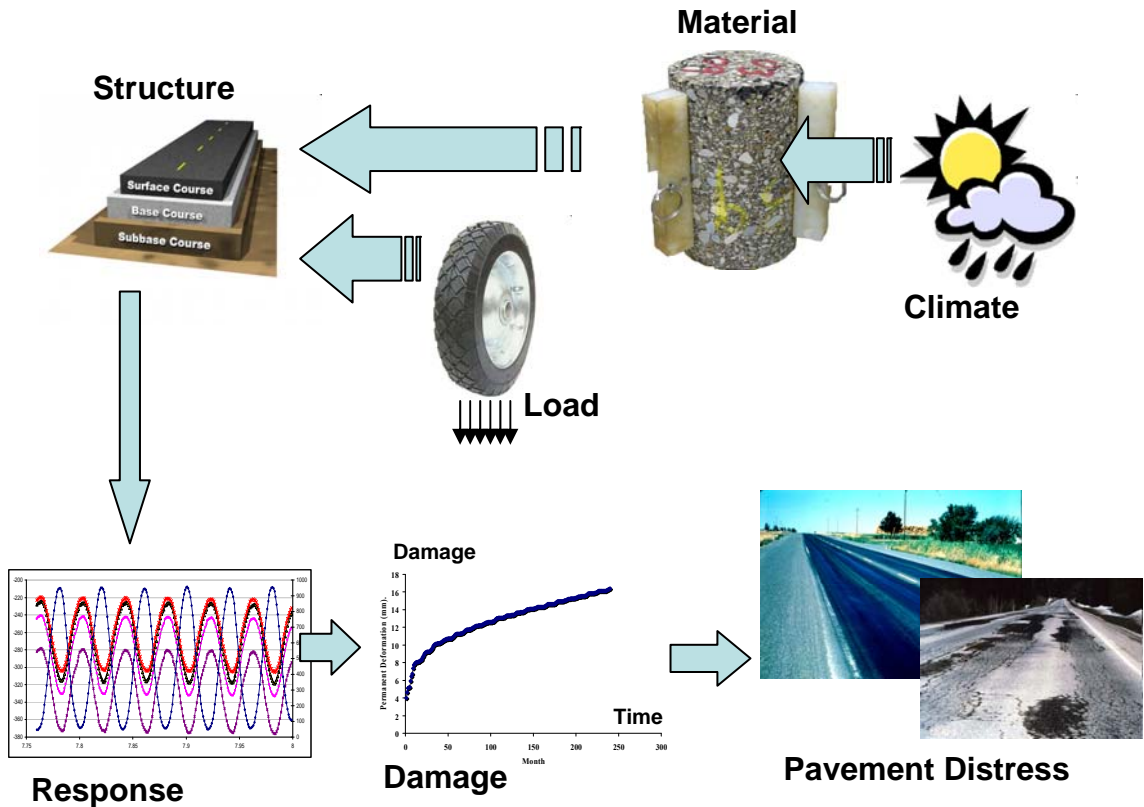


Figure 7 NCHRP Asphalt pavement M-E design process

There are three hierarchical levels in the MEPDG: Level 1, Level 2, and Level 3, with the accuracy of prediction increasing from Level 3 to Level 1. The descriptions for each level are shown below [40, 76, 78]:

- I. Level 1 input provides the highest level of accuracy of inputs. Thus, inputs obtained using Level 1 procedures would have the lowest level of uncertainty or error. Level 1 would typically be used for obtaining inputs for designing heavily trafficked pavements or wherever there is dire safety or economic consequences of early failure. Level 1 material input requires laboratory and/or field testing, such as the dynamic modulus testing of HMA or site-specific axle load spectra data collections,

or FWD deflection testing. Obtaining Level 1 inputs requires more resources and time than the other two levels.

- II. Level 2 input provides an intermediate level of design input and would be closest to the typical procedures used for many years with earlier editions of the AASHTO Pavement Design Guide. This level could be used when resources or testing equipment are not available for tests required for Level 1. Level 2 inputs typically would be user selected possibly from an agency database. It could be derived from a limited testing program, or could be estimated through correlations.
- III. Level 3 input provides the lowest level of accuracy. This level might be used for design where there were minimal consequences of early failure (lower volume roads). Inputs typically would be user selected default values or typical averages for the region.

Flow Number

The flow number was widely used to determine the rutting distress as well as permanent deformation characteristic since mid-70s [79, 80]. This test is based on the result from repeated loading and unloading of an HMA specimen where the permanent deformation of the specimen is recorded as a function of load cycles. Normally, a 0.1 second loading followed by a 0.9 second dwells (rest time) is applied to the specimen as shown in Figure 8 [27, 81, 82]. In addition, an effective temperature, often referred as rutting temperature, is used for the test [6, 83].

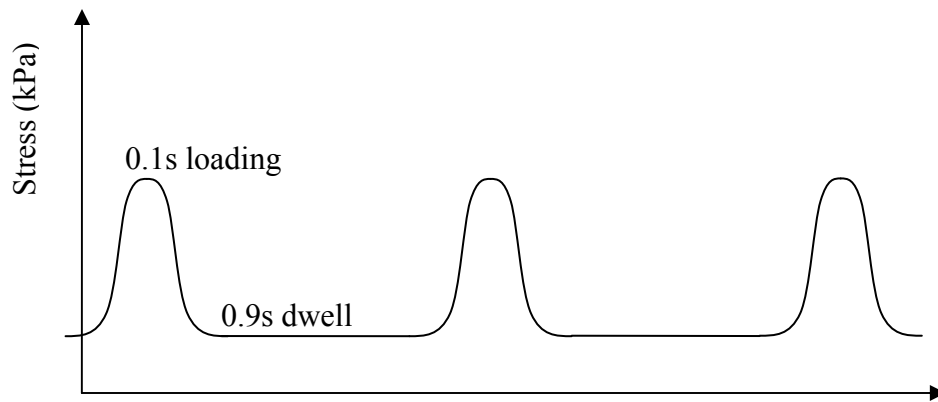


Figure 8 Loading and unloading of Flow Number Test

There are three stages of flow that occur during this type of test which are primary, secondary and tertiary [27]. Under primary flow, there is a decrease in the strain rate with time. With continuous repeated load applications the next phase is secondary flow, which is characterized by a relatively constant constraint strain rate. The material enters tertiary flow when the strain rate begins to increase as the test progresses [84]. Tertiary flow indicates that the specimen is beginning to deform significantly and the individual aggregates that makes up the skeleton of the mix are moving past each other [85-87]. The point or cycle number at which pure plastic shear deformation occurs is referred to as the “Flow Number”. Figure 9 illustrates the typical relationship between the total accumulative plastic strain and number of load cycles. Flow number is based upon the initiation of tertiary flow or the minimum point of strain rate curve [83] as shown in Figure 10. In addition, the flow number has been recommended as a rutting indicator for asphalt mixes [27, 75, 79, 84]

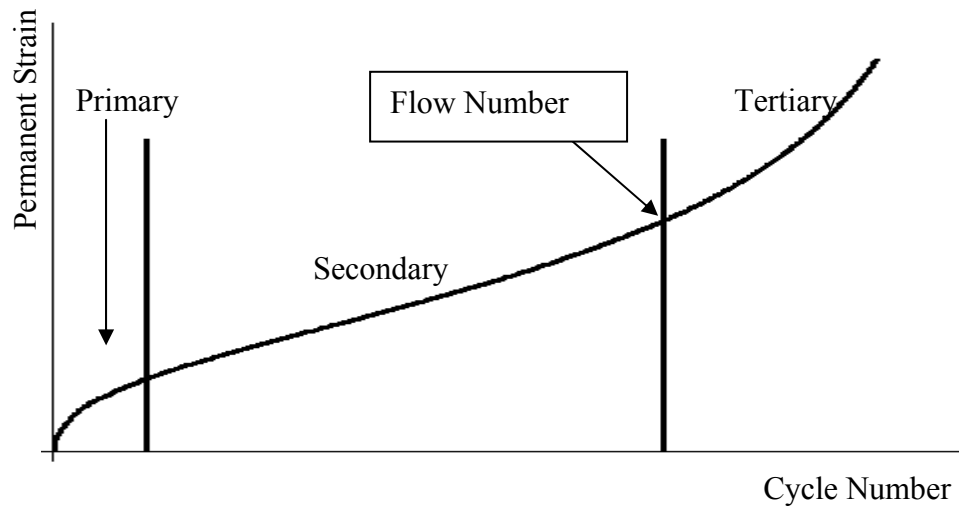


Figure 9 Flow Number Test Result

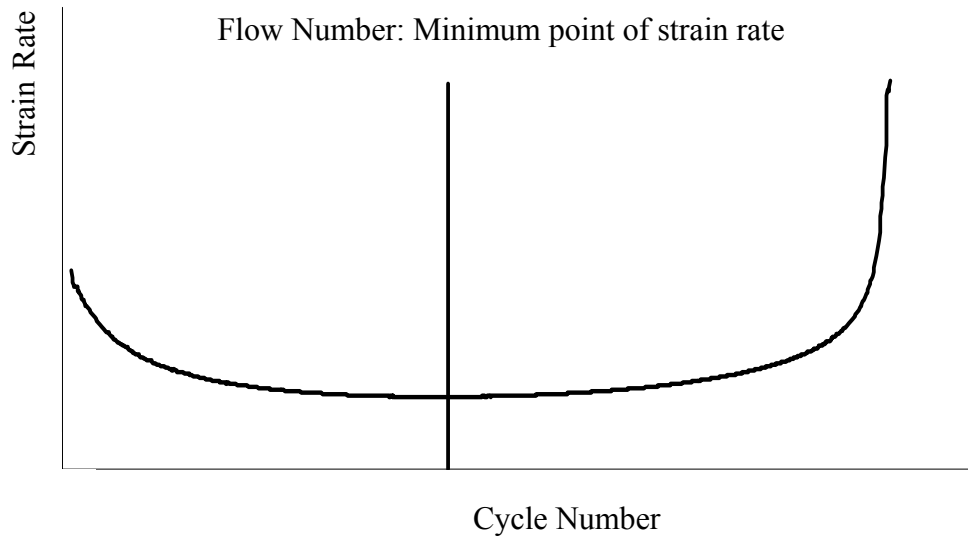


Figure 10 Strain Rate versus Cycle Number from Flow Number Test

Flow Number Literature Review

In 1974, Brown and Snaith (1974) performed experiments to investigate the effect and response of an asphalt mixture from repeated load [88]. The failure of the asphalt

mixture was defined as the cycle number when a marked deformation occurred. Results from these experiments were [88]:

1. The strain increased when temperature increased or the stress applied increased;
2. The strain increased when the confining stress increased; and
3. The strain rate was time dependent when the frequencies above 1 Hz were applied.

In 1984, Brown and Cooper performed repeated triaxial load tests at varying mixture's gradation, confining stresses and binder grade (based on penetration) [89]. The results showed [89]:

1. The penetration grade slightly affected the development of permanent shear strain in the specimen; and
2. The gradation of the mixture affected the shear strain significantly. Higher shear strain was found under fewer load cycles for gap-graded mixtures.

In 1995, Mallick et al. (1995) investigated the effects of air voids on repeated loading test [90]. These tests were correlating to field rutting performance with the measured strain from a repeated load test. The tests were performed at 60°C (an average of high pavement temperature in the United States) based on the ASTM D4123-82 standard specification. Various loads and confining pressures were used in the test. A logarithmic relationship was found between air voids and permanent strain when a 826.8kPa normal pressure and a 137.8kPa confining pressure were applied. The results also indicated that samples at or below 3.0% air void level underwent dilation and samples with greater than 3.0% air voids underwent consolidation. The authors indicated samples underwent dilation reflected the field performance (e.g. shoving). Mallick et al.

(1995) also analyzed the rutting behavior using the field procured samples under the same condition (e.g. 826.8kPa normal pressure and a 137.8kPa confining pressure). A strong correlation was found between permanent strain and rutting rate and it was concluded the dynamic confined testing could be used to identify rutting performance of a mixture.

In 1996, Brown and Gibb (1996) investigated the roles of asphalt binder and aggregate on permanent deformation using the uniaxial compression [91]. Different binder contents, binder types and aggregate gradation were used. It was found the aggregate of the mixture carries the load to resist permanent deformation when the binder's stiffness decreased. The repeated loading (uniaxial compression) was better at identifying the permanent deformation because the accumulated strains were related or similar to field conditions.

In 2002, Witczak et al. defined the cycle number where shear deformation happened as flow number (F_N) [29]. Witczak et al. (2002) indicated F_N can be used to identify the quality of asphalt mixture in terms of rutting resistance. Kaloush and Witczak (2002) indicated that the repeated load test can be used for different applications [84]. They found out that confined testing had a good relationship with field results. In addition, the axial or radial strain could be used for flow time measurement.

Further investigation of flow number testing was performed by Zhou and Scullion (2003) [13]. Similar to Witczak et al. (2002), Zhou and Scullion (2003) found that there was a good correlation between field permanent deformation and F_N . They also indicated

that F_N could be used to compare the quality of the mixtures in terms of rutting performance.

A study on effects of binder content on F_N was performed by Mohammad et al (2005) [58, 92]. Different binder contents were used by the author during the F_N test. It was found that the F_N was not as sensitive as dynamic modulus test for the changes in asphalt content based on statistical analysis.

Traditional Flow Number Determination and Other Existing Approaches

The traditional method locates the minimum point of strain rate versus cycle number as the flow number directly from the measured data [81, 93, 94]. However, one low data point could result in a misleading flow number value. Figure 11 shows the result from the flow number test. It is observed that several minimum points of strain rate versus cycle number were found. This is the misleading part in using the traditional method. Thus, a new approach is needed to determine the flow number value.

Since mid-70s, several permanent deformation methods and approaches have been proposed. The rutting models including Power-law model [80], VESYS model, Ohio State model, Superpave Models, and AASHTO 2002 Models were developed [13, 79]. In addition, the data smoothing techniques such as polynomial fitting model, moving average periods (MAPs) and regression technique were used to describe the permanent deformation curve [95, 96]. Zhou et al. (2004) proposed a three-stage deformation model to determine the three stage (primary, secondary, and tertiary) deformation behavior in flow number test. Zhou et al. (2004) indicated that the Power-law model is capable and was selected to describe the deformation curve at primary stage. In addition to this, a

simple linear model was selected to represent the curve at the secondary stage [79]. These two models are the key to form the Three-Stage Deformation model. A sample of F_N identification using Three-Stage Deformation model is shown in Figure 12.

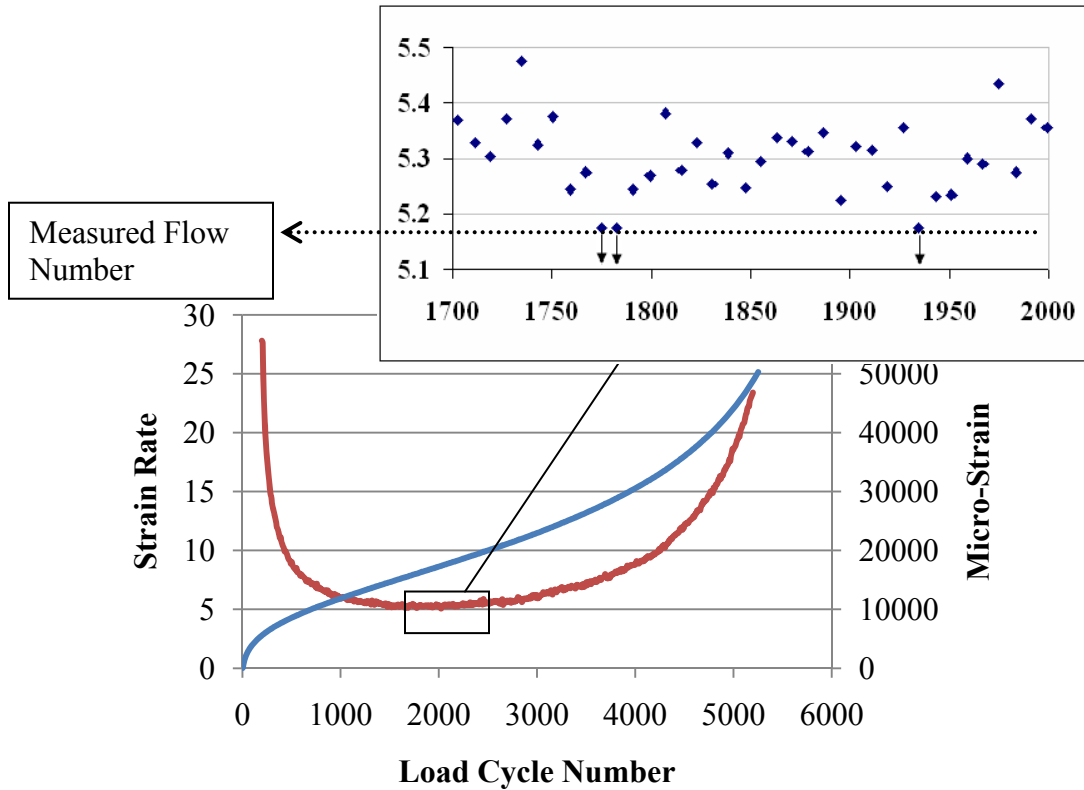


Figure 11 Typical Plot of Strain Rate versus Load Cycle Number and the Miscalculation

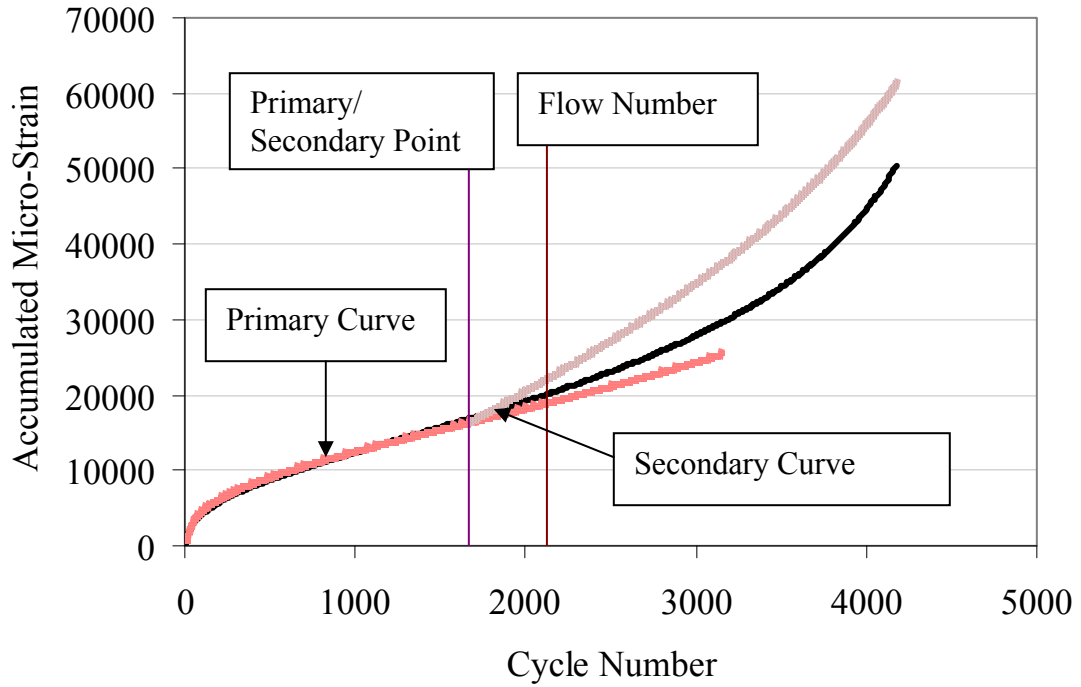


Figure 12 Flow Number from Three-Stage Deformation Model by Zhou et al. (2004)

Archilla et al. (2007) proposed a method to model the deformation curve by calculating the differential of strain rate divide by twice the sampling interval, and then smoothed the curve by running a five-point moving average for each cycle [95].

$$\frac{d(\varepsilon_p)_i}{dN} = \frac{(\varepsilon_{pN_{i+1}} - \varepsilon_{pN_{i-1}})_i}{2\Delta N} \text{ by Archilla et al. (2007)}$$

where,

N : Cycle Number;

N_i : Current load cycle; and

ε_p : Accumulated Permanent Strain.

Bausano and Williams examined the flow number by plotting creep stiffness times cycles versus cycle [97]. This method defined the flow number as the maximum point at the curve of stiffness times cycles versus cycles. In addition, flow number using this method was found to be more repeatable and reproducible by the lower coefficient of variations compared to the existing model. Bausano and Williams (2008) also indicated a second polynomial was found to provide the same accuracy and precision of measuring flow number when compared to 6th order polynomial. A sample of the Bausano and Williams' method is shown in Figure 13.

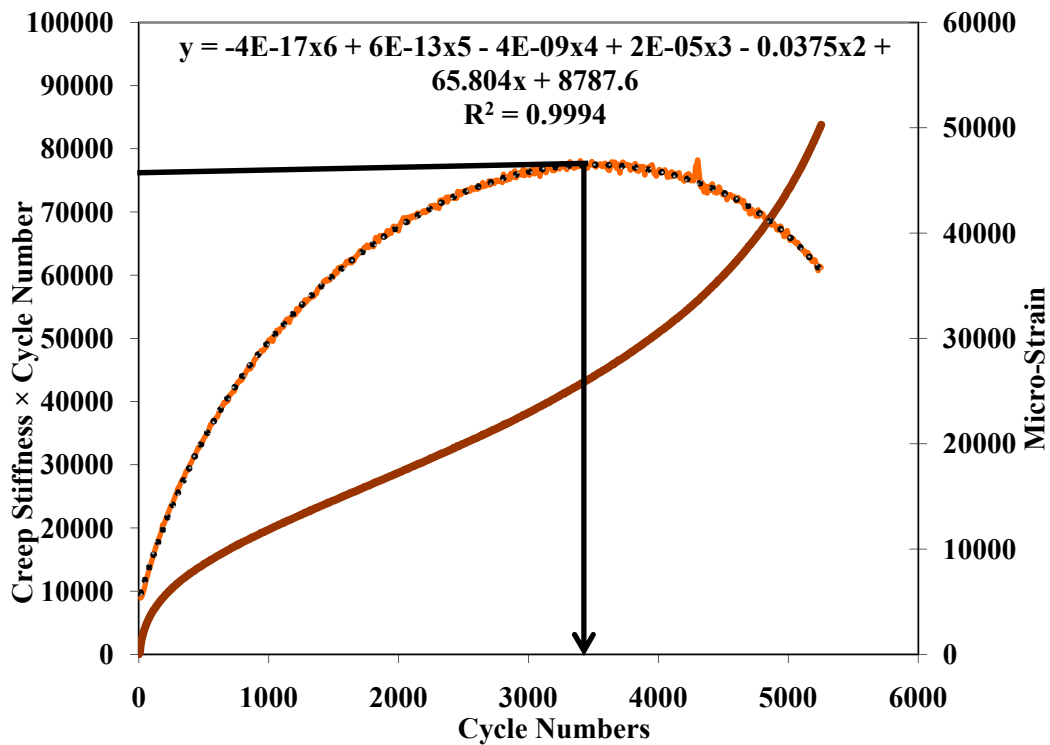


Figure 13 Flow Number from Creep Stiffness times Cycles versus Cycle Number Curve by Bausano and Williams (2008)

Biligiri et al. (2007) evaluated several mathematical models and recommended a comprehensive mathematical model to determine the flow number. The composite model, also referred to as Francken Model, was utilized in this calculation [96]:

$$\varepsilon_p(N) = AN^B + C(e^{DN} - 1)$$

where,

- $\varepsilon_p(N)$: Permanent deformation or permanent strain;
 N : Number of loading cycles; and
 A, B, C and D: Regressions Constants.

This model was then differentiated and the inflection point (also known as critical point) of the curve was defined as the flow number [96]:

$$\frac{d^2\varepsilon_p(N)}{dN^2} = A \cdot (B-1) \cdot N^{B-2} + C \cdot D^2 \cdot e^{D \cdot N}$$

CHAPTER 3: EXPERIMENTAL DESIGN

Asphalt mixture preparations and performance testing were completed by using the Superpave Mix Design Specification, SP-2 [98]. A total of three different mix sizes (mixture nominal maximum aggregate size) ranged from size 3 to 5 (19.0mm to 9.5mm) were chosen in this project. Additionally, the traffic level of these design mixes ranged from 0.3 million equivalent single axle loads (ESALs) to 30 million ESALs.

For asphalt mixture performance testing, dynamic modulus and flow number tests were employed. Two air void levels (i.e. 4% and 7% air void levels) were used and three replicate specimens were prepared for each test (at each temperature and each frequency), and an average value is presented in this thesis. The test results were analyzed using statistical methods which are discussed in ensuing sections. The general test flow chart is illustrated as Figure 14.

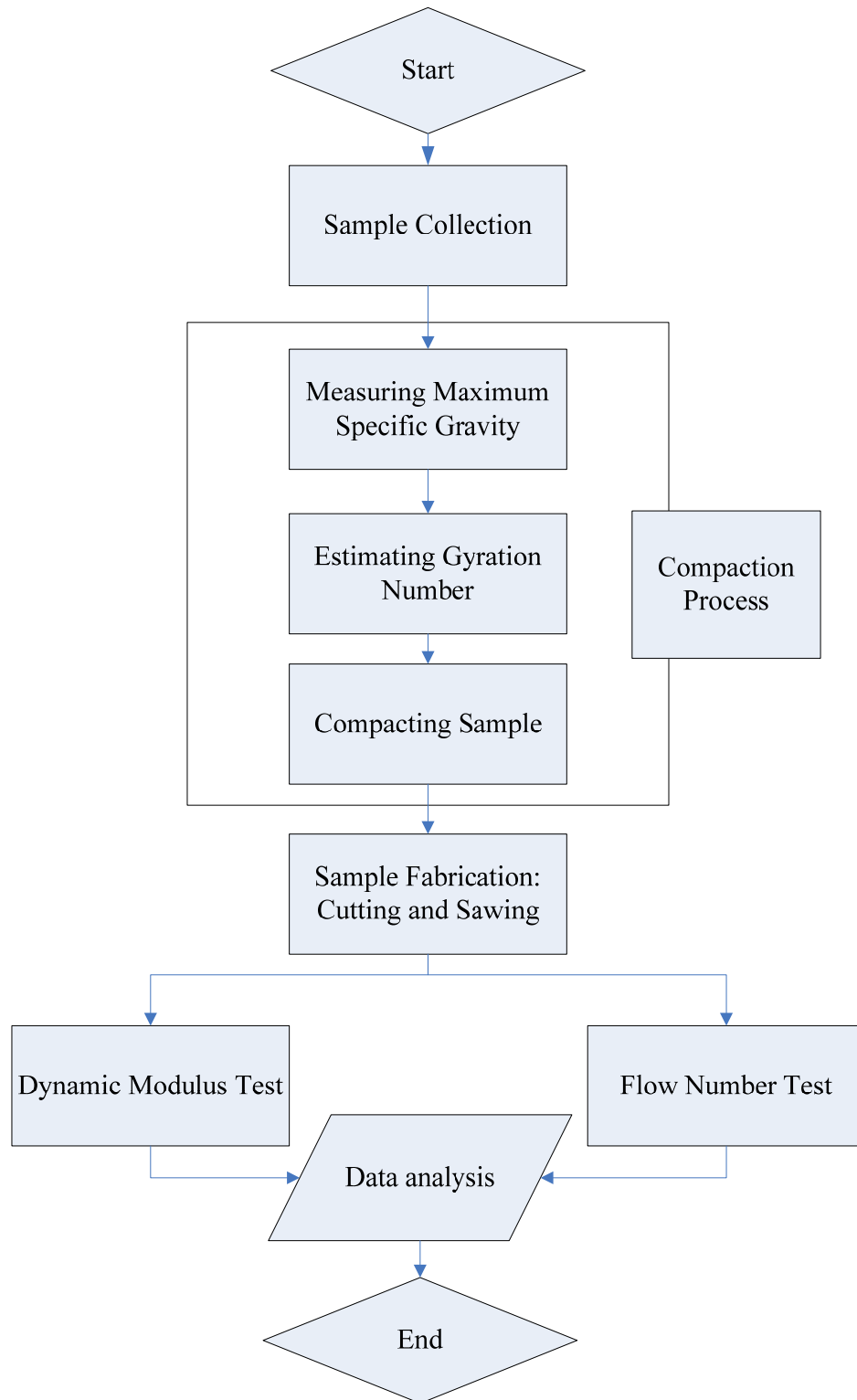


Figure 14 General Flow Chart for the Experimental Design

Sample Collection

All the samples collected for this project are located within Michigan State and they were collected during the summer time from year 2002 to 2005. Figure 15 shows the sample collection area in the state of Michigan [99]. Approximately 25% of the mixtures were collected from the Upper Peninsula and the rest of the sampled mixtures were from the Lower Peninsula. Table 3 shows the information of all the samples collected at each job site.



Figure 15 Mixture Collection Area¹ in Michigan State²

¹ Note: “★” indicated the location where mixtures were collected

² Michigan State Map was obtained from Destination360 [20]

Table 3 Asphalt Mixture Information

Mix size	Traffic Level	Project Location
3	E10	Interchange of US-23 and M 59 (Hartland Township, Livingston County)
		US-12 (Michigan Ave), Dearborn ---- From Firestone(Evergreen Rd) to I-94
	E30	M 53 (From South of 28 Mile Road to North of 33 Mile Road), Macomb, Michigan
4	E1	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)
	E3	M-52 (From the Saginaw/Shiawassee County line northerly to South Branch of the Bad River in the village of Oakley, City of St. Charles)
		M-90, Lexington, MI (From Babcock Road to Farr Road)
	E10	M-53 , Detroit (From M-3 to M-102)
	E30	M102, Wayne and Macomb Counties (From M-53 to I-94)
5	E1	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)
		M-38, Ontario-Houghton-Baraga Counties (From M-26 to Baraga Plains Road)
	E3	US-2, Bessemer, MI (From Wisconsin/Michigan State Line to Eddy Street, Wakefield)
	E10	I-75BL, Auburn Hills, MI (From north of Woodward Avenue northeasterly to Opdyke Road in the city of Auburn Hills and Pontiac, Oakland County)
		I-96, MI (From West of Oakland County line to Novi Road, in the cities of Wixom and Novi, Oakland County)
	E30	I-75, MI (From South Junction of I-475 to North Junction of I-475)
		I-75, MI (From the Ohio State line northerly to La Plaisance Road in the township of Erie, La Salle, and Monroe, Monroe County)

Note:

Mix Size: 3 – 19.0mm
 4 – 12.5mm
 5 – 9.5mm

Traffic Level:
 E1 – Traffic < 1 millions ESALs
 E3 – Traffic < 3 millions ESALs
 E10 – Traffic < 10 millions ESALs
 E30 – Traffic < 30 millions ESALs

*ESALs: Equivalent single axle

Compaction Process

In order to compact a sample to the desired volumetric properties, there were three procedures needed to follow: 1) measuring the theoretical maximum specific gravity; 2) measuring the bulk specific gravity and determining air voids, and; 3) estimating the number of gyrations and volume of mixture used. These procedures will be explained in the following sections.

Rice Test (Theoretical Maximum Specific Gravity)

The Rice Test was performed to determine the theoretical maximum specific gravity (G_{mm}) and density of the asphalt mixture according to ASTM D2041 [100]. 2000g of material for each type of sample during the compacting process was used for the Rice Test and was left on the table to dry for one day.

Bulk Specific Gravity and Air Void

The sample's bulk specific gravity (G_{mb}) and density test were performed according to ASTM D2726 [101]. Utilizing the test results from the Rice Tests (G_{mm}) and the G_{mb} , the air voids for each sample were determined.

Estimating Gyration Number and Mixture Volumetric Property

The desired gyration number and mixture volumetric property can be estimated by using a trial mixture by calculating its estimated bulk specific gravity (G_{mb} estimated), corrected bulk specific gravity, theoretical maximum specific gravity and air void level. In this project, a trial 1200g mixture for each mixture type was used for the 100mm

diameter specimens. All the mixtures were compacted using a trial gyration number (i.e. 120 gyrations). Figure 16 shows the pine gyratory compactor used in this project.



Figure 16 Pine Gyratory Compactor

During the compaction, the height for each gyration was recorded. For each gyration, the estimated G_{mb} can be calculated using the following equation [102]:

$$Estimated \ G_{mb} = \frac{W_m / \gamma_{mx}}{\gamma_w}$$

where,

W_m : Mass of Specimen (gram);

γ_{mx} : Density of water (1 g/cm³); and

γ_w : Volume of Sample (cm³).

The estimated G_{mb} was then compared with measured G_{mb} (G_{mb} calculated using the ASTM D2726 [101]) to find out the correction factor. The correction factor can be easily calculated using the equation below [102]:

$$Correction_Factor = \frac{Measured_G_{mb}}{Estimated_G_{mb}}$$

The measured G_{mb} for each gyration can be found by multiply the correction factor with the estimated G_{mb} . Figure 17 shows a sample of estimated and corrected G_{mb} calculated in this project.

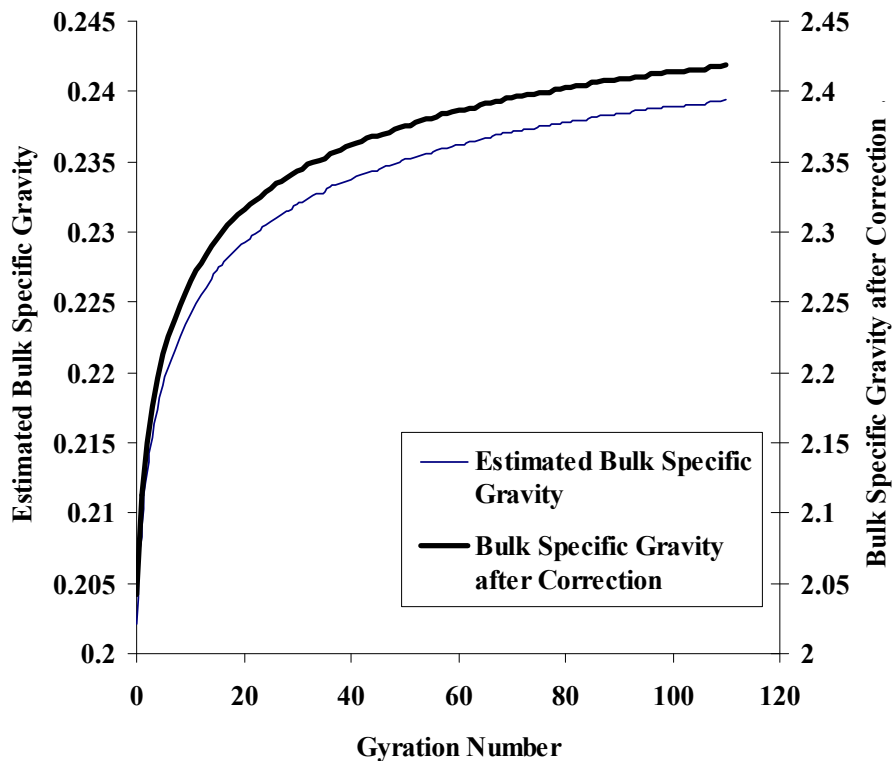


Figure 17 Estimated and Corrected Bulk Specific Gravity for Trial Sample

The air void level for each gyration number was then calculated using the corrected G_{mb} . The equation to find out the air void level is [103]:

$$Air_Void(\%) = 1 - \frac{G_{mb}}{G_{mm}}$$

Figure 18 shows a sample of air void level calculated at each gyration number. The gyration number was then estimated using this graph. In example, Figure 18 shows that a gyration number 84 was needed in order to compact the sample to air void level of 4%. In addition to this, the height of the sample could be estimated using the equation below:

$$Sample_Height = \frac{1}{G_{mb} \cdot \pi \cdot r^2} \times Sample_weight$$

where,

Sample_Height: Height of Sample (mm);

G_{mb} : Corrected Bulk Specific Gravity at the desired gyration number;

π : 3.142;

r: Radius of the mold (mm); and

Sample Weight: Weight of the sample (gram).

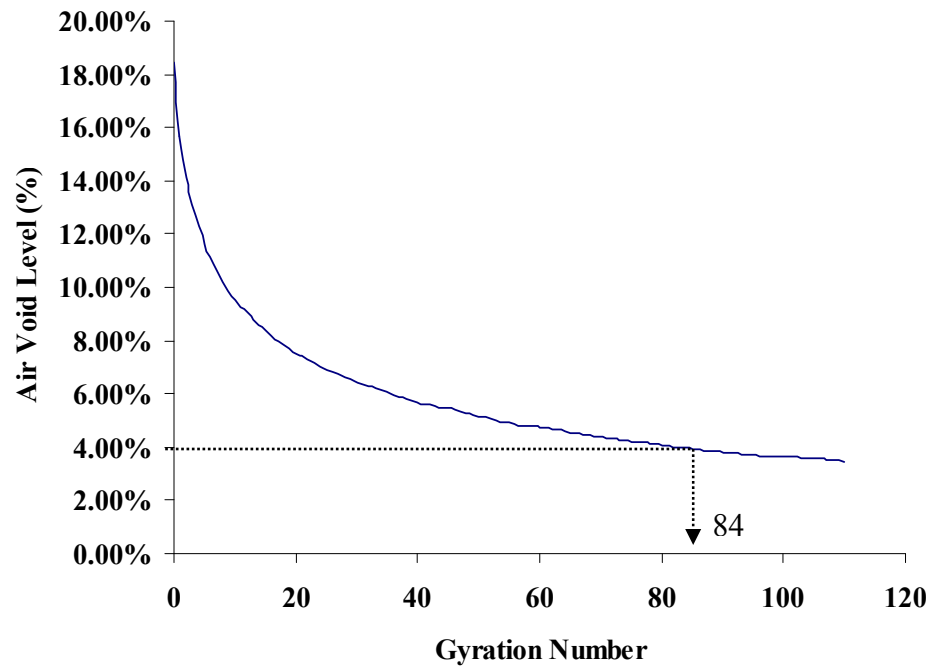


Figure 18 Air Void Level for a Trial Sample

Sample Fabrication

All the compacted samples were fabricated (i.e. cutting and sawing to the desired size) prior to the asphalt mixture performance testing. Samples were cut at a height of 150mm and a diameter of 100mm by using diamond masonry saw after the compaction process shown at Figure 19. Additionally, Figure 20 shows the samples after fabrication.

After the asphalt concrete specimens were cut, all the samples' bulk specific gravity (G_{mb}) was measured again. It was notable that the sample drying process took approximately seven days before measuring sample's dry weight for G_{mb} .



Figure 19 Cutting and Coring Process



Figure 20 Asphalt Mixture after Cutting and Coring process

Dynamic Modulus Test

The dynamic modulus test was conducted according to AASHTO TP62-03 [59]. The purpose of the Dynamic Modulus ($|E^*|$) test is to find out the dynamic modulus, $|E^*|$ of the asphalt mixture. $|E^*|$ is the modulus of a viscoelastic material. The dynamic modulus of a viscoelastic test is a response developed under sinusoidal loading condition [36, 104]. In this project, an IPC UTM 100 [105] was used for $|E^*|$ testing as shown in Figure 21.

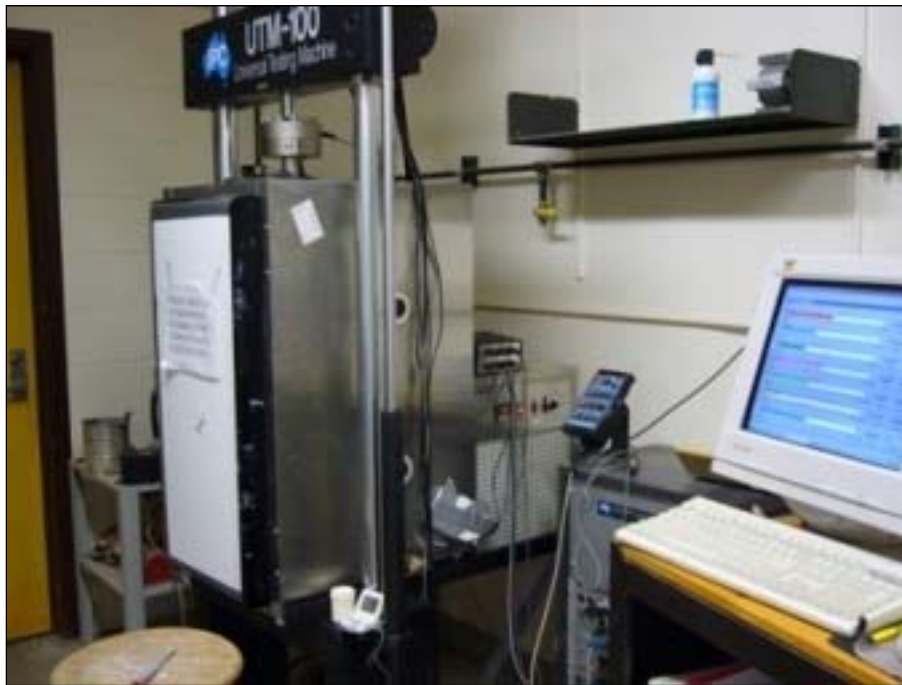


Figure 21 Dynamic Modulus Test Device (IPC UTM 100)

All the samples were attached with platens with high strength glue to the side of the sample by using the loading platen device prior to the $|E^*|$ testing (shown in Figure 22). Samples were then attached with three Linear Variable Differential Transformers

(LVDTs) and placed in the environment chamber. Temperatures and temperature equilibrium time used for $|E^*|$ in this project are shown in Table 4.



Figure 22 Platen Loading Device

Table 4 Test Temperatures and Temperature Equilibrium Time for $|E^*|$ Test

Test Temperature (°C)	Temperature Equilibrium Time from Room Temperature (Hour)
-5	12
4	8
13	6
21.3	4
39.2	7

Both top and bottom surfaces of the samples were covered with a friction reducing end treatment cream. After that, samples were loaded into the dynamic modulus test device shown below in Figure 23.



Figure 23 Dynamic Modulus Test Setup

The dynamic modulus test was started after the temperature in the transducer device display reached the required test temperature. In addition, the frequencies used in this test were 0.1hz, 0.5hz, 1hz, 5hz, 10hz and 25hz. During the test, the recovered axial strain was controlled to be between 50 and 100 in order to obtain a precise $|E^*|$ by adjusting the positive dynamic stress and static stress level [60]. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to

calculate the dynamic modulus and phase angle. Test results were recorded after the test was done. Figure 24 shows the typical result from the $|E^*|$ test.

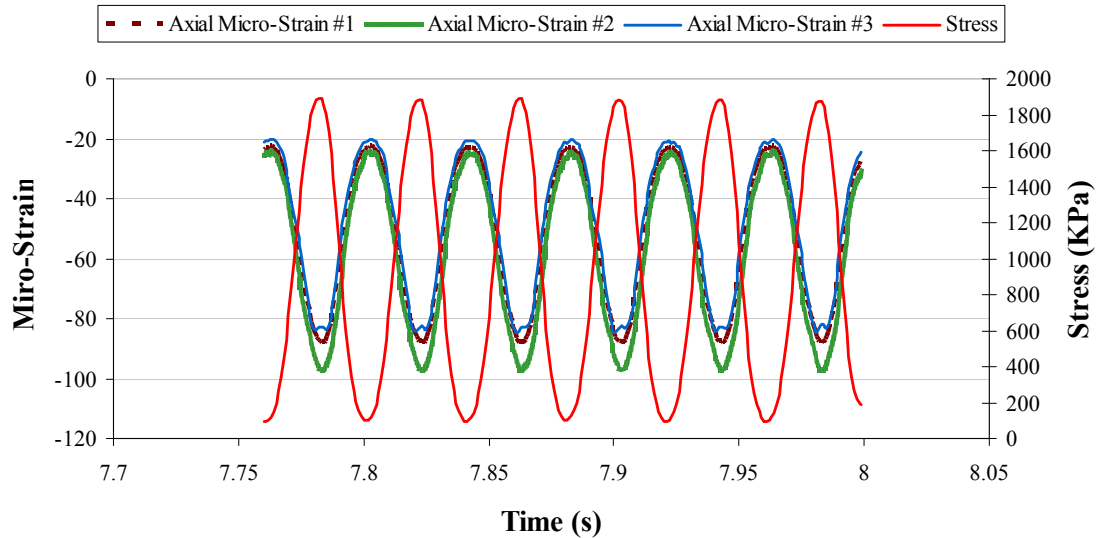


Figure 24 Sample Test Results of Dynamic Modulus Test¹

Flow Number Test

The flow number test, also called dynamic creep or repeated creep test, was widely used to determine the rutting distress as well as permanent deformation characteristic since mid-1970s [79, 80]. This test was performed based on NCHRP Report 465 [36] and NCHRP 9-19 [18]. The test for flow number is based upon results from repeated loading and unloading of a HMA specimen where the permanent deformation of the specimen is recorded as a function of the number of load cycles. A sample size of 100mm diameter by 150mm height was used. Samples were tested under unconfined conditions and the duration of 0.1 second loading time, followed by 0.9 second

¹ Stress (1 curve) and strain (3 curves) in dynamic loading using 25 Hz frequency at temperature -5°C

dwells were used in this test (shown in Figure 25). During the test, the permanent strain at each test cycle was recorded. The F_N can be located at the minimum point of the strain rate versus cycle number slope.

Flow Number test is a destructive test where a compressive stress was applied until the sample fail. Figure 26 shows the failing sample after the flow number test.

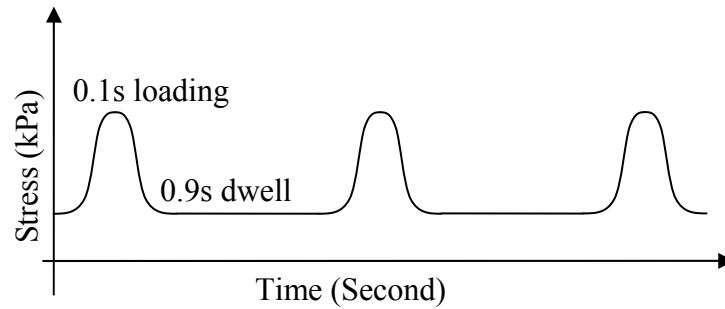


Figure 25 Loading and unloading of Flow Number Test

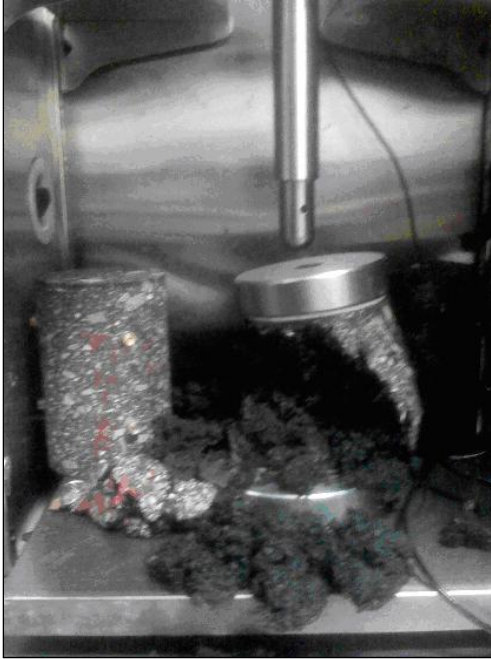


Figure 26 Sample Fail after the Flow Number Test

Loading Level used in Flow Number Test

It is important to determine the magnitude of loading level used in each F_N test because this will significantly affects the F_N . The NCHRP 9-19 used 69kPa for loading stress and 3kPa for contact stress for F_N unconfined test [27, 34]. This loading level was defined for the intermediate and high test temperature in the dynamic modulus test. However, this loading level might not be feasible for some of the mixtures (e.g. high traffic level mixture) as the samples would not undergo tertiary flow. A discussion with Dr. Williams and based on the previous research [35, 81, 93, 106], stress level of 600kPa (simulates from the gyratory compactor) and 30kPa for contact stress were determined for this test.

Effective Rutting Temperature

Effective temperature is defined as a single temperature at which amount of permanent deformation would occurred equivalent to that measured by considering each season separately throughout the year [83]. The effective pavement temperature for rutting, which defined by the temperature of 20mm below the surface of the pavement, was shown as below [81]:

$$T_{\text{eff rutting}} = 30.8 - 0.12Z_{\text{cr}} + 0.92 \text{ MAAT}_{\text{design}}$$

where,

$T_{\text{eff rutting}}$: Effective Rutting Temperature ($^{\circ}\text{C}$);

Z_{cr} : Critical depth down from pavement surface (mm);

$\text{MAAT}_{\text{design}}$: Mean annual air temperature ($^{\circ}\text{C}$);

and,

$\text{MAAT}_{\text{design}}$: $\text{MAAT}_{\text{Average}} + K_{\alpha} \sigma_{\text{MAAT}}$

where,

$\text{MAAT}_{\text{Average}}$: Average annual air temperature;

K_{α} : Appropriate reliability level of 90%; and

σ_{MAAT} : Standard deviation of distribution of MAAT for site location.

The critical depth, Z_{cr} , is 20mm in this case. The $\text{MAAT}_{\text{average}}$ were collected from the Michigan State Climatology Office from stations around the entire Michigan State. In this study, the calculation of σ_{MAAT} used was difference due to climate in Michigan.

Traditional σ_{MAAT} calculated using from historical $\text{MAAT}_{\text{Average}}$. Michigan climate was

known to have a huge temperature difference between winter and summer period (about a 72°C difference). Hence, using the traditional σ_{MAAT} calculation was not appropriate. In this study, the σ_{MAAT} was calculated based on historical $MAAT_{Average}$ from each month in a year. The effective temperature was calculated at each Michigan Department of Transportation region (shown in Figure 27): Superior Region, North Region, Grand Region, Bay Region, Southwest Region, University Region and Metro Region [107]. An average of $T_{eff\ rutting}$, 45°C computed from each region was used as the F_N test temperature.

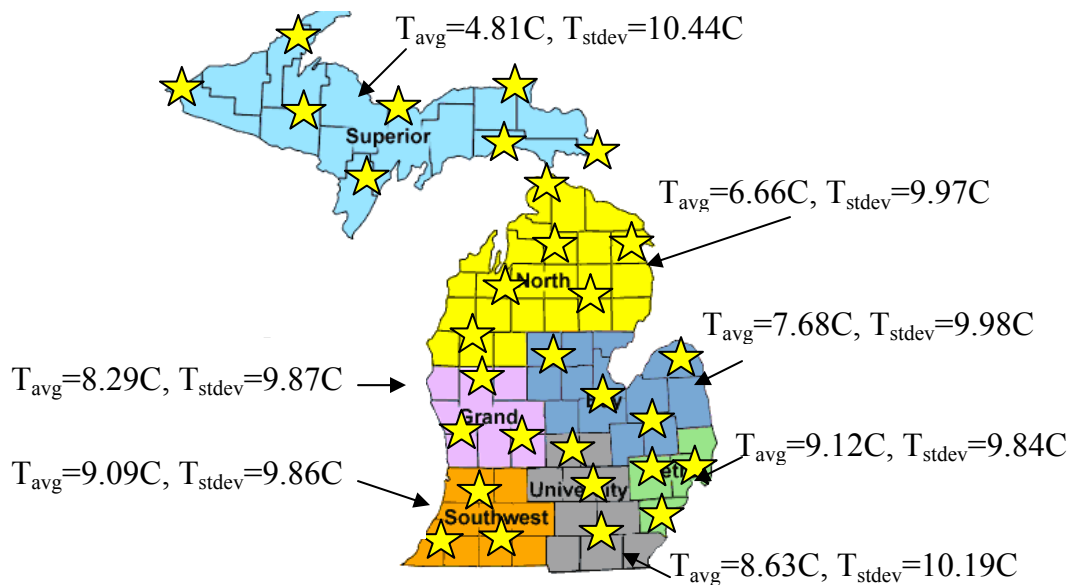


Figure 27 MAAT Average and MAAT Standard Deviation in Michigan State¹

¹ Map taken from the MDOT Website

Flow Number Measurement

A number of research studies have focused on the linkage between material properties and pavement performance. Part of the efforts in this research was the development of Superpave Simple Performance Tests (SPT). One of the Superpave SPT is the repeated loading or dynamic creep test. The output of this test is flow number, which is the initiation of tertiary flow. A common method in examining the flow number is to locate the lowest point in the strain rate versus cycle number curve, or the minimum value of the strain rate. However this method may provide confusion due to the variation of the test data. Researchers have been trying to discover new effective methods for determining flow number. Their efforts have led to the development of several excellent approaches. However, these methods need to be more refined in order to improve the user-friendliness to engineers, researchers, and even students. A new simple stepwise method was developed and evaluated in this project.

The proposed stepwise increase approach provides a practical and consistent method to determine the initiation of tertiary flow [108, 109]. Stepwise increase means a gradual increase, or increase step by step in mathematical terms [109]. This approach utilizes the traditional method (locate minimum point on the curve of strain rate versus cycle number) and emphasizes the smoothing technique used to determine the flow number. Three simple steps and an assumption were applied in this method. A brief algorithm to identify the flow number using stepwise approach is shown in the following section.

Step 1: Smoothing the measured permanent deformation by re-allocating the measured results with an assumption of permanent strain will only maintain at the same point or increase over the load cycle number.

Figure 28 shows the results from the test. The non-uniform, discontinuous data points that led to the subjective analysis and miscalculation of the flow number are highlighted in Figure 29 as well. As mentioned previously, the proposed method emphasizes the smoothing technique and re-allocation method. This method shifted the discontinuous data points forward along the x-axis (cycle number) by not changing the strain level to give a stepwise increasing trend. For example in Figure 29, point 3 was shifted forward to replace point 6, and points 4, 5 and 6 were move backward to replace point 3; point 8 shifted forward to replace point 10, and point 9 and 10 move backward to replace point 8. All of the non-uniform discontinuous data points can easily be shifted using the excel function called “Sort Ascending.” Figure 30 shows the shifted data points using the stepwise method proposed.

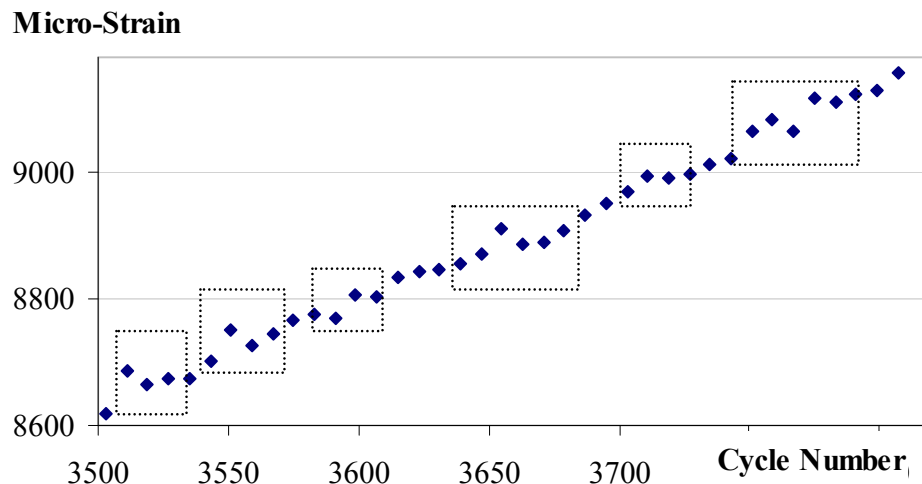


Figure 28 Measured Permanent Deformations versus Cycle Number

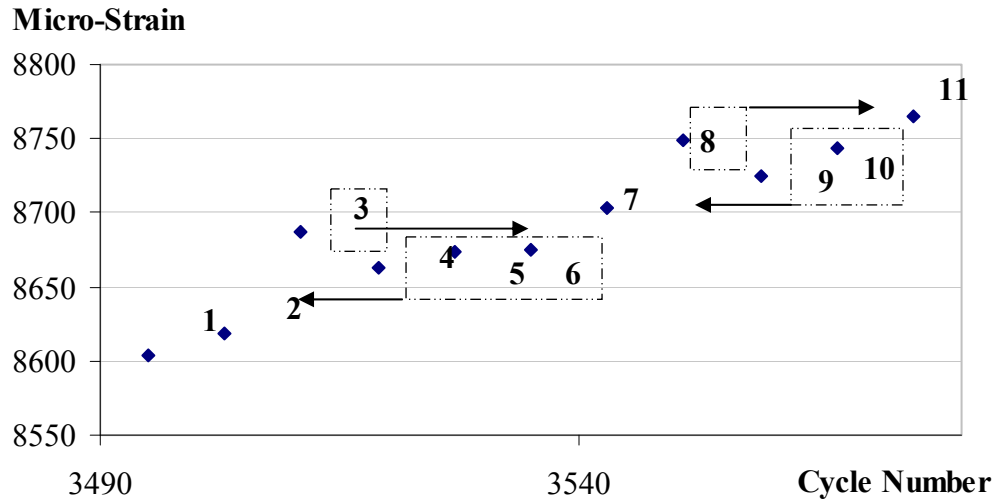


Figure 29 Reallocation of the Deceptive Plots

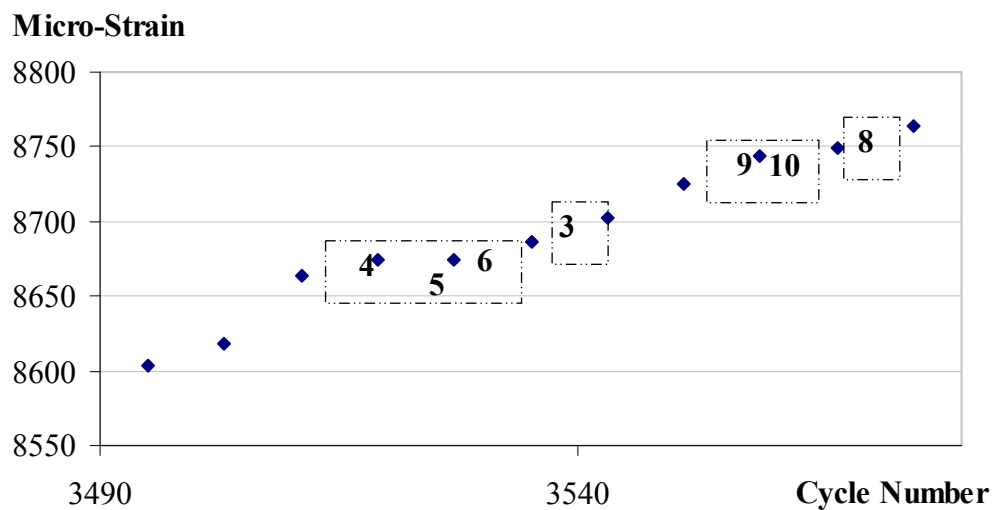


Figure 30 Modified Permanent Deformation versus Load Cycle

Step 2: Calculate the strain rate using the modified permanent deformation result

This step determines the strain rate using the modified data set (data set modified in step 1). The strain rate is calculated by dividing the permanent strain by loading cycle number at each cycle:

$$\text{Strain_Rate} = \frac{\varepsilon}{N}$$

Step 3: Determine the flow number by locating the minimum point of strain rate versus load cycle curve.

For this step, the flow number can be found by locating the minimum point from the curve of strain rate versus cycle number. There is no flow number if the minimum point of strain rate versus load cycle curve is equal to the maximum cycle number.

CHAPTER 4: TEST RESULTS AND FIELD INFORMATION

Introduction

The laboratory tests (including flow number and dynamic modulus tests) were conducted at Michigan Technological University. Table 5 shows the descriptor for the sample used in this study. Dynamic modulus ($|E^*|$) for different mixtures were tested using an IPC Universal Testing Machine (UTM). Temperatures used in $|E^*|$ test were -5°C, 4°C, 13°C, 21.3°C and 39.2°C, and frequencies used were 0.1hz, 0.5hz, 1hz, 5hz, 10hz and 25hz. The air void level used in this project was 4% and 7%. One analysis file was obtained for each load frequency and temperature. A total of three to six replicates specimens were tested for each mixture type. Results from $|E^*|$ test were plotted and are shown in the following section.

The field information obtained including rutting performance, traffic data and pavement structure. The field rutting performance and pavement structure were provided by Michigan Department of Transportation (MDOT) [110] and the traffic information were obtained from MDOT Traffic Monitoring Information System (MDOT TMIS). All this information is shown in the following section as well.

Table 5 Descriptors for each Asphalt Mixture

Mix size	Traffic Level	Descriptors
3	E10	3E10I
		3E0 II
	E30	3E30 I
4	E1	4E1 I
	E3	4E3 I
		4E3 II
	E10	4E10 I
E30	4E30 II	
5	E1	5E1 I
		5E1 II
	E3	5E3 I
	E10	5E10 I
		5E10 II
	E30	5E30 I
5E30 II		

Dynamic Modulus Test Results

As mentioned previously, the dynamic modulus test was conducted according to AASHTO TP62-03 [59]. An IPC UTM-100 machine [105] was used for the $|E^*|$ testing. The temperatures used were -5°C, 4°C, 13°C, 21.3°C and 39.2°C. The frequencies used in this testing were 0.1hz, 0.5hz, 1hz, 5hz, 10hz, and 25hz. A total of three replicates samples were tested for each of the fourteen mixtures at each single test. The recoverable axial micro-strain in this test was controlled within 50 and 100 micro strain so that the material were in the viscoelastic range [60]. Results of the dynamic modulus test are shown in Figure 28 to Figure 37.

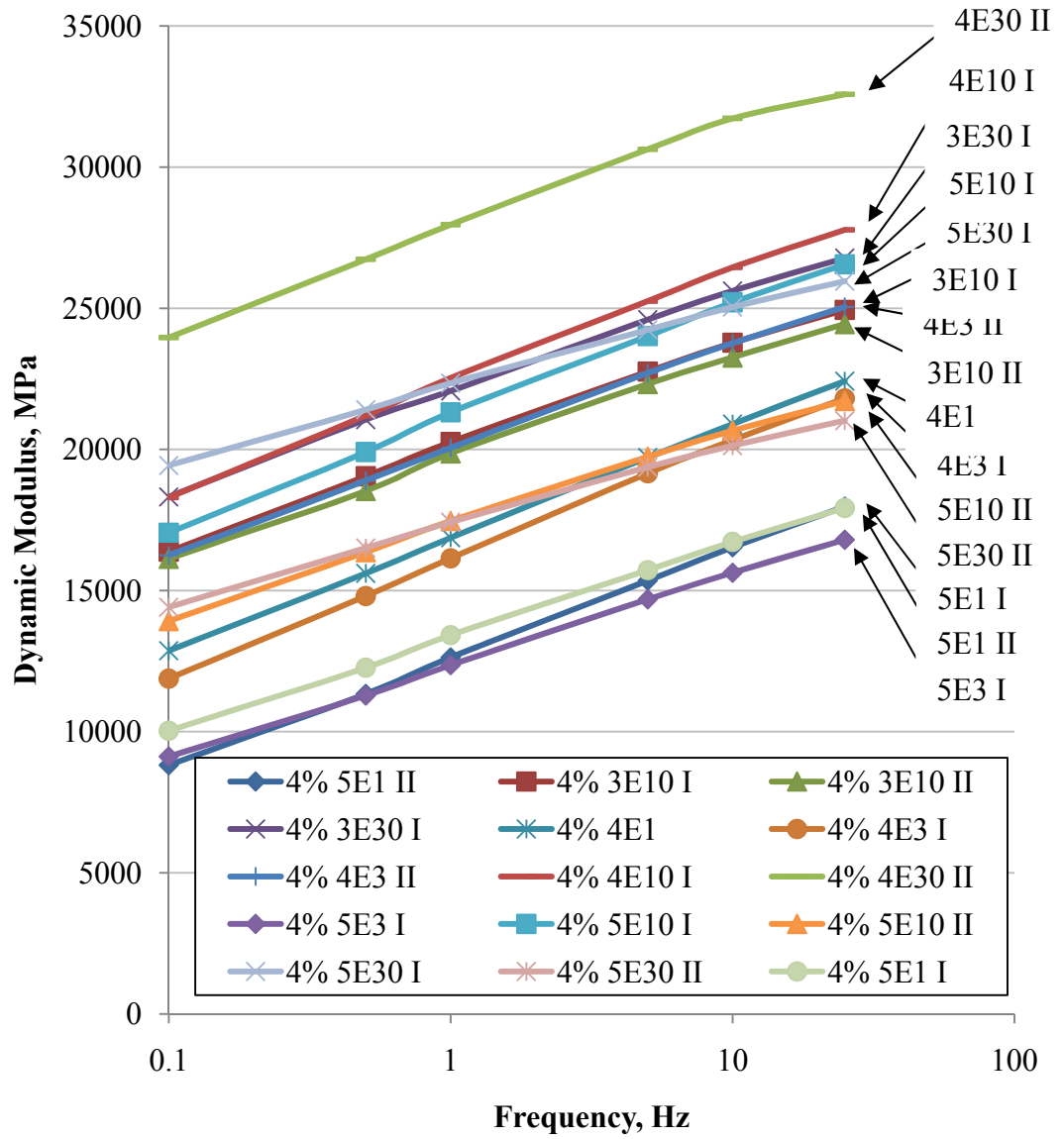


Figure 31 Dynamic Modulus for 4% Air Void Level at -5°C

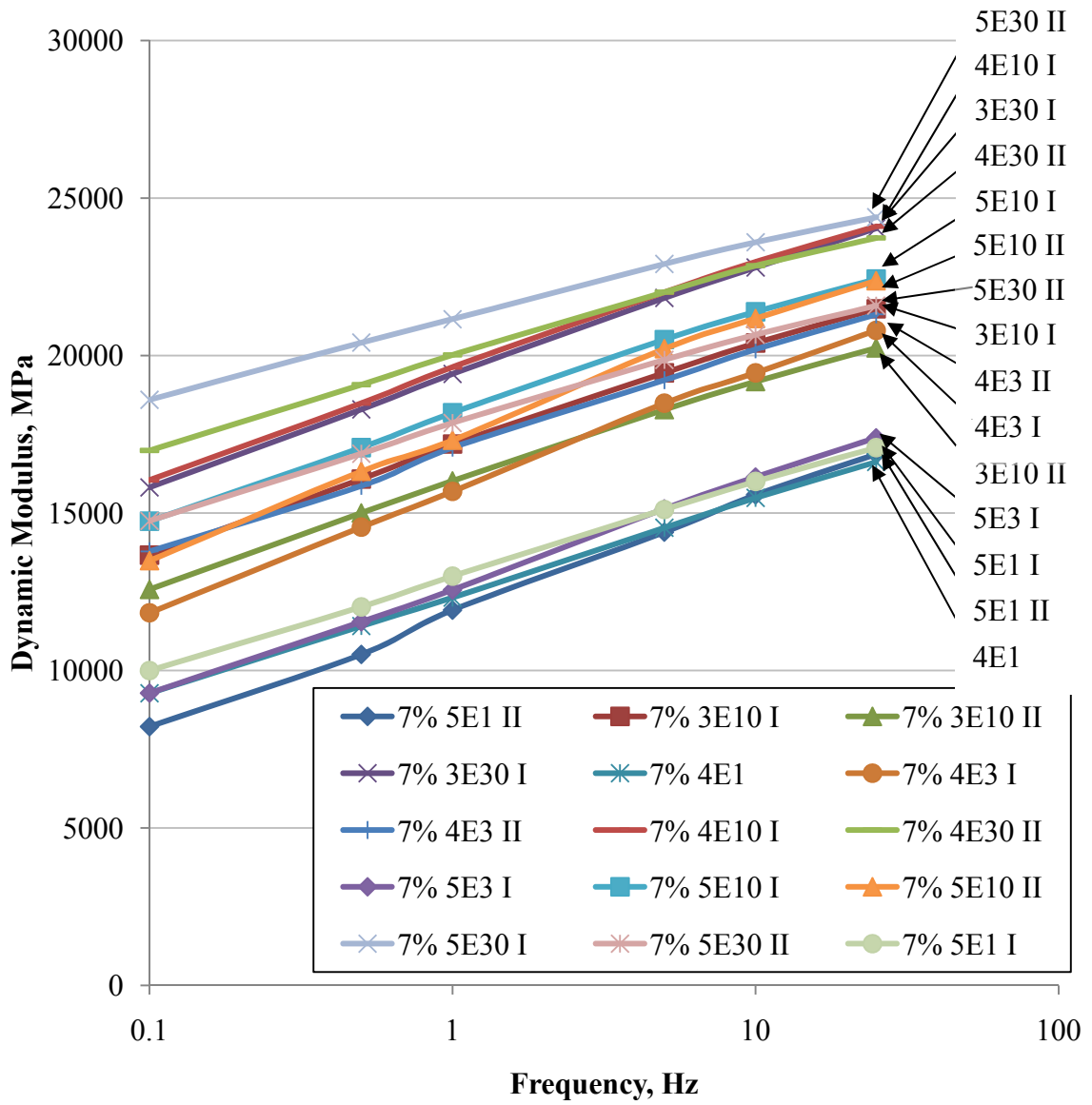


Figure 32 Dynamic Modulus for 7% Air Void Level at -5°C

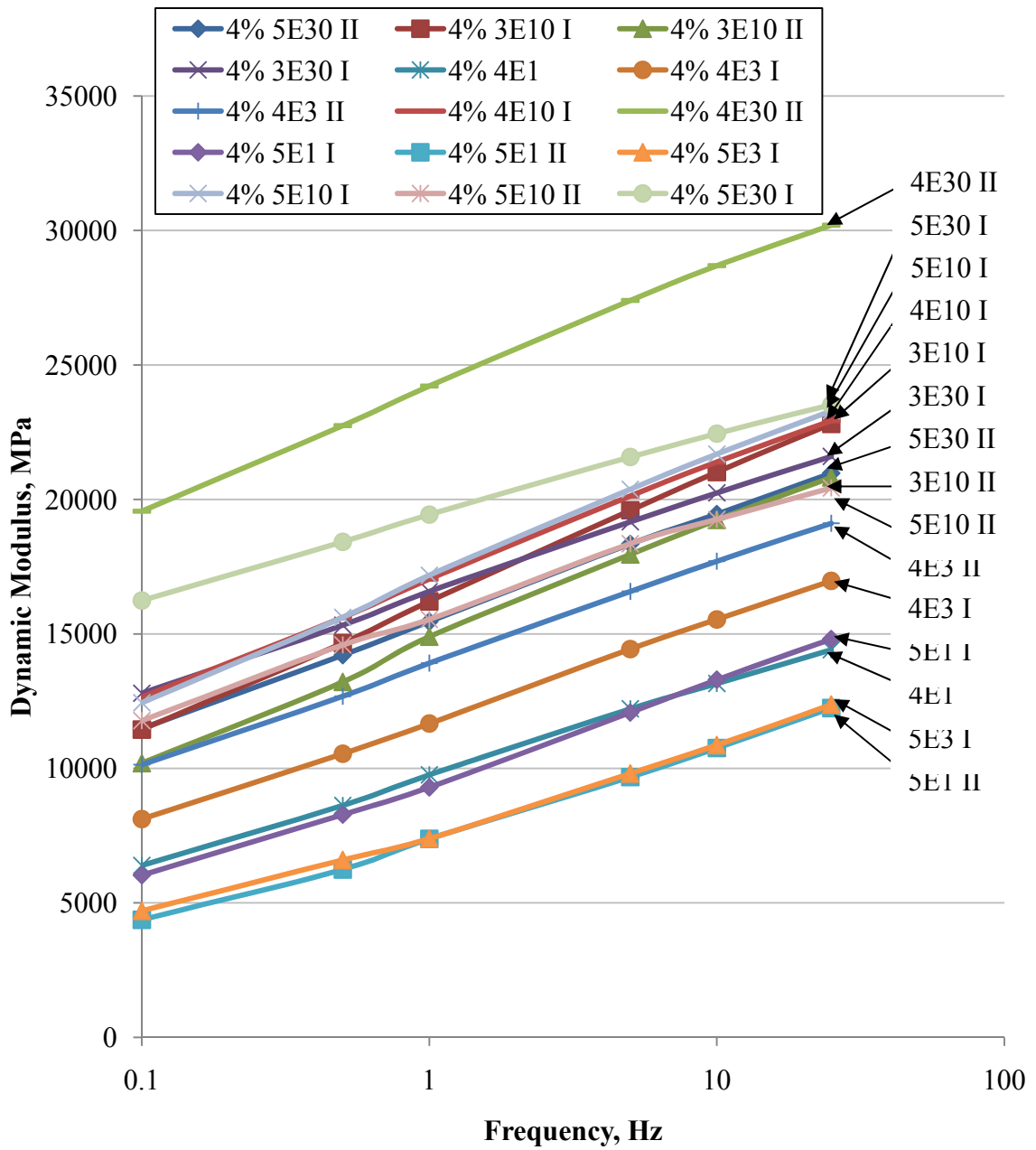


Figure 33 Dynamic Modulus for 4% Air Void Level at 4°C

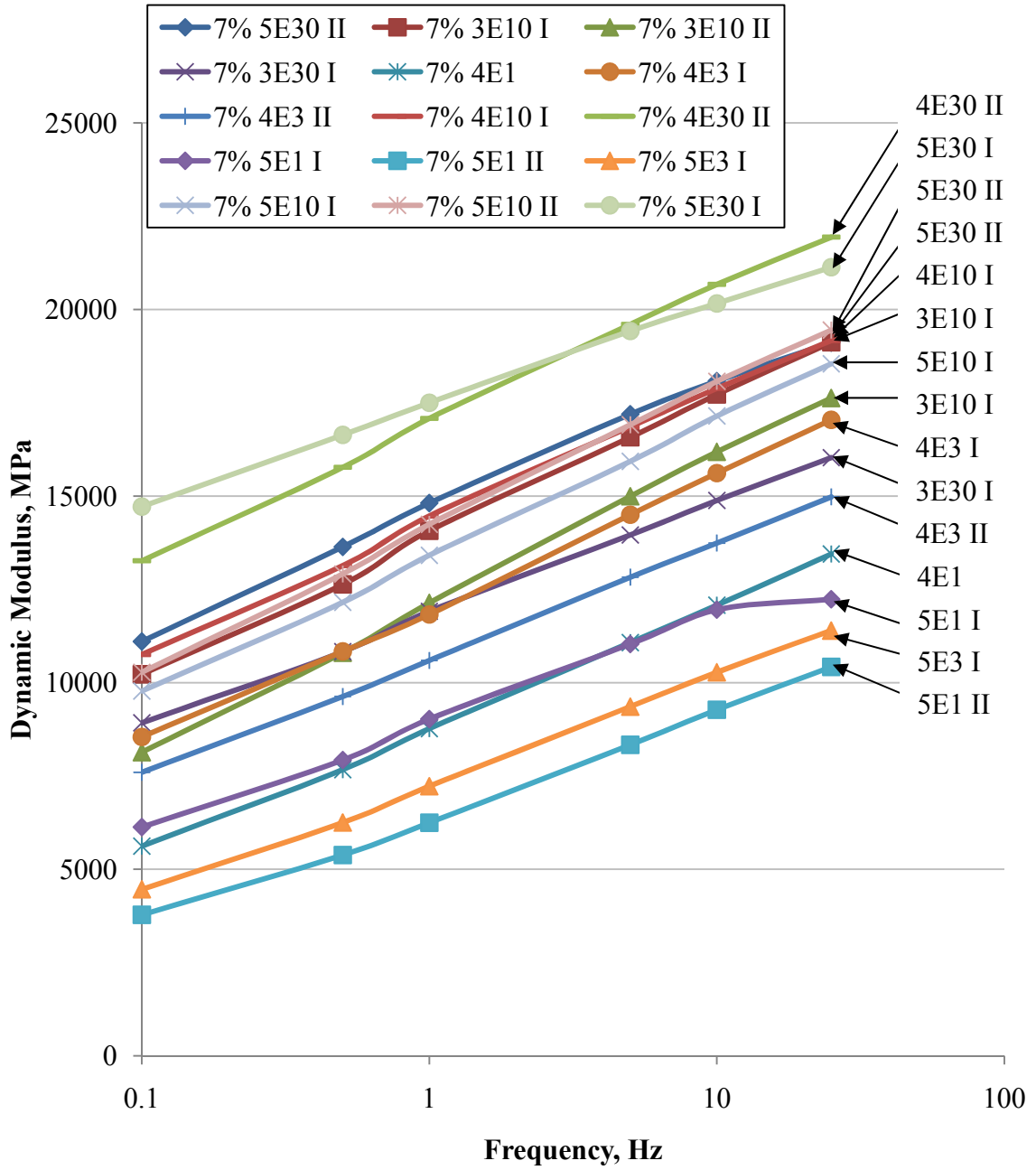


Figure 34 Dynamic Modulus for 7% Air Void Level at 4°C

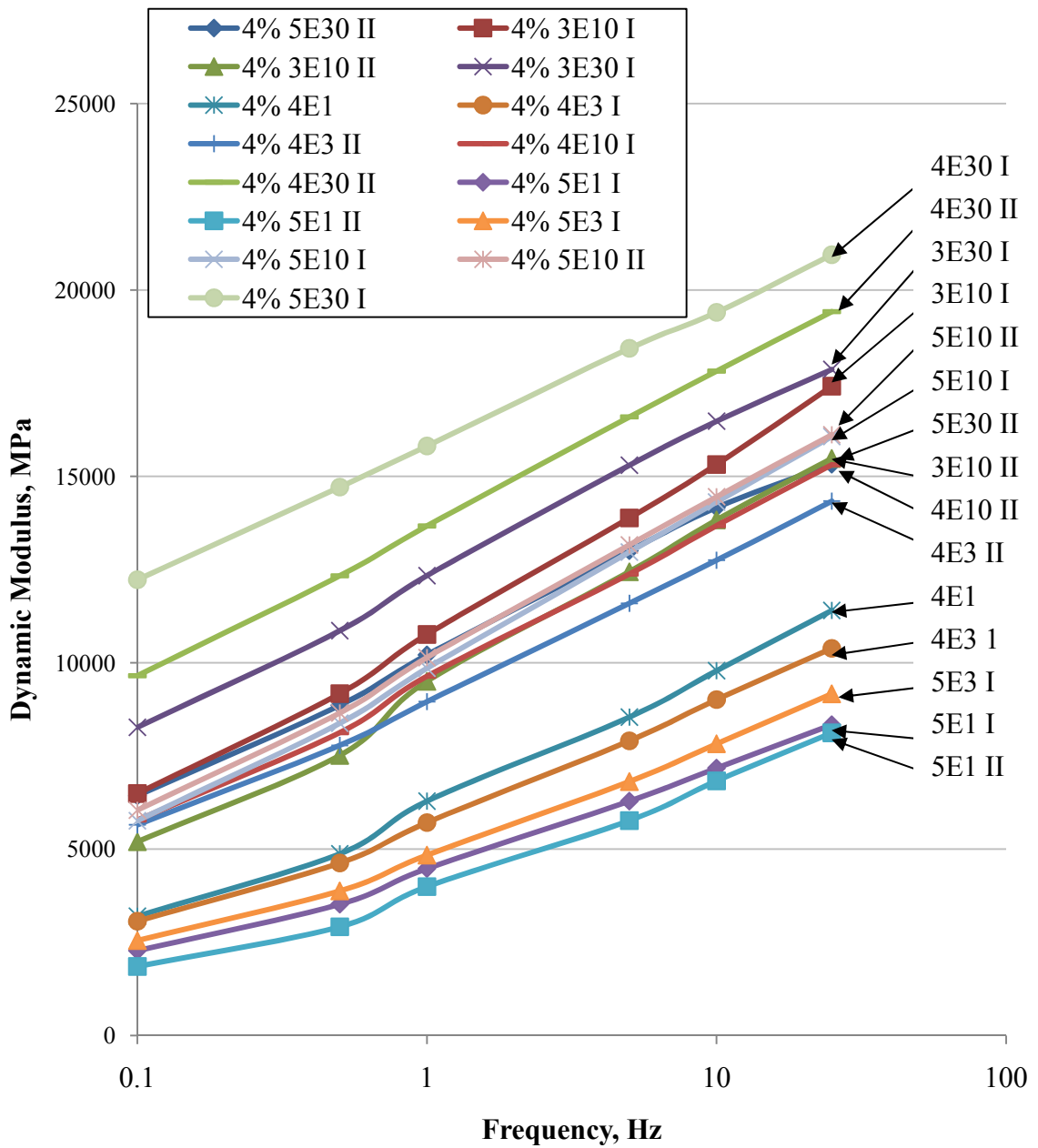


Figure 35 Dynamic Modulus for 4% Air Void Level at 13°C

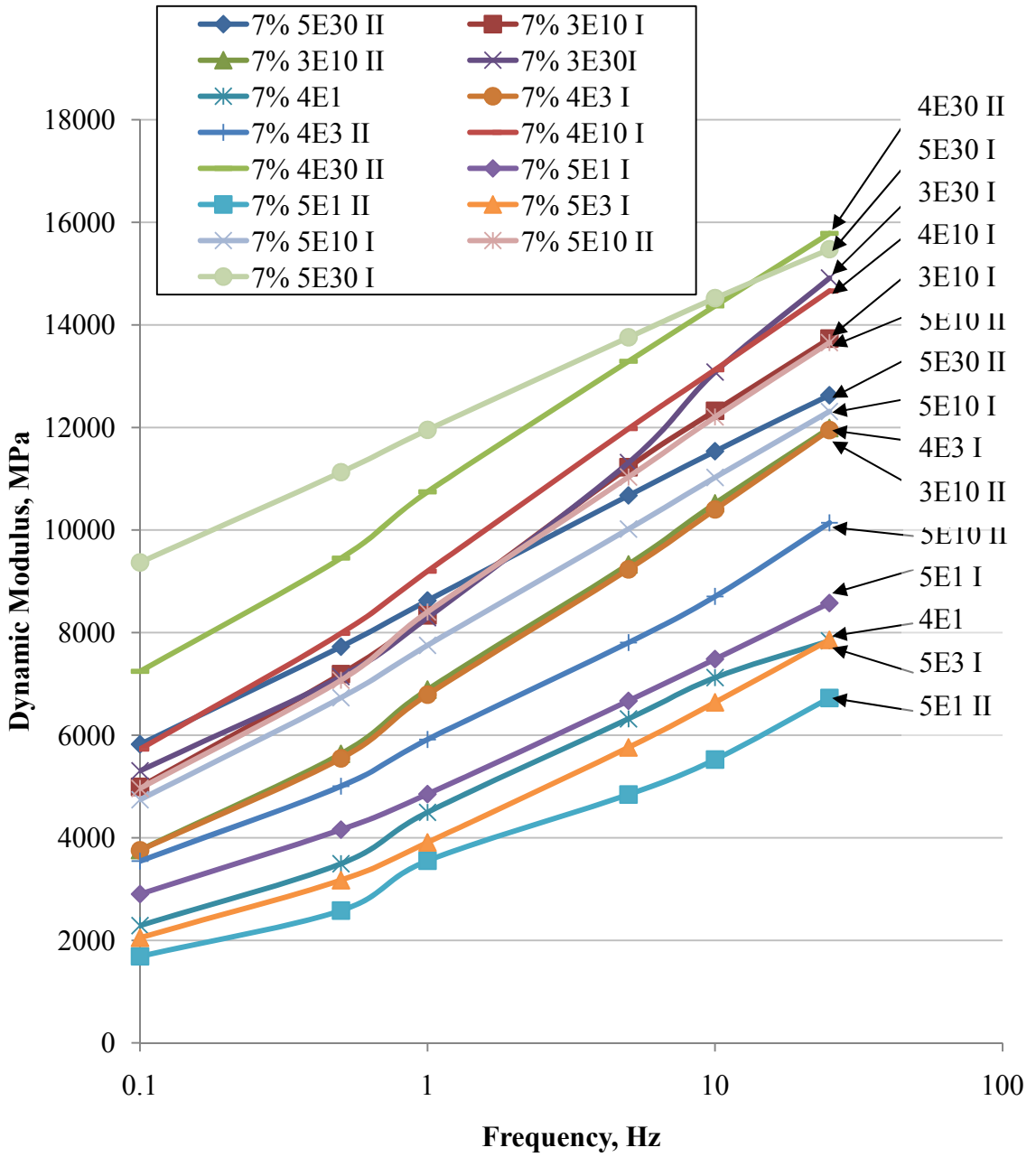


Figure 36 Dynamic Modulus for 7% Air Void Level at 13°C

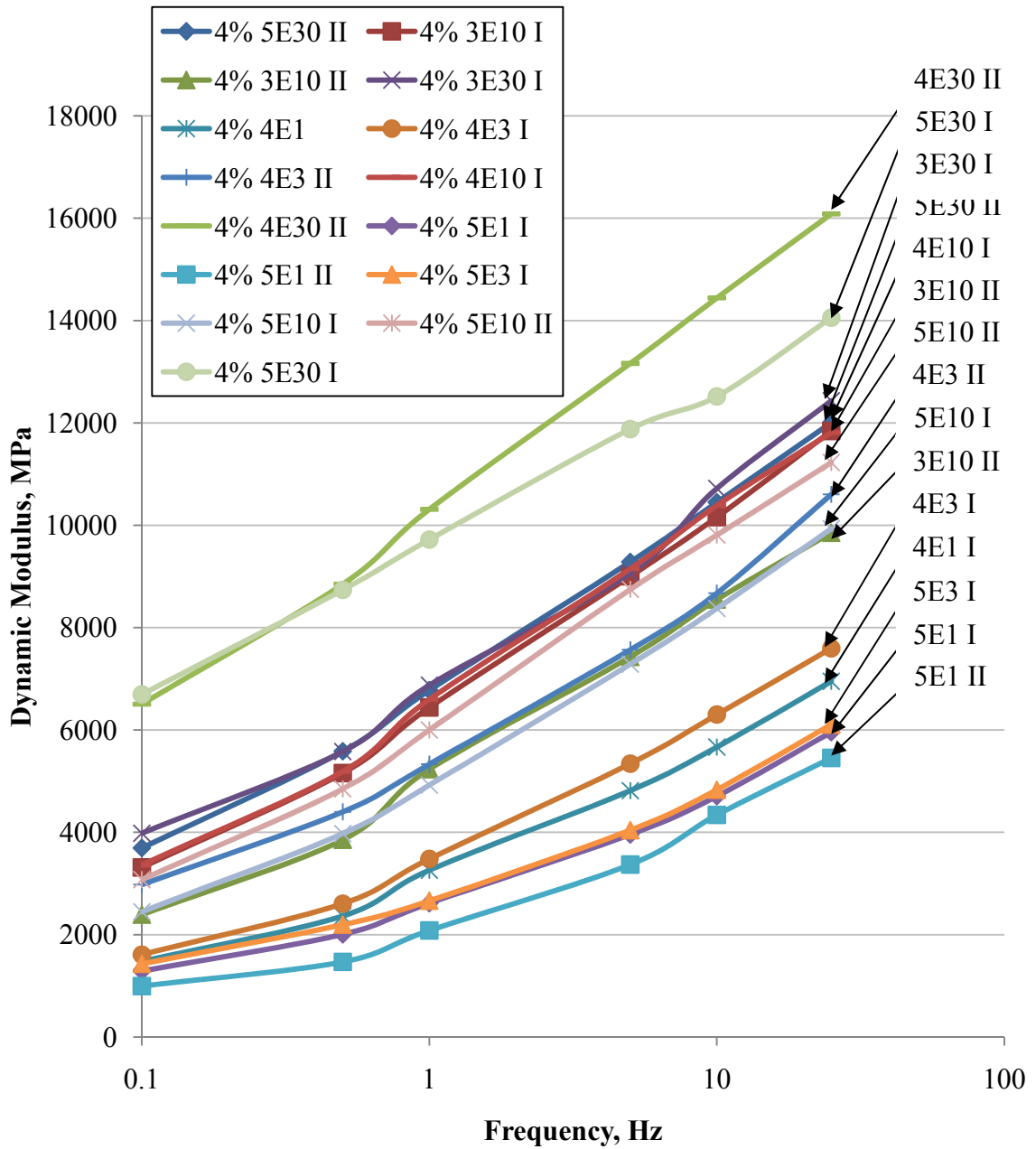


Figure 37 Dynamic Modulus for 4% Air Void Level at 21.3°C

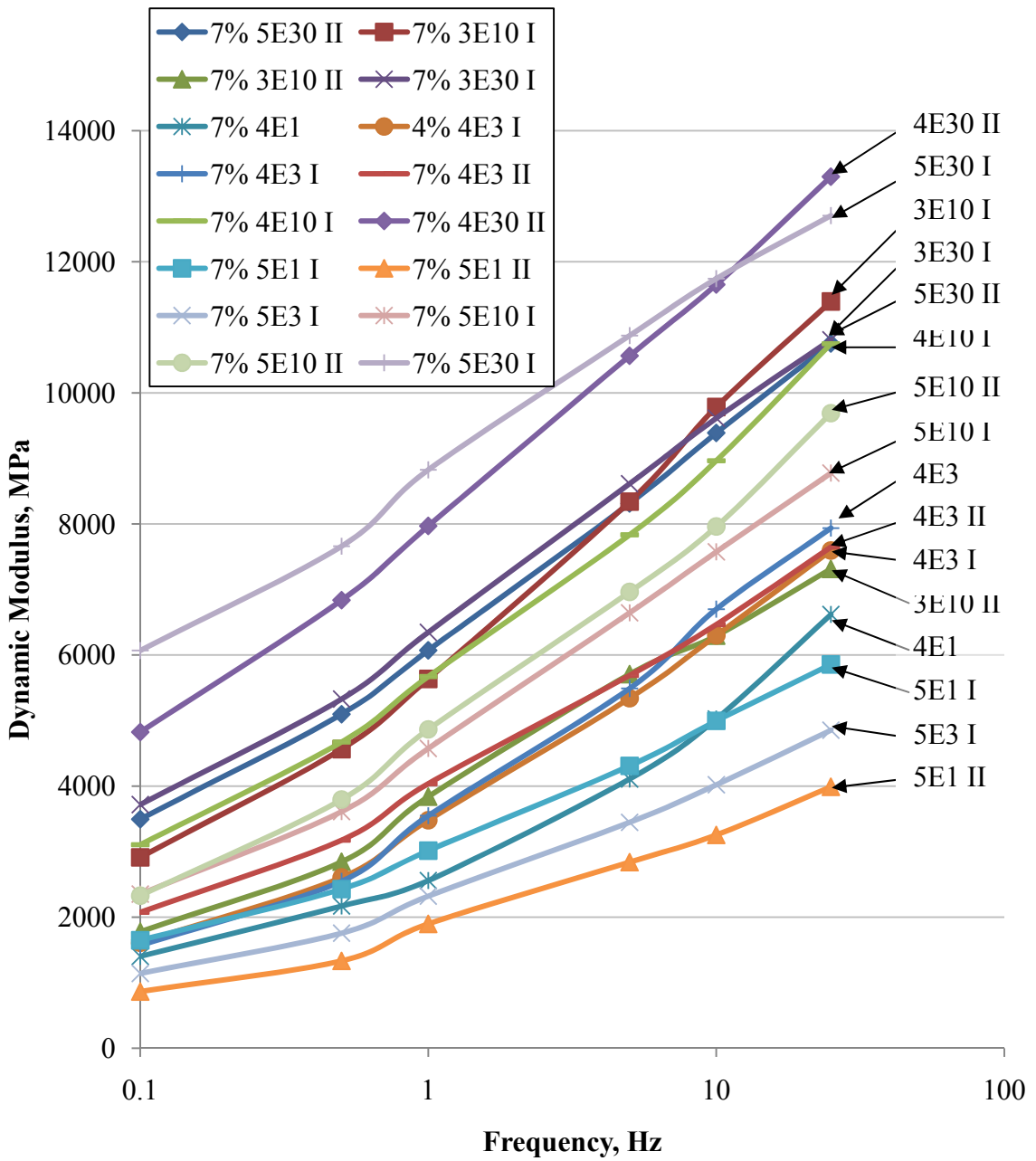


Figure 38 Dynamic Modulus for 7% Air Void Level at 21.3°C

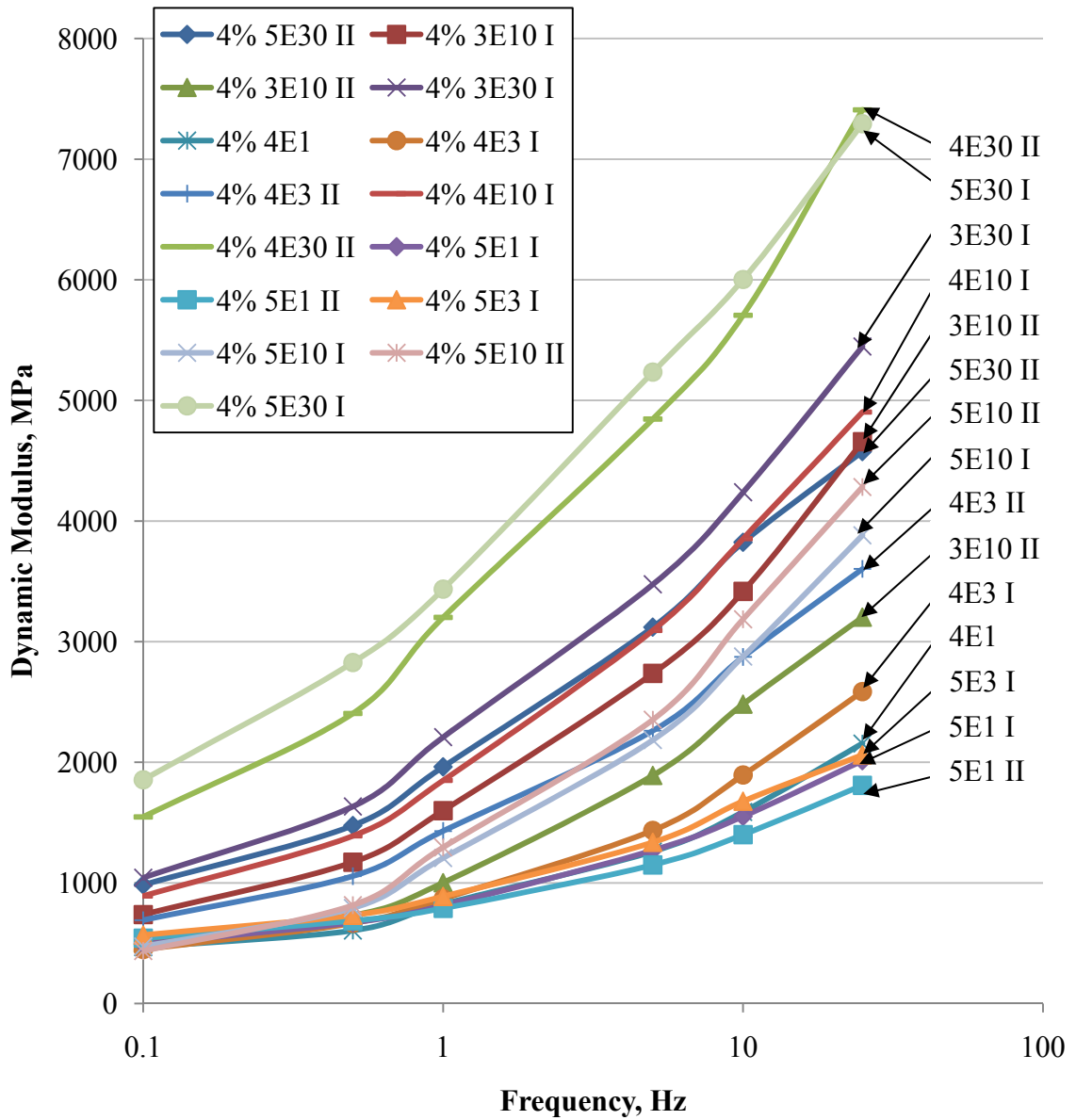


Figure 39 Dynamic Modulus for 4% Air Void Level at 39.2°C

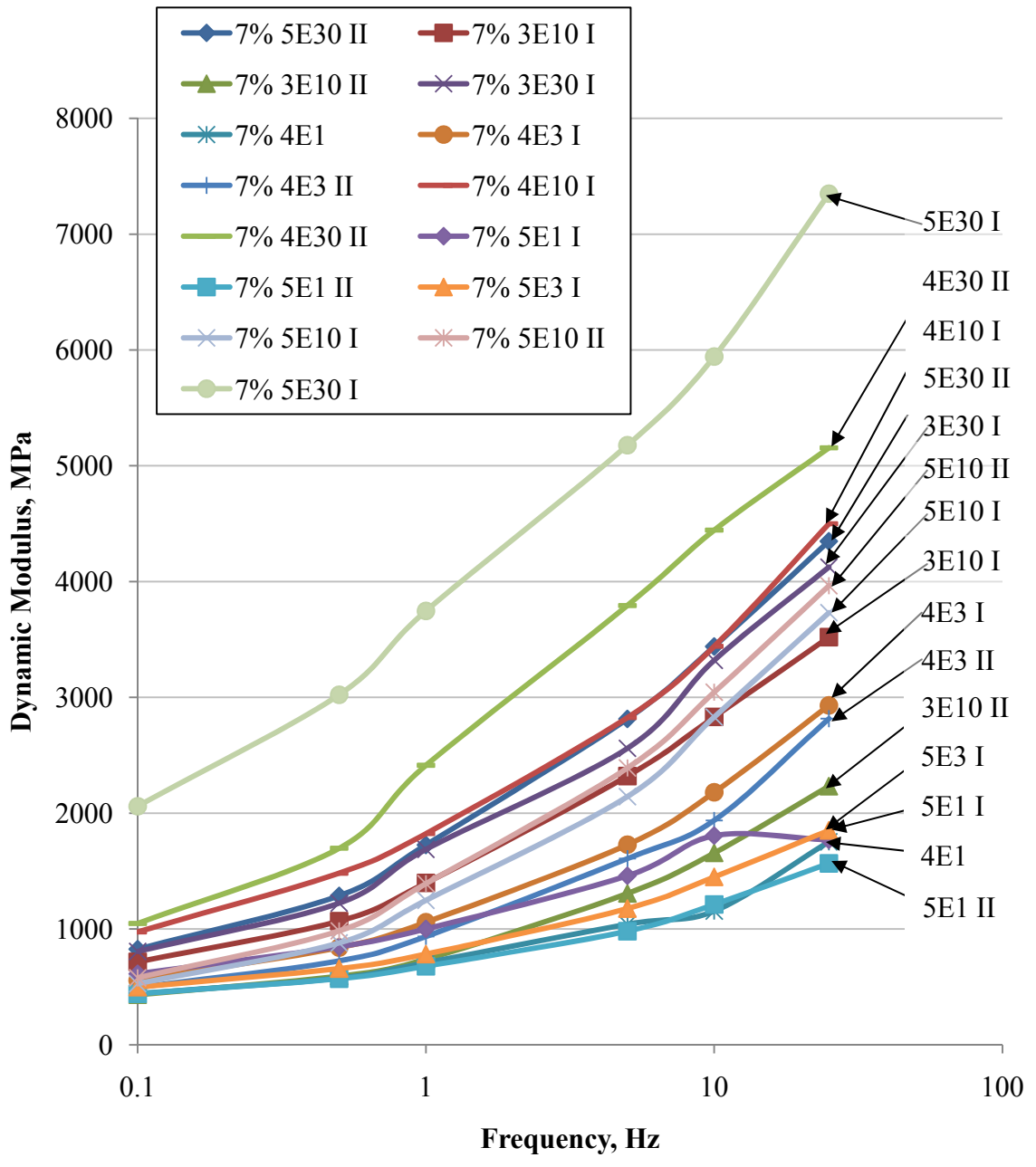


Figure 40 Dynamic Modulus for 7% Air Void Level at 39.2°C

Flow Number Test Results

The flow number test was conducted according to NCHRP Report 465[83] with unconfined testing. During the flow number testing, some of the mixtures did not undergo tertiary flow because these mixtures have a very higher stiffness (high modulus). A simple approach to determine the flow number of asphalt mixtures during a dynamic creep test was used in this project. The results of the flow number testing is shown in Table 6.

Table 6 Average Flow Number Measured using Stepwise Approach

Descriptors	Test Temperature	4% Air Void Level		7% Air Void Level	
		Average	Standard Deviation	Average	Standard Deviation
3E10I	45	3029	330	1759	92
3E0 II	45	1731	308	725	69
3E30 I	45	13099	3279	4829	777
4E1 I	45	320	35	134	11
4E3 I	39.2	No FN	No FN	No FN	No FN
4E3 II	45	13995	3093	1710	-
4E10 I	45	11136	420	-	-
4E30 II	-	-	-	-	-
5E1 I	45	468	327	346	-
5E1 II	45	450	17	251	111
5E3 I	45	439	193	220	50
5E10 I	39.2	No FN	No FN	No FN	No FN
5E10 II	39.2	No FN	No FN	No FN	No FN
5E30 I	45	No FN	No FN	No FN	No FN
5E30 II	45	No FN	No FN	No FN	No FN

Field Rutting Results

The field rutting performance was provided by the Michigan State Department of Transportation (MDOT) [110]. Field data for all HMA pavements with up to seven years in service performance were collected in this study. An average rutting value from the left and right lanes was used in this study. The summary of the field rutting result are show in Table 6.

Table 7 Field Rutting Results

Mix Name/ Type	Year	Average Rut Value (left/right), inch
3E10 I	2003	0.000
	2005	0.035
	2007	0.170
3E10 II	2003	0.000
	2007	0.245
3E30 I	2002	0.000
	2005	0.080
	2007	0.169
4E3 I	2005	0.000
	2006	0.136
4E3 II	2000	0.000
	2002	0.218
	2004	0.067
	2006	0.207
4E10 I	2003	0.000
	2005	0.057
	2007	0.114

Table 7 Field Rutting Results Continue

Mix Name/ Type	Year	Average Rut Value (left/right), inch
4E30 II	1999	0.000
	2000	0.057
	2002	0.105
	2004	0.058
	2006	0.275
5E1 II	2005	0.000
	2006	0.245
5E3 I	2005	0.000
	2007	0.245
5E10 I	2006	0.000
	2007	0.156
5E10 II	2006	0.000
	2007	0.155
5E30 I	2000	0.000
	2001	0.158
	2003	0.027
	2005	0.039
	2007	0.161
5E30 II	2006	0.000
	2007	0.180

Pavement Structure

The pavement structure and maintenance associate with each mixture type was provided by the Michigan State Department of Transportation (MDOT) [110]. Most of the pavement structure (i.e. base and sub-base) are not recorded well. A summary of these results are shown in Table 7.

Table 8 Pavement Structure and Maintenance or Construction Method of the Mixture Collected from the Field

Mix Type	Base Thickness (inch.)	Sub-base Thickness (inch.)	Comments
3E10 I	Not found	Not found	
3E10 II	6.3"	18.1"	
3E30 I	6.3"	18.1"	
4E1 I	8"	18"	
4E3 I	Overlay	Overlay	Not found in plans
4E3 II	mill and resurface	mill and resurface	Not found in plans
4E10 I	Not found	12"	
4E10 I	mill and resurface	mill and resurface	Not found in plans
4E10 II	6.3"	18.1"	
4E3 I	3"	14"	
4E30 II	mill and resurface	mill and resurface	Not found in plans
5E1 I	8"	18"	
5E1 II	Overlay	Overlay	Not found in plans
5E3	mill and resurface	mill and resurface	Not found in plans
5E3 II	8"	21"	
5E3 II	8"	21"	
5E10 I	mill and resurface	mill and resurface	Not found in plans
5E10 II	Mill and Overlay	Mill and Overlay	Not found in plans
5E30 I	7.9"	17.7"	
5E30 II	concrete pavement repair	concrete pavement repair	Not found in plans

Traffic Information

The traffic information at for each project was obtained from Michigan State Department of Transportation (MDOT) [110]. Traffic survey data at year 2007 was used. An equivalent single axle load was also calculated using the information obtained from MDOT. A summary of the traffic information is shown in Table 9.

Table 9 Traffic Information for each Mixture

Mix Name/ Type	Project	Year	AADT¹	No. of Equiv. Truck	ESALs²
3E10 I	M-59 Brighton	2003	47933	2927	4.05E+05
		2005	49213		
		2007	48298		
3E10 II	Michigan Ave, Dearborn	2003	23761	522	9.59E+04
		2007	25081		
3E30 I	Vandyke, Detroit	2002	24706	1322	2.03E+05
		2005	27471		
		2007	31289		
4E3 I	Lansing, MI	2005	8058	248	3.27E+04
		2006	6805		
4E3 II	Lexington	2000	7594	111	1.71E+04
		2002	7594		
		2004	8206		
		2006	6805		
4E10 I	M-53 Detroit	2003	16701	859	1.44E+05
		2005	17147		
		2007	15266		
4E10 II	Michigan Ave	2003	23761	522	9.59E+04
		2007	24617		
4E30 I	I-94 Ann Arbor (SMA)	2000	51601	6296	8.44E+05
		2001	5224		
		2003	54460		
		2005	49256		
		2007	54841		
4E30 II	8 Mile Road	1999	58143	5722	7.80E+05
		2000	57070		
		2002	66062		
		2004	70426		
		2006	60279		
5E1 II	M-38	2005	586	31	4.91E+03
		2006	698		
		2007	60937		

¹ Annual Average Daily Traffic

² Equivalent single axle loads

Table 9 Traffic Information for each Mixture continues

Mix Name/ Type	Project	Year	AADT¹	Number of Equivalence Truck	ESALs²
5E3 I	Bessemer, MI	2005	49213	279	3.72E+04
		2007	50170		
5E10 I	Auburn Hill	2006	16636	691	9.63E+04
		2007	16837		
5E10 II	Oregon, OH	2006	64553	718	1.30E+05
		2007	66782		
5E30 I	I-75 Clarkston	2000	62421	2836	4.06E+05
		2001	65781		
		2003	63873		
		2005	60055		
		2007	60858		
5E30 II	I-75 Toledo	2006	62117	3330	4.94E+05

¹ Annual Average Daily Traffic

² Equivalent single axle loads

CHAPTER 5: ANALYSIS AND DISCUSSIONS

Introduction

Currently, the analysis of the pavement structure was not used in this project due to the limited information obtained. Hence, the analysis and discussion of the results fall into five main categories as follows:

1. Analysis and discussions of dynamic modulus test results;
2. Evaluation of field rutting performance;
3. Evaluation of traffic data;
4. Analysis of field rutting performance over various traffic levels; and
5. Development of specifications for dynamic modulus.

For the first category, the dynamic modulus was analyzed using different methods including recommendations from the literature review ($E^*/\sin\phi$, E^* , different traffic levels, etc). The main objective is to determine appropriate criteria from dynamic modulus testing that can be used in developing the specification for dynamic modulus. The second and third categories were analyzed to determine an appropriate parameter for the comparison the field rutting performance, traffic levels and dynamic modulus. The fourth category is to analyze the quality of the mixture on the field based on the mixture design. Lastly, the fifth category is the most important part in the entire study, which is to develop the criteria of the dynamic modulus based on current results and information obtained.

Analysis and Discussions of Dynamic Modulus Test Results

Based on the literature review, there were two kinds of parameters from the dynamic modulus test used in evaluating the pavement rutting performance. There are $|E^*|$ and $|E^*|/\sin\phi$. In this study, these two parameters were both evaluated. Figure 38 and Figure 39 show $|E^*|$ tested at different traffic levels (E1, E3, E10 and E30). For each frequency, an average of $|E^*|$ at the same traffic level over different aggregate size (size 3, 4 and 5) was plotted. Similarly, $|E^*|/\sin\phi$ at 4% and 7% air void levels over various traffic levels are shown in Figure 40 and Figure 41, respectively. It is notable that these data are the test results from the test temperature of 39.2°C, which is a rutting test temperature. As expected, the dynamic modulus values are increased when the design traffic level increased. This also indicated that mixtures with higher modulus values are able to resist more rutting or allow higher traffic volumes. For $|E^*|/\sin\phi$, it is noticeable that this trend (traffic level increased, $|E^*|/\sin\phi$ increased) is not apparent at the 0.1 hertz and 0.5 hertz frequencies for the test results at 39.2°C.

Based on the current dynamic modulus test results, $|E^*|$ was found to be more suitable in developing the specification because it is more consistent in terms of traffic level when compared to $|E^*|/\sin\phi$.

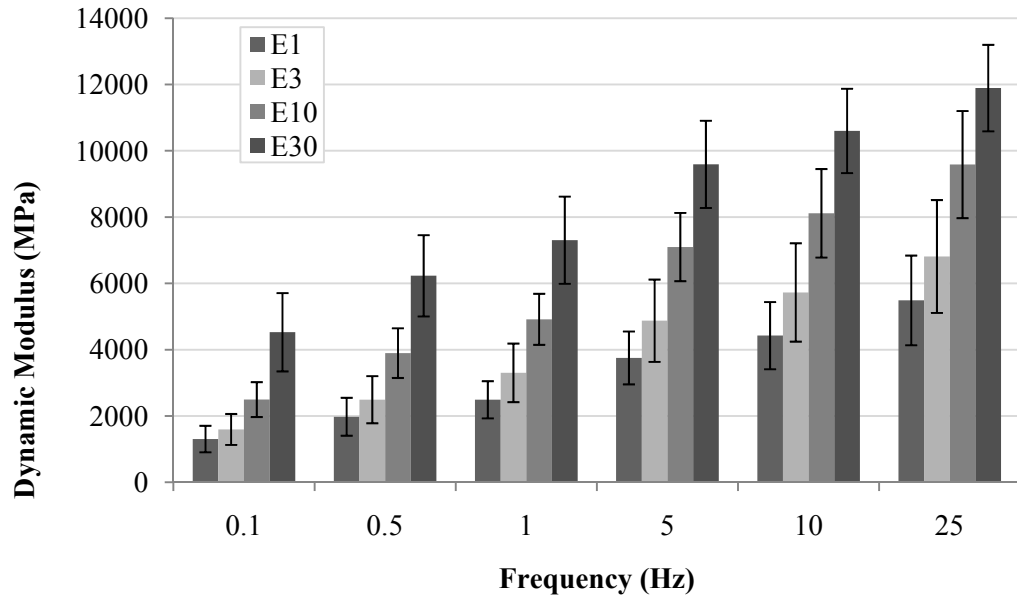


Figure 41 $|E^*|$ over Various Traffic Levels at the Air Void level of 4% (21.3°C)

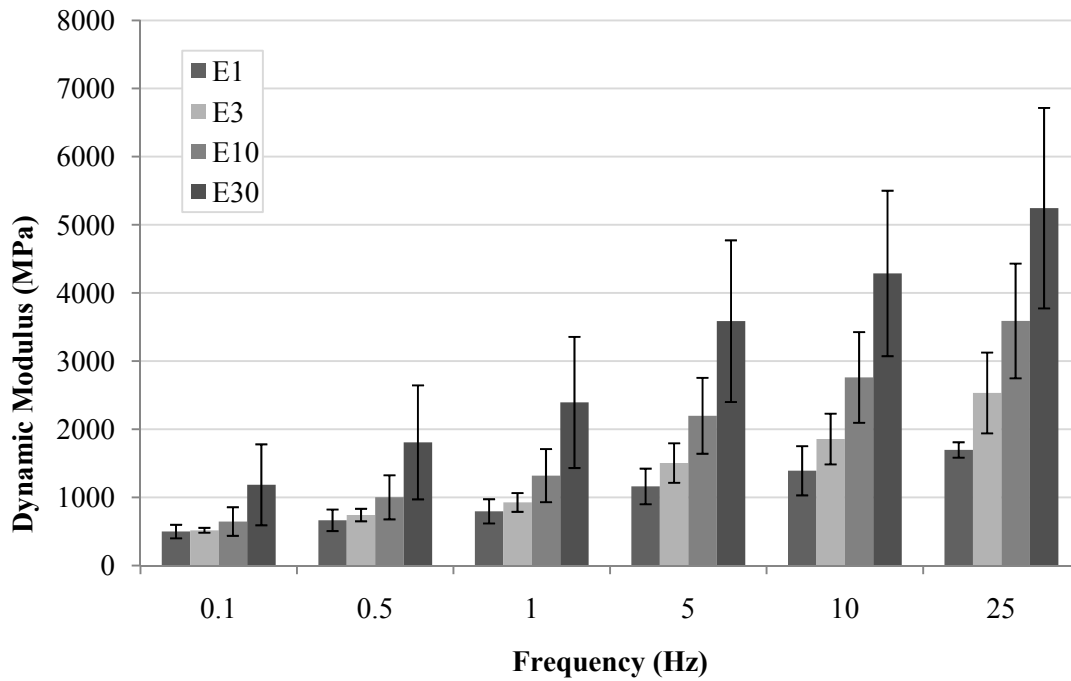


Figure 42 $|E^*|$ over Various Traffic Levels at the Air Void level of 7% (39.2°C)

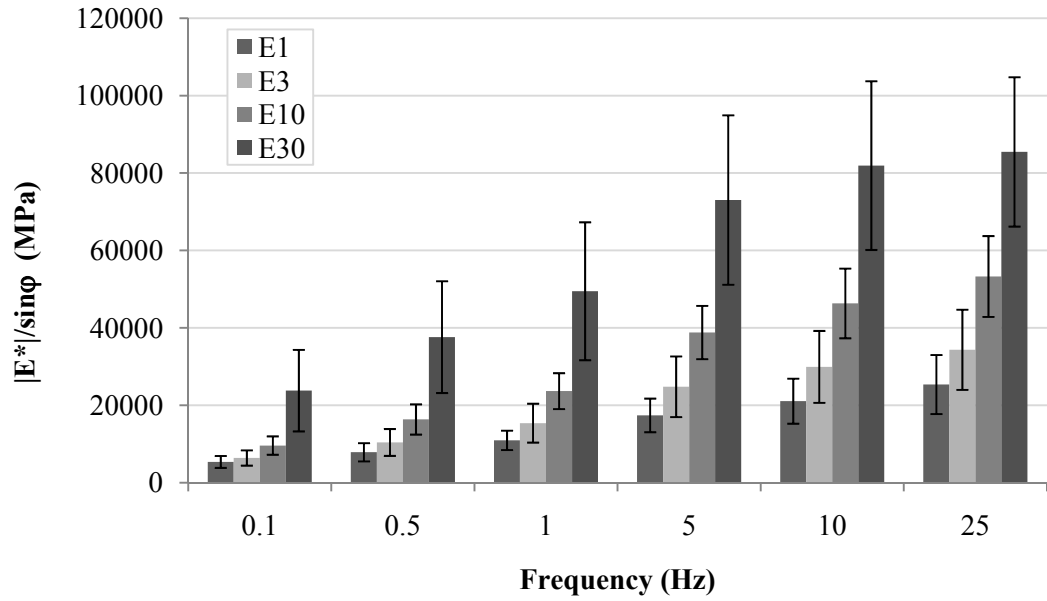


Figure 43 |E*/sinφ over Various Traffic Levels at the Air Void level of 4% (21.3°C)

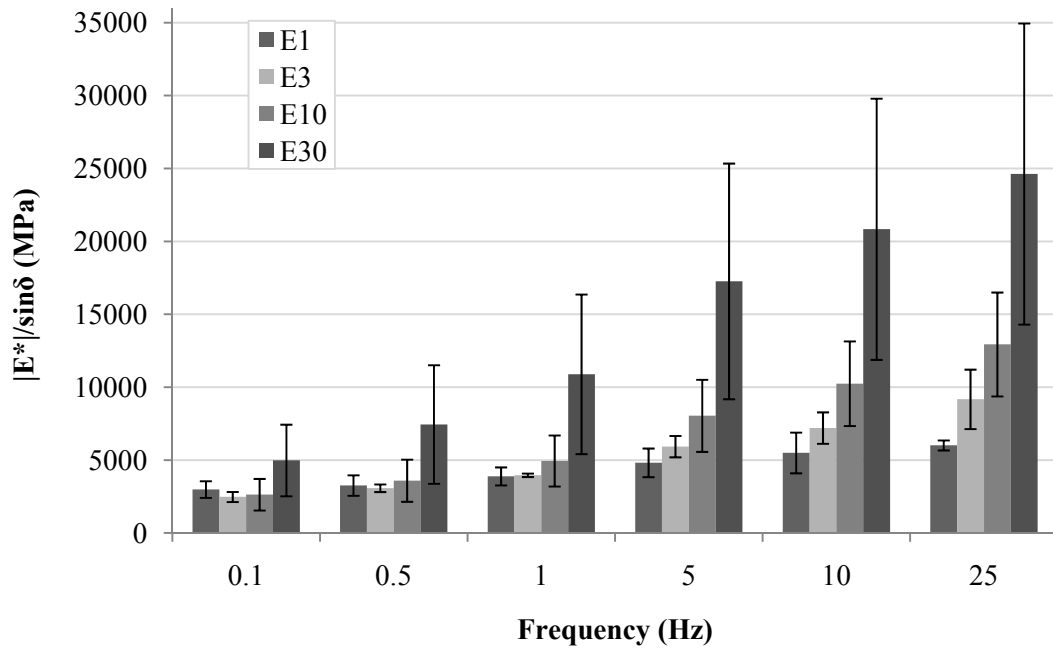


Figure 44 |E*/sinφ over Various Traffic Levels at the Air Void level of 7% (39.2°C)

Analysis of Flow Number Results

In this section, the flow number measurement using a Stepwise approach was verified by comparing the flow number from stepwise approach with the Three-stage Model [79], the mathematical product of Creep Stiffness and Cycles versus Cycles method [111] and FNest method [95]. All the flow number data were compared and shown in Figure 45 to Figure 48. It can be observed that the stepwise method has flow number measurements similar to the Three-Stage and the mathematical product of Creep Stiffness and Cycles versus Cycles methods. The correlation between stepwise method and these two methods was excellent, by showing the R-square ≥ 0.98 . The flow number measured from the stepwise method was significantly higher than the FNest method. As mentioned previously, Archilla et. al. [95] recommended that a more stable method that is less dependent on operator input and interoperation was needed for FN_{est} Method.

In this study, the proposed stepwise method was compared with the traditional method. Figure 48 shows the comparison results. It was observed the correlation between stepwise and traditional method was fair (R-square=0.64). It is worth noting that the traditional method may provide a misleading flow number due to some deceptive points as previously mentioned.

Even though the flow number can be well-defined by all the methods discussed, the proposed stepwise method was determined to be more practical and easier to compute.

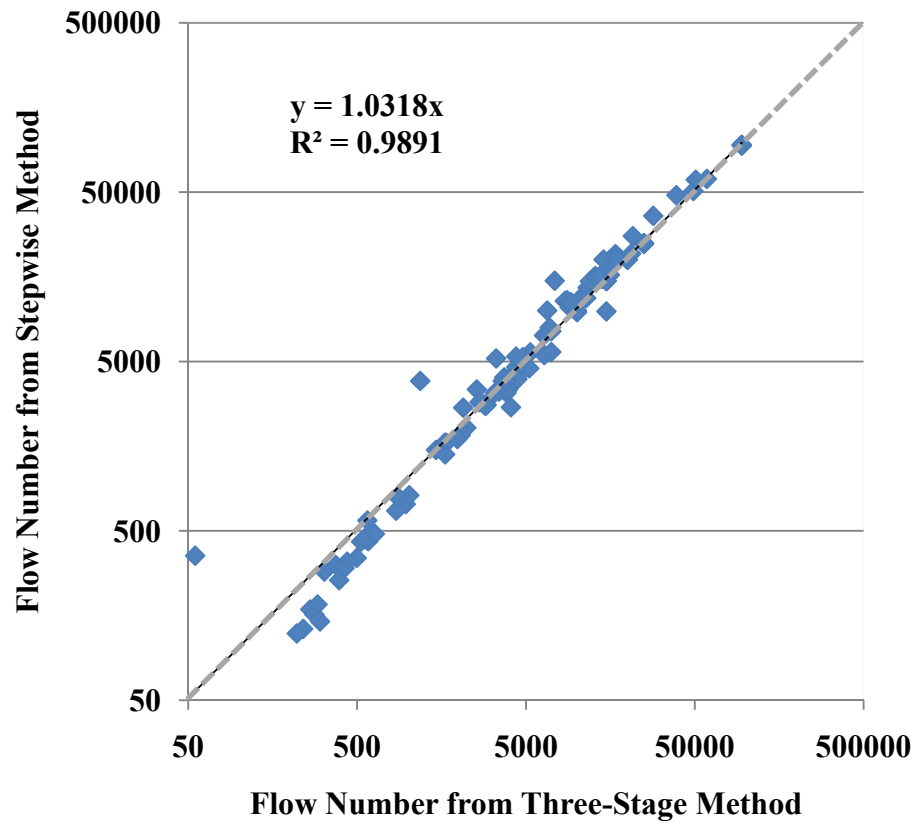


Figure 45 Comparisons of Stepwise and Three-Stage Methods

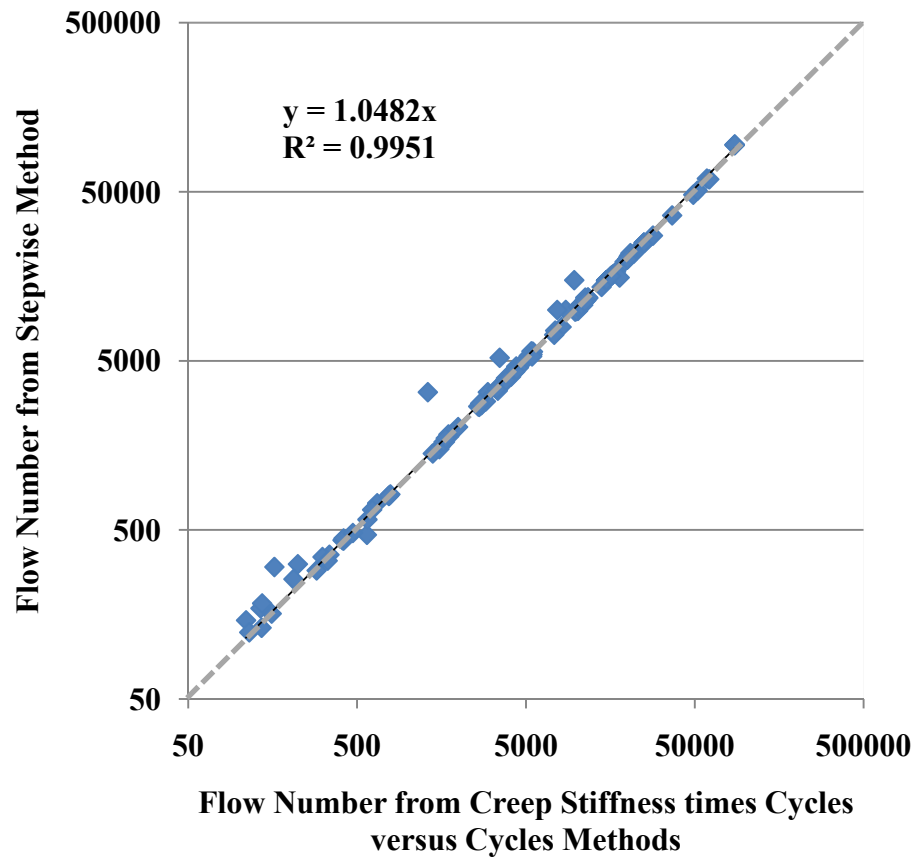


Figure 46 Comparison of Stepwise and Creep Stiffness times Cycles versus Cycles Methods

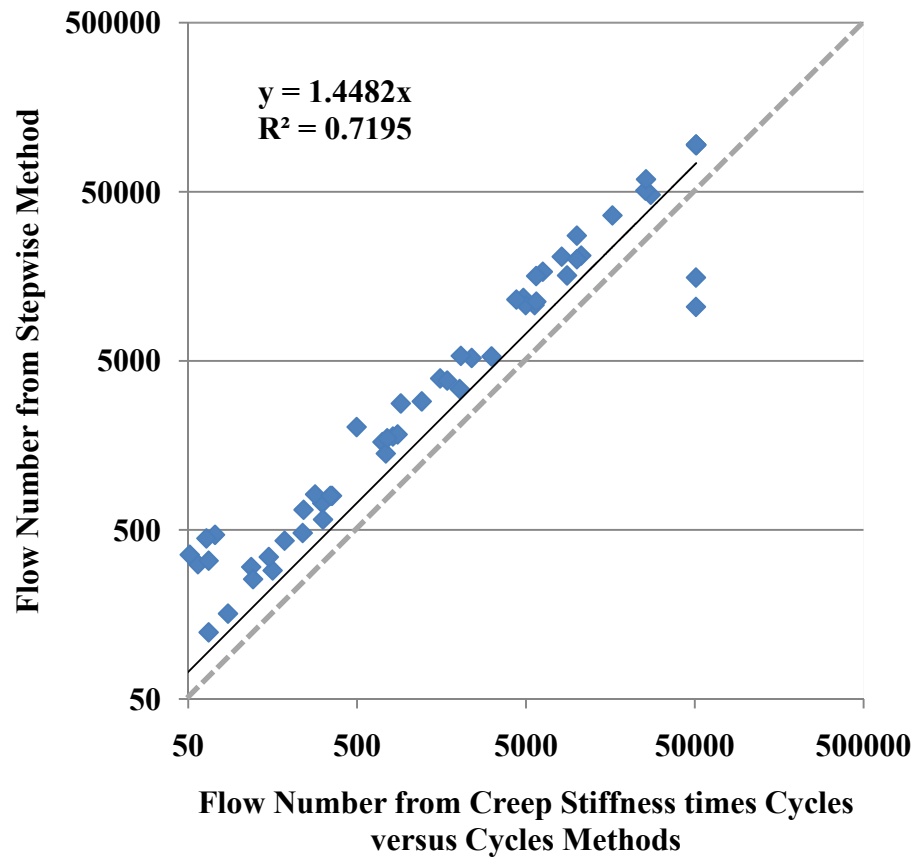


Figure 47 Comparison of Stepwise and FNeSt Methods

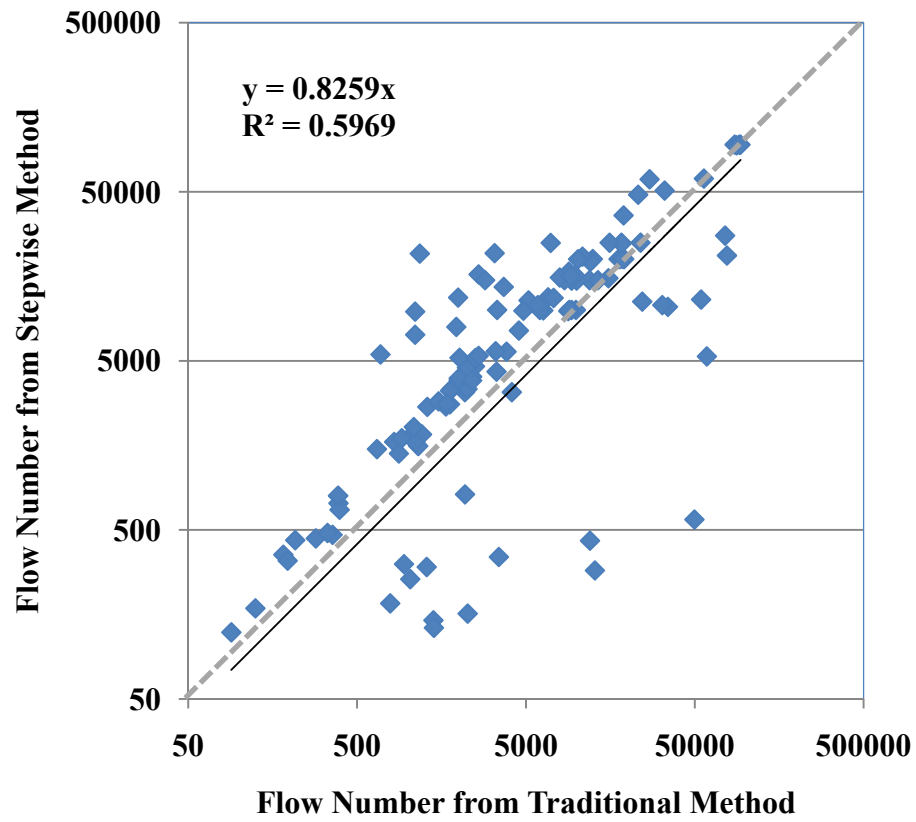


Figure 48 Comparison of Stepwise and Traditional Methods

Relationship between Deformation Rate and Stepwise Flow Number

Previous studies indicated that the rate of deformation (slope of the secondary flow) in the dynamic creep test correlated well with permanent deformation [82]. In addition, the rate of deformation was an important factor for determining the final flow number [112]. In this study, flow number was computed using the stepwise method at 39.2°C and 45°C. Also, air void levels ranging from 4% to 7% were used. Figure 49 shows the comparison between the stepwise flow number and rate of deformation for all mixtures tested. It is notable that the rate of deformation was computed using the stepwise modified dataset. Observations of Figure 49 indicate that an excellent relationship was found when a regression analysis using the equation below was employed:

$$\text{Flow Number} = a \times FN_{\text{slope}}^b$$

Where “a” and “b” are regression coefficients and FN_{slope} is the rate of deformation. Since the equation above was built using different temperatures and air void levels, an R-square of 0.96 showed that this equation is able to compute flow number of an asphalt mixture using the rate of deformation tested at any temperature and any air void level. In this case, “a” and “b” were calibrated and determined to be 18,113 and -0.96, respectively. Four potential benefits were identified from using equation above:

- 1) Flow number can be computed for the test that does not undergo tertiary flow
- 2) The computation of effective rutting temperature can be neglected.

- 3) The duration of the dynamic creep test can be shortened.
- 4) The dynamic creep test could become a non-destructive test if a lower number of cycles is used.

It is recommended that more tests should be conducted to further validate the calculation.

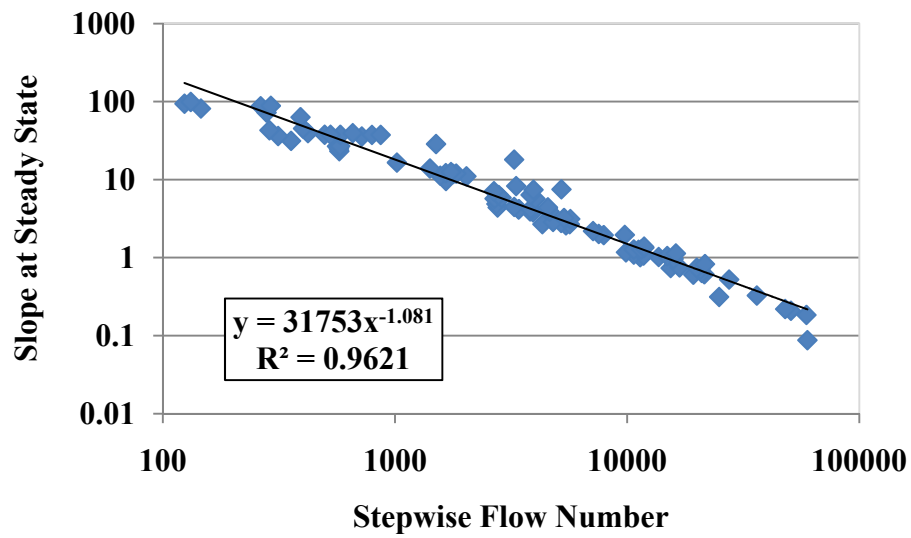


Figure 49 Relationship of Flow Number and Rate of Deformation at Secondary Stage

Evaluation of Field Rutting Performance

All the field rutting performance is plotted into a single graph and is shown in Figure 42. All the field data collected were up to 7 years. It is notable that the rutting of a pavement would decrease if pavement maintenance was schedule for that year. It was observed that three pavements underwent maintenance –4E3I, 4E3II and 5E30I. According to MDOT, the maximum allowable pavement rutting is 0.25 inches [113]. This means that pavement maintenance is needed when the field rutting reaches approximately 0.25 inches. Based on the field rutting performance data collected from MDOT, the pavements indicated had maintenance between 3rd and 5th year for 4E3I; between 2nd and 4th year for 4E3II; and between 1st and 3rd year for 5E30I. For pavements that did have maintenance, it is observed that most of the pavements had rut depths around or below 0.25 inches, except 4E3I which was 0.27 inches.

In this research project, an average amount of rutting per year was calculated based on the current information. It was assumed that the field rutting increased linearly within 3 years period. Even though this does not truly reflected the trend of rutting in the field (rutting generally increases exponentially in the field), however, it was assumed the different was not significant within the short period (1 to 3 years). The actual pavement life (known as “actual life index”) can be calculated using following equation:

$$\text{Actual Life Index: } \frac{Rutting_{Allow}}{Rutting_{Actual}}$$

where,

Actual Life Index: An index indicated the theoretical pavement life in the field, year;

Rutting_{Allow}: Allowed maximum rutting, 0.25 inch; and

Rutting_{Actual}: Actual rutting in the field per year, inch/year.

The average of pavement rutting and actual life index for each mixture is shown in Table 9. It is notable that mixtures with larger actual life index indicated the pavement will last longer in the field. This information will be used for different traffic levels and in the development of dynamic modulus specification criteria.

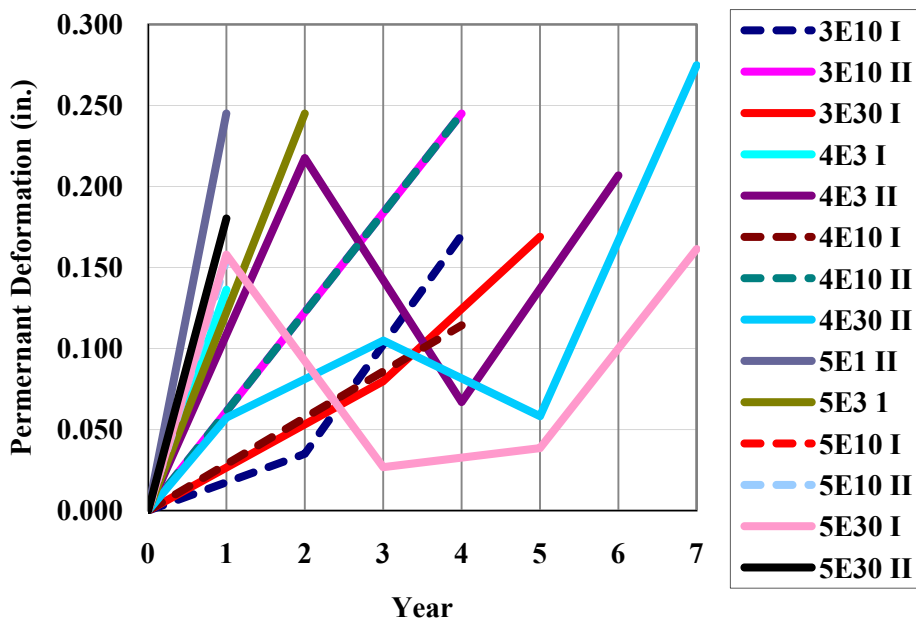


Figure 50 Field Pavement Rutting Performance

Table 10 Field Rutting Performance and Mixture's Actual Life Index

Mix Name/ Type	Year	Average Rut Value (left/right), inch	Average Rut Value (left/right), inch/year	Actual Life Index, Year
3E10 I	2003	0.000	0.0425	5.8824
	2005	0.035		
	2007	0.170		
3E10 II	2003	0.000	0.0613	4.0816
	2007	0.245		
3E30 I	2002	0.000	0.0356	7.0221
	2005	0.080		
	2007	0.169		
4E3 I	2005	0.000	0.1363	1.8337
	2006	0.136		
4E3 II	2000	0.000	0.0894	2.7980
	2002	0.218		
	2004	0.067		
	2006	0.207		
4E10 I	2003	0.000	0.0286	8.7500
	2005	0.057		
	2007	0.114		
4E10 II	2003	0.000	0.0613	4.0816
	2007	0.245		
4E30 I	2000	0.000	0.1049	2.3838
	2001	0.210		
	2003	0.096		
	2005	0.116		
	2007	0.305		
4E30 II	1999	0.000	0.0632	3.9587
	2000	0.057		
	2002	0.105		
	2004	0.058		
	2006	0.275		
5E1 II	2005	0	0.2450	1.0204
	2006	0.245		
5E3 I	2005	0.000	0.1225	2.0408
	2007	0.245		

Table 10 Field Rutting Performance and Mixture’s Actual Life Index continues

Mix Name/ Type	Year	Average Rut Value (left/right), inch	Average Rut Value (left/right), inch/year	Actual Life Index, Year
5E10 I	2006	0.000	0.1564	1.5988
	2007	0.156		
5E10 II	2006	0.000	0.1547	1.6158
	2007	0.155		
5E30 I	2000	0	0.0751	3.3308
	2001	0.158		
	2003	0.027		
	2005	0.039		
	2007	0.161		
5E30 II	2006	0	0.1803	1.3869

Evaluation of Traffic Data

In this project, equivalent single axle loads (ESALs) for each mixture was calculated based on the traffic information obtain from the MDOT TMIS. The traffic level for each mixture type is shown in Table 10. It is assumed that the pavement will fail and need maintenance when the accumulated field traffic reaches the designed traffic level. The design pavement life (known as design life index) can be calculated using following equation:

$$\text{Design Life Index: } \frac{ESALs_{Allow}}{ESALs_{Actual}}$$

where,

Design Life Index: An index indicated the theoretical pavement life based on design, year;

ESALs_{Allow}: Designed asphalt mixture’s traffic level, ESALs; and

ESALs_{Actual}: Actual traffic level in that area, ESALs/year.

The designed life index of each mixture is shown in Table 11. It is notable that the larger value in design life index indicated the pavement will last longer based on the design. This information will be compared with field rutting performance.

Table 11 Traffic Level for each Mixture Type

Mixture Type	Designed Traffic Level, ESALs
E1	1 million
E3	3 millions
E10	10 millions
E30	30 millions

Table 12 Field Traffic Level and Design Life Index

Mix Name/ Type	Field Traffic Level, ESALs ¹	Maximum Designed Traffic Level, ESALs	Design Life Index, year
3E10 I	4.05E+05	1.00E+07	23.74
3E10 II	9.59E+04	1.00E+07	100.26
3E30 I	2.03E+05	3.00E+07	142.10
4E3 I	3.27E+04	3.00E+06	88.21
4E3 II	1.71E+04	3.00E+06	168.69
4E10 I	1.44E+05	1.00E+07	66.77
4E10 II	9.59E+04	1.00E+07	100.26
4E30 I	8.44E+05	3.00E+07	34.18
4E30 II	7.80E+05	3.00E+07	36.98
5E1 II	4.91E+03	1.00E+06	195.83
5E3 I	3.72E+04	3.00E+06	77.54
5E10 I	9.63E+04	1.00E+07	99.85
5E10 II	1.30E+05	1.00E+07	73.96
5E30 I	4.06E+05	3.00E+07	71.05
5E30 II	4.94E+05	3.00E+07	58.39

¹ Equivalent single axle loads

Analysis of Field Rutting Performance over Various Traffic Levels

Table 12 and Table 13 are simplified from Table 9 and Table 11, respectively. Mixtures in these two tables (Table 12 and Table 13) were also reorganized to rank quality of mixture from good to bad. Based on Table 12, it is observed that most of the high traffic level mixtures (E10 and E30) have higher actual life index, which is as expected (mixtures with higher traffic level have higher life index). For Table 13, it shows the life of the mixture based on the design traffic level (design traffic level versus field traffic level) and will not reflect the quality of the mixture. In general, none of the construction and design is perfect in terms of mixture design and mixture production. The performance of mixtures are often affected by climate, human error during construction, humidity, asphalt plant production, etc which resulted in producing a bad mix. The perfection of a mixture in terms of design and production can be determined using the Rank Index:

$$\text{Rank Index: } \frac{\text{Actual_Life_Index}}{\text{Design_Life_Index}} \times 100\%$$

The Rank Index represents the perfection of a mixture where 100% mean perfect and 0% means the mixture will fail immediately after placing in the field. In this project, the Rank Index was measured and is shown in the Table 14. It was observed that only one mix (5E1, M38) falls below 1% and the highest was approximately 24.8% of perfection. Overall, all the mixtures could be accepted and used in developing the specification criteria for the Simple Performance Test.

Table 13 Ranking from the Actual Life Index Based on Field Rutting Performance

Rank	Mix Type	Project Location	Actual Life Index, Year*
1	4E10 I	Interchange of US-23 and M 59 (Hartland Township, Livingston County)	8.7500
2	3E30 I	US-12 (Michigan Ave), Dearborn ---- From Firestone(Evergreen Rd) to I-94	7.0221
3	3E10 I	M 53 (From South of 28 Mile Road to North of 33 Mile Road), Macomb, Michigan	5.8824
4	3E10 II	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)	4.0816
5	4E10 II	M-52 (From the Saginaw/Shiawassee County line northerly to South Branch of the Bad River in the village of Oakley, City of St. Charles)	4.0816
6	4E30 II	M-90, Lexington, MI (From Babcock Road to Farr Road)	3.9587
7	5E30 I	M-53 , Detroit (From M-3 to M-102)	3.3308
8	4E3 II	M102, Wayne and Macomb Counties (From M-53 to I-94)	2.7980
9	4E30 I	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)	2.3838
10	5E3 1	M-38, Ontario-Houghton-Baraga Counties (From M-26 to Baraga Plains Road)	2.0408
11	4E3 I	US-2, Bessemer, MI (From Wisconsin/Michigan State Line to Eddy Street, Wakefield)	1.8337
12	5E10 II	I-75BL, Auburn Hills, MI (From north of Woodward Avenue northeasterly to Opdyke Road in the city of Auburn Hills and Pontiac, Oakland County)	1.6158
13	5E10 I	I-96, MI (From West of Oakland County line to Novi Road, in the cities of Wixom and Novi, Oakland County)	1.5988
14	5E30 II	I-75, MI (From South Junction of I-475 to North Junction of I-475)	1.3869
15	5E1 II	I-75, MI (From the Ohio State line northerly to La Plaisance Road in the township of Erie, La Salle, and Monroe, Monroe County)	1.0204

* Based on Field Rutting

Table 14 Ranking from the Design Life Index Based on Traffic Levels

Rank	Mixture	Design Life Index, Year*
1	5E1 II	195.83
2	4E3 II	168.69
3	3E30 I	142.1
4	3E10 II	100.26
5	4E10 II	100.26
6	5E10 I	99.85
7	4E3 I	88.21
8	5E3 I	77.54
9	5E10 II	73.96
10	5E30 I	71.05
11	4E10 I	66.77
12	5E30 II	58.39
13	4E30 II	36.98
14	4E30 I	34.18
15	3E10 I	23.74

* Based on Traffic Levels

Table 15 Ranking of the Mixture's Quality Based on Rank Index

Mix Type	Project Location	Rank Index, %
3E10 I	Interchange of US-23 and M 59 (Hartland Township, Livingston County)	24.78
4E10 I	US-12 (Michigan Ave), Dearborn ---- From Firestone(Evergreen Rd) to I-94	13.10
4E30 II	M 53 (From South of 28 Mile Road to North of 33 Mile Road), Macomb, Michigan	10.71
4E30 I	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)	6.97
5E30 I	M-52 (From the Saginaw/Shiawassee County line northerly to South Branch of the Bad River in the village of Oakley, City of St. Charles)	4.69
3E30 I	M-90, Lexington, MI (From Babcock Road to Farr Road)	4.14
3E10 II	M-53 , Detroit (From M-3 to M-102)	4.07
4E10 II	M102, Wayne and Macomb Counties (From M-53 to I-94)	4.07
5E3 I	M-26, South Range, Houghton County (From Kearsarge Street to Tri-Mountain Ave.)	2.63
5E30 II	M-38, Ontario-Houghton-Baraga Counties (From M-26 to Baraga Plains Road)	2.38
5E10 II	US-2, Bessemer, MI (From Wisconsin/Michigan State Line to Eddy Street, Wakefield)	2.18
4E3 I	I-75BL, Auburn Hills, MI (From north of Woodward Avenue northeasterly to Opdyke Road in the city of Auburn Hills and Pontiac, Oakland County)	2.08
4E3 II	I-96, MI (From West of Oakland County line to Novi Road, in the cities of Wixom and Novi, Oakland County)	1.66
5E10 I	I-75, MI (From South Junction of I-475 to North Junction of I-475)	1.60
5E1 II	I-75, MI (From the Ohio State line northerly to La Plaisance Road in the township of Erie, La Salle, and Monroe, Monroe County)	0.52

Development of Trial Dynamic Modulus Specification

In this project, the trial specification criteria of dynamic modulus were developed based field rutting performance and contractor warranty criteria. The rutting performance in the field was shown in a previous section by using the term called the Actual Life Index. In this section, the Actual Life Index was used; incorporating contractor warranty criteria and dynamic modulus test results to develop the SPT specification. The contractor warranty for the pavement is summarized in Table 15 [113].

Table 16 Contractor Warranty for Asphalt Pavement

Warranty Period	Work Type
2 years	Chip Seal
	Micro-Surfacing
	Crack Treatment
3 years	Non-Structural Overlays
	Cold Mill and Resurfacing
	Hot-in-place Recycling
5 years	Repair/ Rehabilitate
	Reconstruction
	Multiple Overlays

The contractor warranty for Asphalt Pavement was used as the quality control and quality assurance (QC/QA) to ensure the performance of the mixture. Based on the information from MDOT [114], most of the mixtures tested in this project were milling and re-surfacing, and only a few mixtures are overlays. Hence, in this study, a 2 year of warranty period was chosen as the one for the design criteria in the SPT development.

The 2 year design period was compared with the Actual Life Index and two category mixtures were defined as: 1) mixtures that meet the warranty, and; 2) mixtures

that not meet the warranty. These two categories are shown in Table 16 and Table 17, respectively.

Table 17 Mixtures That Meet the Warranty Specification

Mixture Type	Actual Life Index, Year
4E10 I	8.75
3E30 I	7.02
3E10 I	5.88
3E10 II	4.08
4E10 II	4.08
4E30 II	3.96
5E30 I	3.33
4E3 II	2.80
4E30 I	2.38
5E3 I	2.04

Table 18 Mixtures That Not Meets the Warranty Specification

Mixture Type	Actual Life Index, Year
4E3 I	1.83
5E10 II	1.62
5E10 I	1.60
5E30 II	1.39
5E1 II	1.02

Table 16 and Table 17 were used to define the qualification of mixtures and used as the references (minimum and maximum point) to develop the criteria for E*. A sample (E* at 39.2°C and 0.1Hz) of how to develop the specification for E* is shown. The first step is to divide the E* in three categories as shown in Table 18, and then defined the minimum criteria of E* based on the following scenarios:

Scenario 1: For 3E10, it is observed that the minimum value of |E*| is 3204 MPa and is defined as a good mixture, hence, this indicates that a lower |E*| is

allowable for the mixture to qualify for the warranty criteria. Hence, a rough estimate of a $|E^*|$ value of 2500MPa is set as the minimum E^* needed.

Scenario 2: For 4E3 mixtures, it is observed that 2585MPa does not meet the warranty criteria. However, an $|E^*|$ value of 3603MPa is sufficient and meets the contractor warranty criteria. Hence, the estimated minimum E^* needed in this case is set at 3000MPa, which is approximately between 2585MPa and 3603MPa.

Scenario 3: For 5E10, it is observed that an $|E^*|$ value of 4232 MPa does not meet the contractor warranty criteria. Hence a slightly higher minimum $|E^*|$ is needed. In this case, the estimated minimum $|E^*|$ needed is set at 4500MPa.

A summary of E^* minimum criteria is shown in Figure 43.

Table 19 Dynamic Modulus for HMA Mixtures that meet Warranty Criteria and did not meet Warranty Criteria at 39.2°C and 0.1Hz

Comments	Mixture Type	Theoretical Pavement Rutting Life Index (Year)	Dynamic Modulus, MPa
HMA Mixtures that meet Warranty Criteria	3E10 I	5.88	340
	3E10 II	4.08	737
	3E30 I	7.02	1043
	4E3 II	2.30	691
	4E10 I	8.75	892
	4E10 II	4.08	350
	4E30 II	3.96	1547
	5E3 I	2.04	567
HMA Mixtures that did not meet Warranty Criteria	5E30 I	3.33	1855
	4E3 I	1.83	448
	5E1 II	1.02	542
	5E10 I	1.60	473
	5E10 II	1.62	435
	5E30 II	1.39	984

		Aggregate Size		
		19.5mm (#3)	12.5mm (#4)	9.5mm (#5)
Traffic Level	E1	n/a	400 MPa	550 MPa
	E3	n/a	500 MPa	600 MPa
	E10	300 MPa	600 MPa	650 MPa
	E30	600 MPa	1000 MPa	1200 MPa

Figure 51 Specification of Dynamic Modulus at Various Traffic Levels and Aggregate Sizes

A similar approach was used to define the minimum criteria of E^* at each temperature and each frequency. The sigmoidal master curve technique was used to connect all these minimum criteria together into one single curve. All the master curves, including mixtures with 4% and 7% air void level were constructed using the reference temperature of -5°C and are shown in Figure 44 to Figure 63. It is recommended that all the future mixtures should be tested at 3 different temperatures (range from -5°C to 40°C) and 5 different frequencies (range from 0.1Hz to 25Hz). A sigmoidal master curve should be constructed and compared with the master curve using the minimum E^* criteria in this project. It is suggested that all the master curves should be constructed using the reference temperature of -5°C and the curve should be higher than the desired master curve using the minimum E^* criteria in this project.

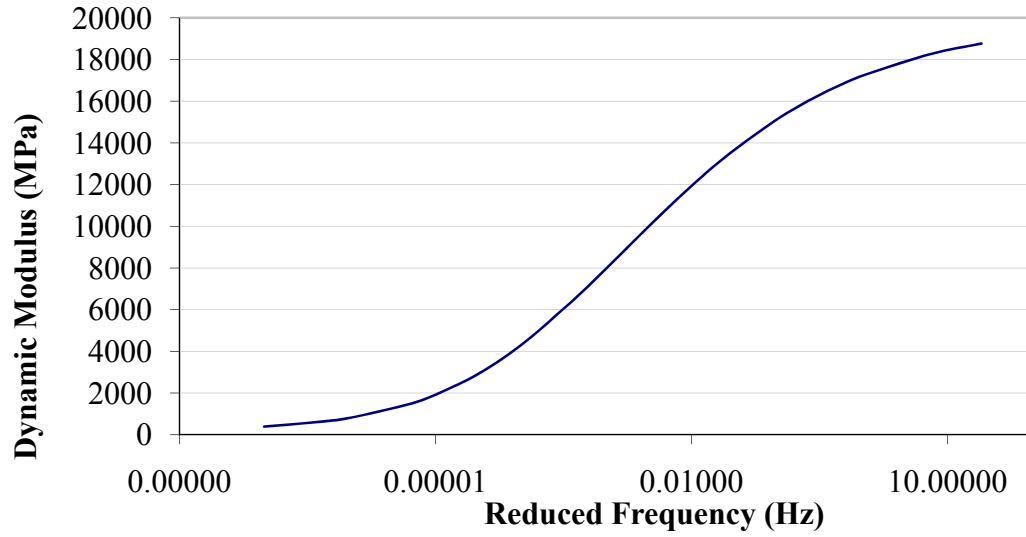


Figure 52 Master Curve for Minimum Required Dynamic Modulus of 3E10 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.2223
α	2.2369
β	-3.5632
γ	0.6759
a	0.0003
b	-0.1123
c	2.4275

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.5239
55.4	-2.8941
70.34	-4.0215
102.56	-6.0082

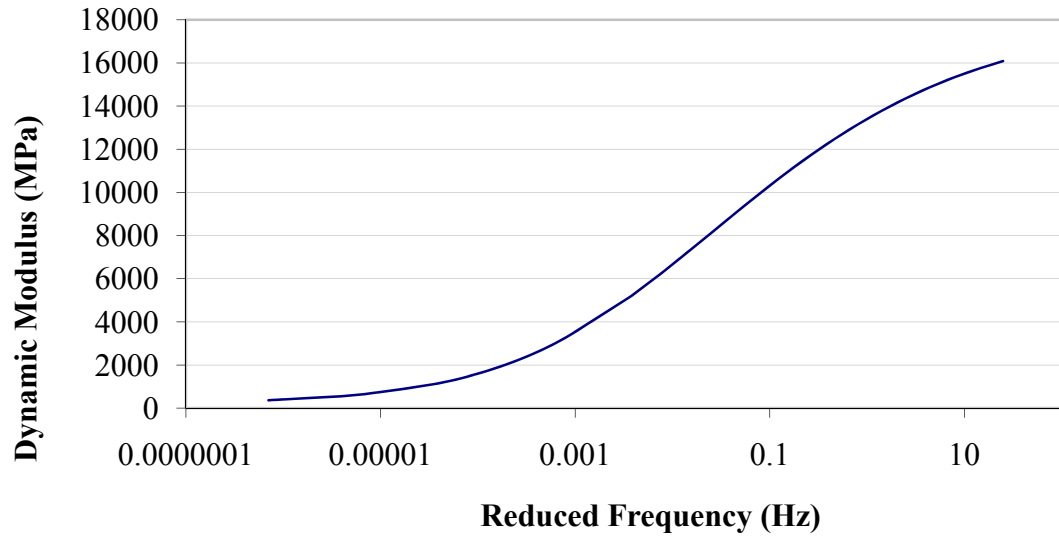


Figure 53 Master Curve for Minimum Required Dynamic Modulus of 3E10 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.3545
α	2.0665
β	-2.6820
γ	0.6816
a	0.0000
b	-0.0678
c	1.5466

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.0739
55.4	-2.1350
70.34	-3.1022
102.56	-5.1511

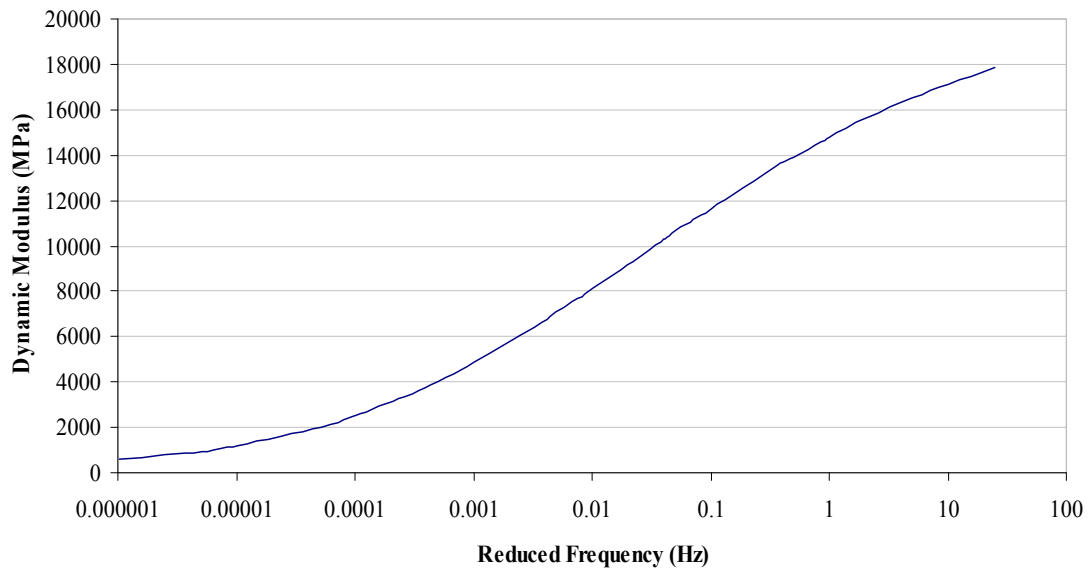


Figure 54 Master Curve for Minimum Required Dynamic Modulus of 3E30 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.1082
α	2.3814
β	-2.6435
γ	0.5508
a	0.0001
b	-0.0700
c	1.5784

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.0749
55.4	-2.1194
70.34	-3.0556
102.56	-4.9867

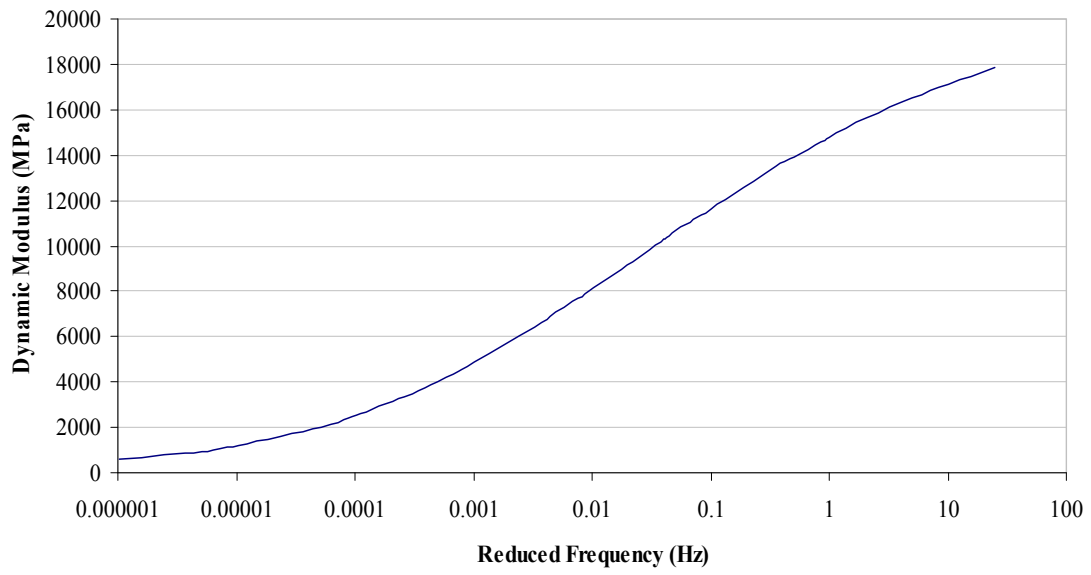


Figure 55 Master Curve for Minimum Required Dynamic Modulus of 3E30 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.1082
α	2.3814
β	-2.6435
γ	0.5508
a	0.0001
b	-0.0700
c	1.5784

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.0749
55.4	-2.1194
70.34	-3.0556
102.56	-4.9867

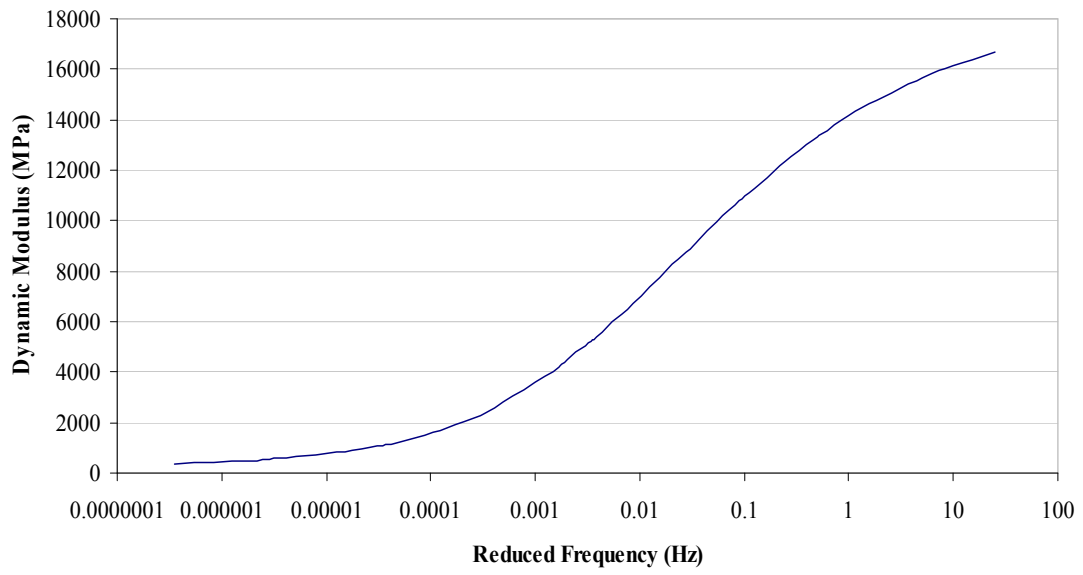


Figure 56 Master Curve for Minimum Required Dynamic Modulus of 4E1 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.5466
$\acute{\alpha}$	1.8752
β	-2.7874
γ	0.7653
a	0.0001
b	-0.0868
c	1.9196

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.2598
55.4	-2.4432
70.34	-3.4670
102.56	-5.4542

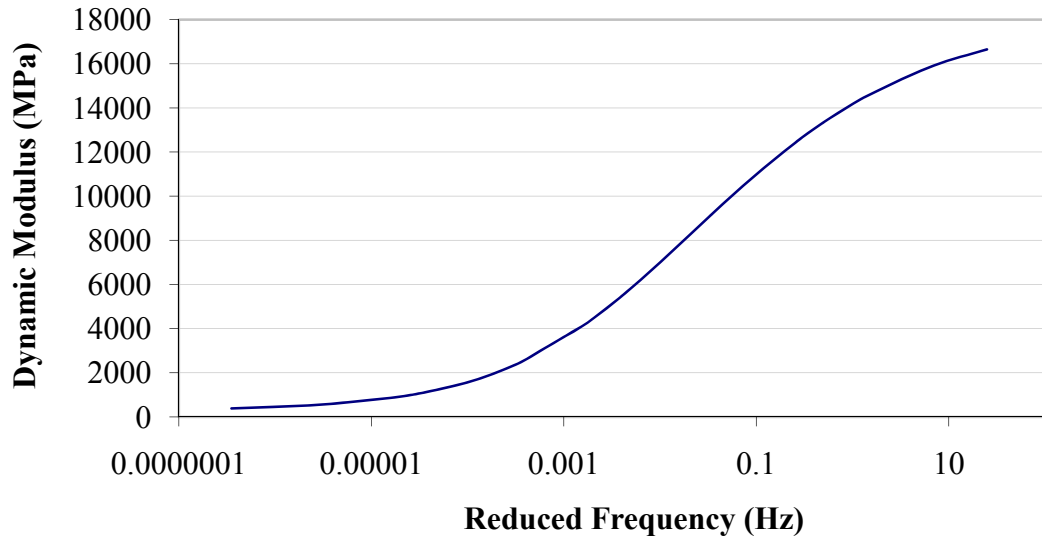


Figure 57 Master Curve for Minimum Required Dynamic Modulus of 4E1 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.4565
α	1.9119
β	-2.3894
γ	0.7179
a	0.0002
b	-0.0837
c	1.8404

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.1949
55.4	-2.3061
70.34	-3.2566
102.56	-5.0640

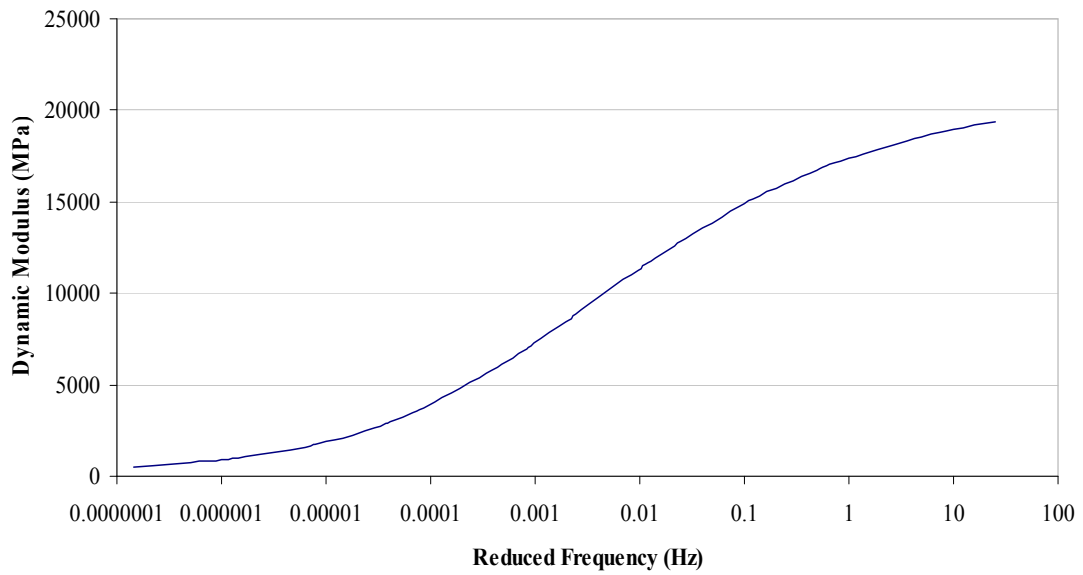


Figure 58 Master Curve for Minimum Required Dynamic Modulus of 4E3 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.4233
α	2.0586
β	-3.2097
γ	0.6506
a	0.0004
b	-0.1255
c	2.6675

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.6157
55.4	-3.0138
70.34	-4.1104
102.56	-5.8456

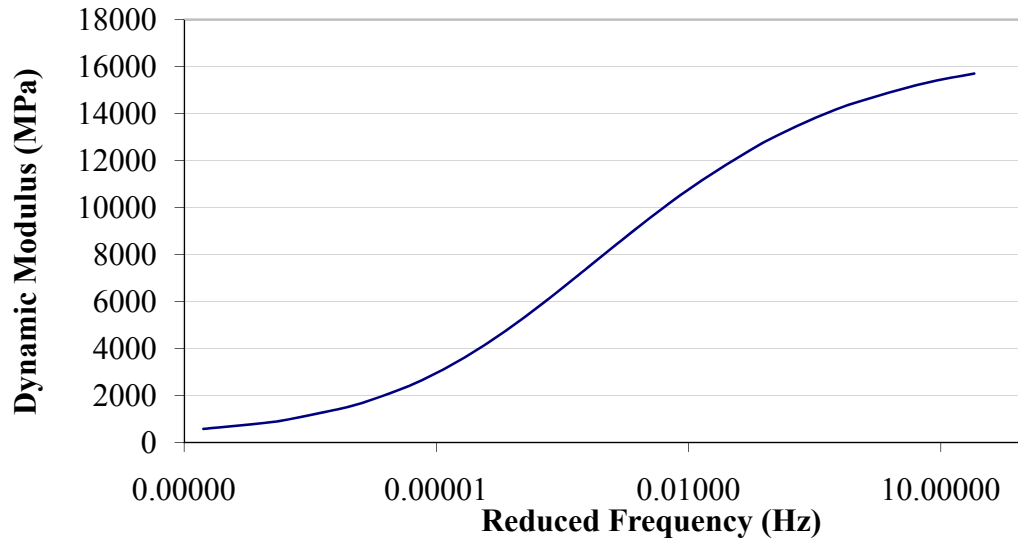


Figure 59 Master Curve for Minimum Required Dynamic Modulus of 4E3 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.4948
α	1.8910
β	-3.3604
γ	0.5897
a	0.0006
b	-0.1574
c	3.3154

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.9697
55.4	-3.6372
70.34	-4.9072
102.56	-6.7715

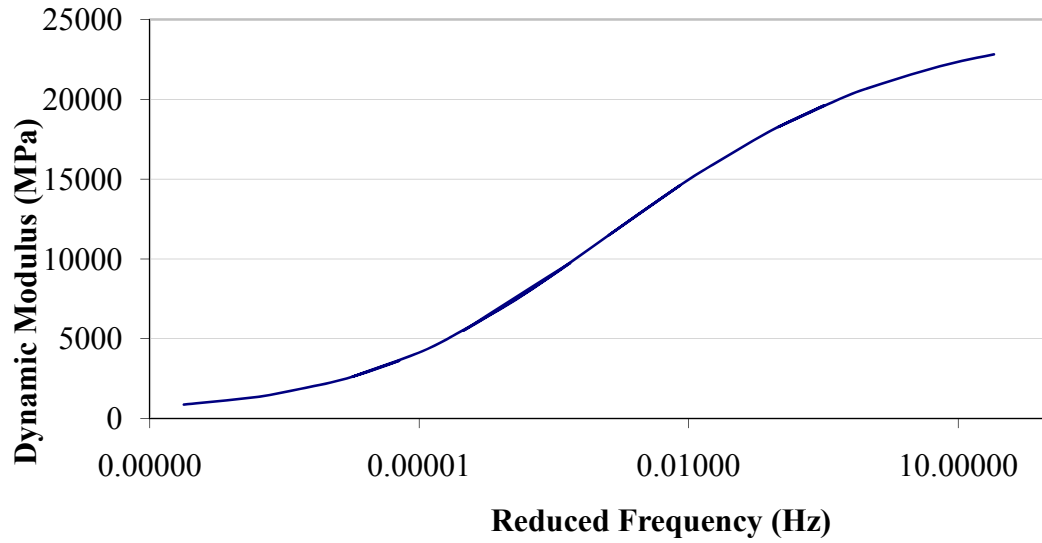


Figure 60 Master Curve for Minimum Required Dynamic Modulus of 4E10 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.5488
$\acute{\alpha}$	2.0095
β	-3.1735
γ	0.5434
a	0.0005
b	-0.1493
c	3.1564

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.8887
55.4	-3.5010
70.34	-4.7429
102.56	-6.6209

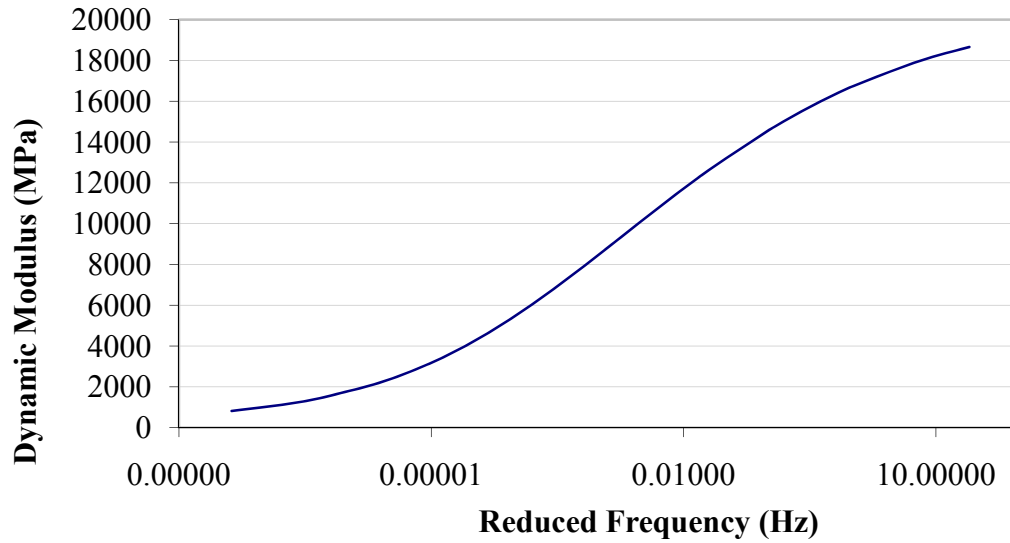


Figure 61 Master Curve for Minimum Required Dynamic Modulus of 4E10 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.5079
α	1.9702
β	-2.9992
γ	0.5299
a	0.0004
b	-0.1266
c	2.7165

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.6781
55.4	-3.1617
70.34	-4.3575
102.56	-6.3736

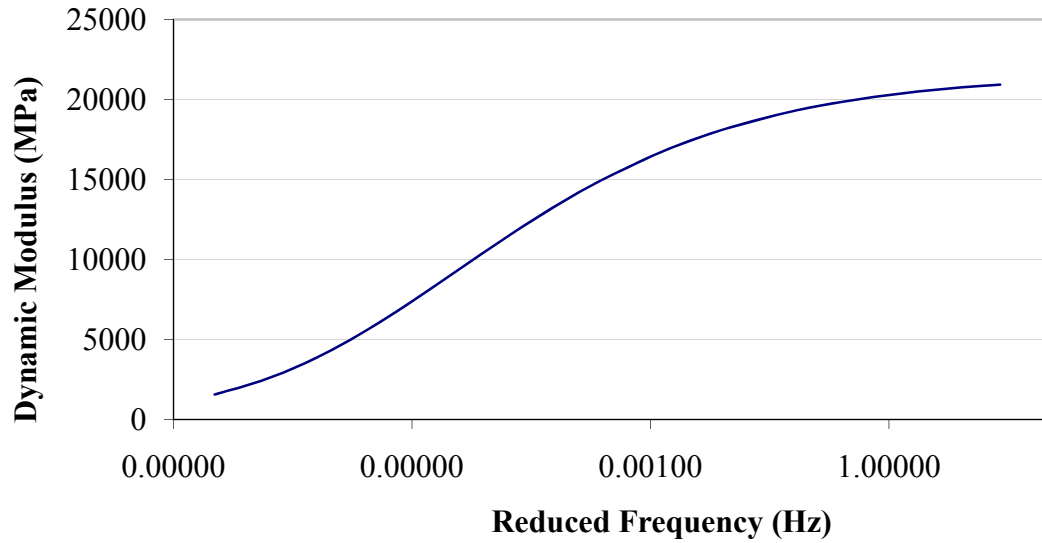


Figure 62 Master Curve for Minimum Required Dynamic Modulus of 4E30 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	3.7702
α	2.7254
β	-4.6031
γ	0.5041
a	-0.0004
b	-0.0403
c	1.1409

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.0598
55.4	-3.6566
70.34	-6.9303
102.56	-7.4831

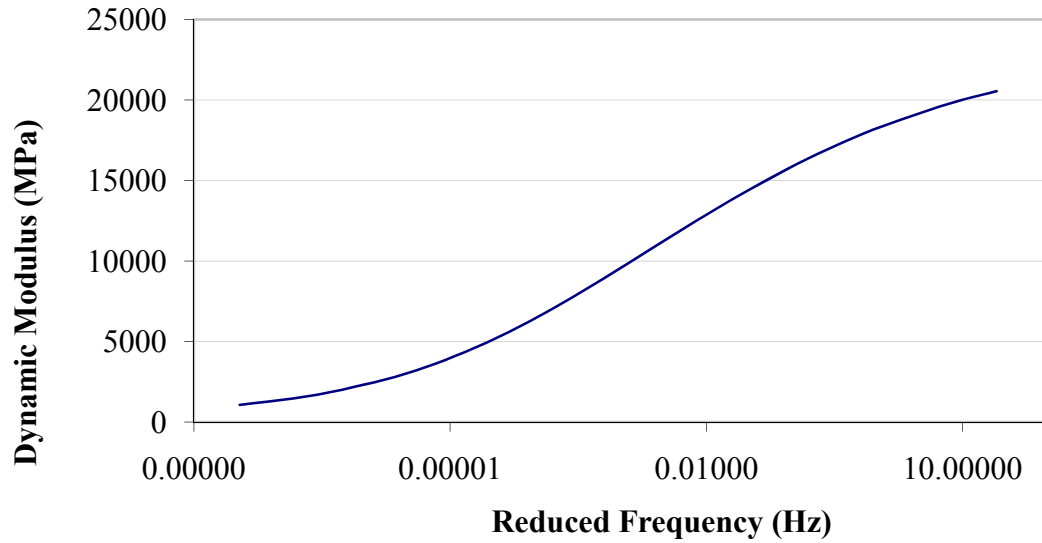


Figure 63 Master Curve for Minimum Required Dynamic Modulus of 4E30 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.5274
α	2.0042
β	-2.8580
γ	0.4778
a	0.0003
b	-0.1161
c	2.5227

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.6008
55.4	-3.0561
70.34	-4.2692
102.56	-6.4643

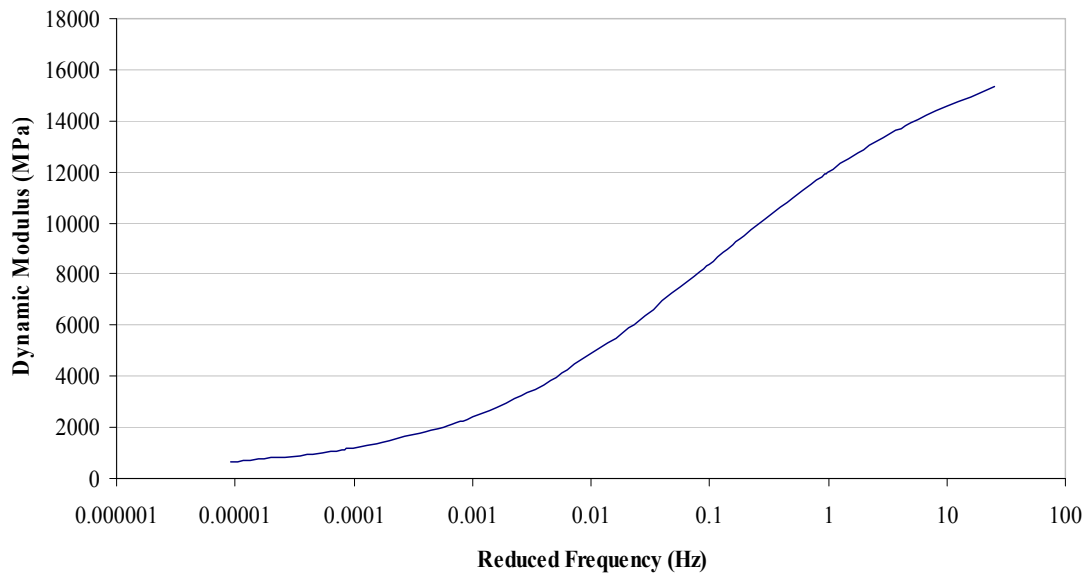


Figure 64 Master Curve for Minimum Required Dynamic Modulus of 5E1 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.6476
α	1.7194
β	-2.3465
γ	0.7428
a	0.0003
b	-0.1044
c	2.2230

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.3526
55.4	-2.5290
70.34	-3.4578
102.56	-4.9507

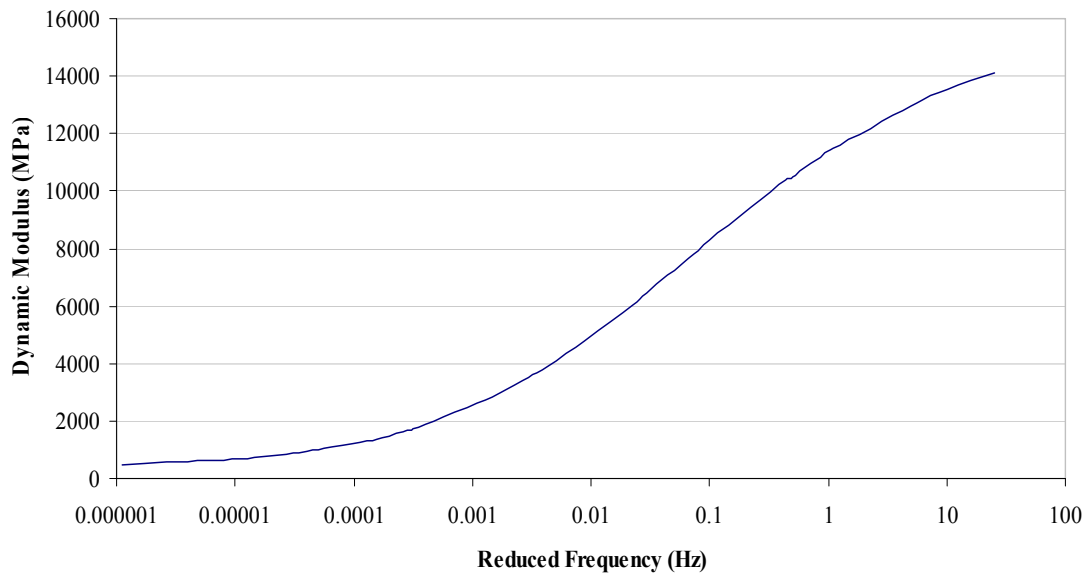


Figure 65 Master Curve for Minimum Required Dynamic Modulus of 5E1 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.6476
α	1.7194
β	-2.3465
γ	0.7428
a	0.0003
b	-0.1044
c	2.2230

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.3526
55.4	-2.5290
70.34	-3.4578
102.56	-4.9507

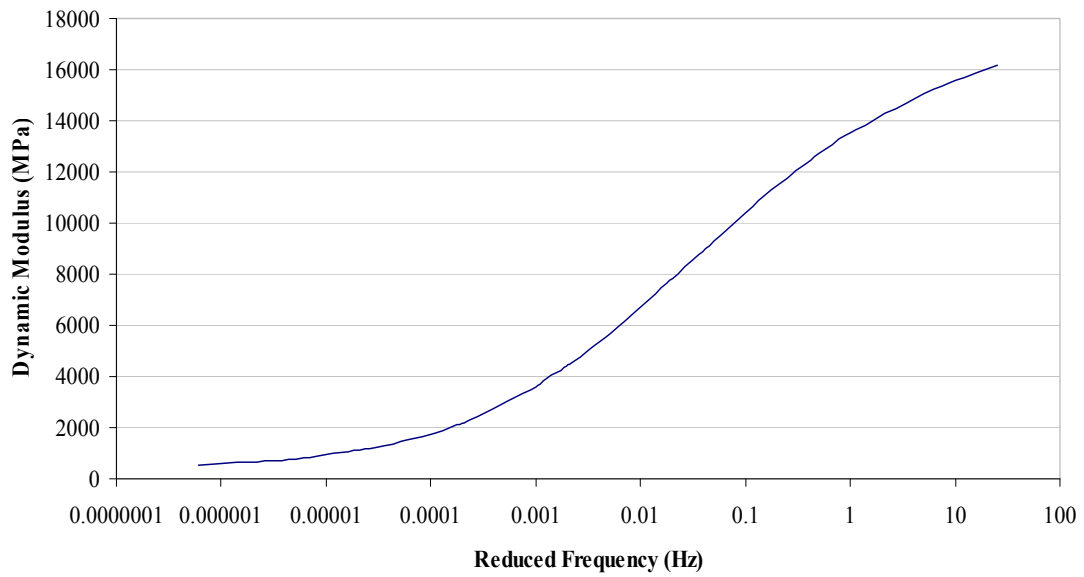


Figure 66 Master Curve for Minimum Required Dynamic Modulus of 5E3 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.6771
α	1.7401
β	-2.5643
γ	0.7240
a	0.0004
b	-0.1132
c	2.4019

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.4509
55.4	-2.7026
70.34	-3.6804
102.56	-5.2128

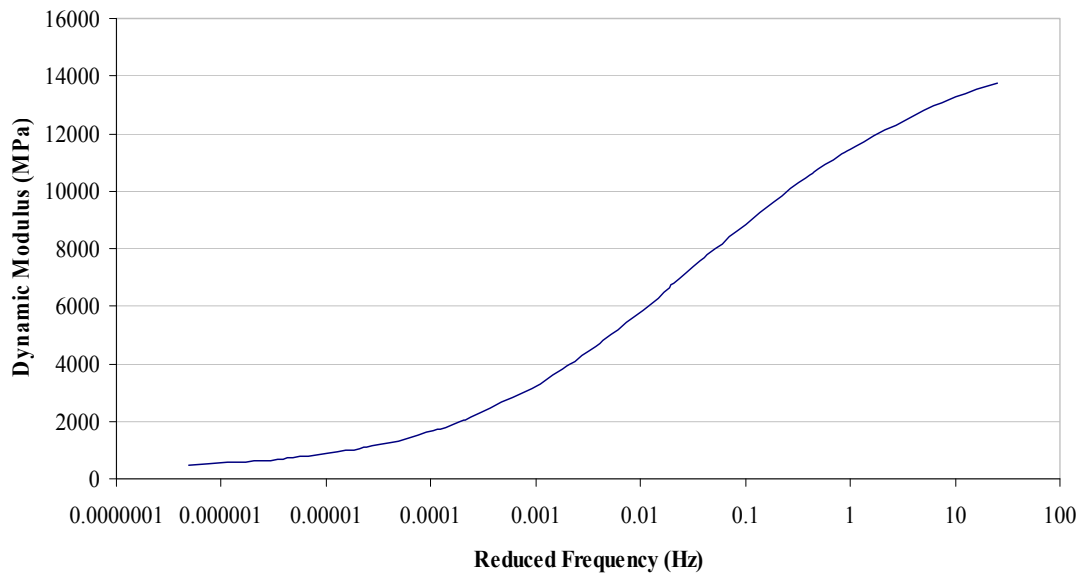


Figure 67 Master Curve for Minimum Required Dynamic Modulus of 5E3 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.6014
α	1.7526
β	-2.5013
γ	0.6852
a	0.0003
b	-0.1093
c	2.3346

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.4296
55.4	-2.6816
70.34	-3.6789
102.56	-5.3158

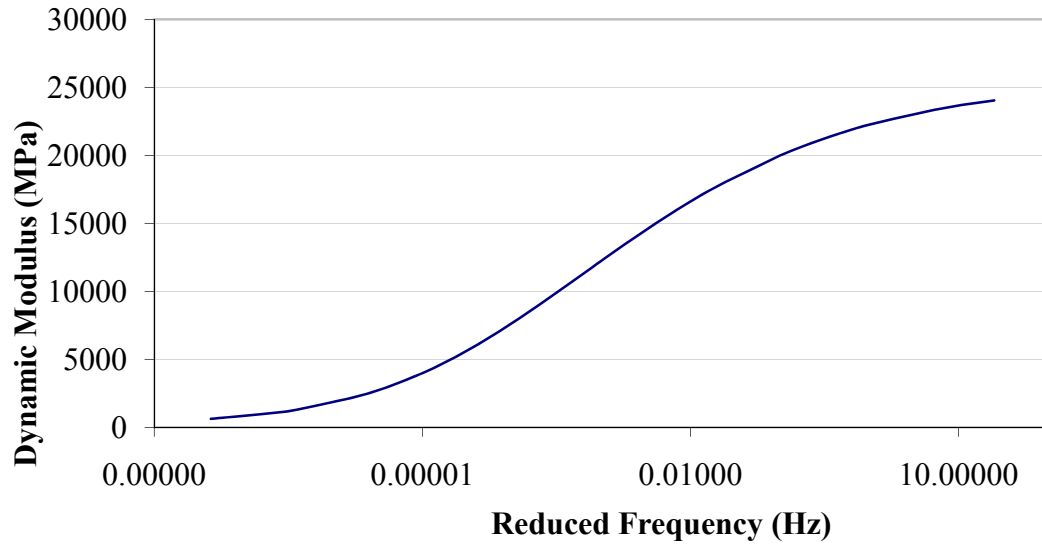


Figure 68 Master Curve for Minimum Required Dynamic Modulus of 5E10 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.2032
α	2.3653
β	-3.6560
γ	0.5996
a	0.0004
b	-0.1300
c	2.7800

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.7052
55.4	-3.2013
70.34	-4.3958
102.56	-6.3667

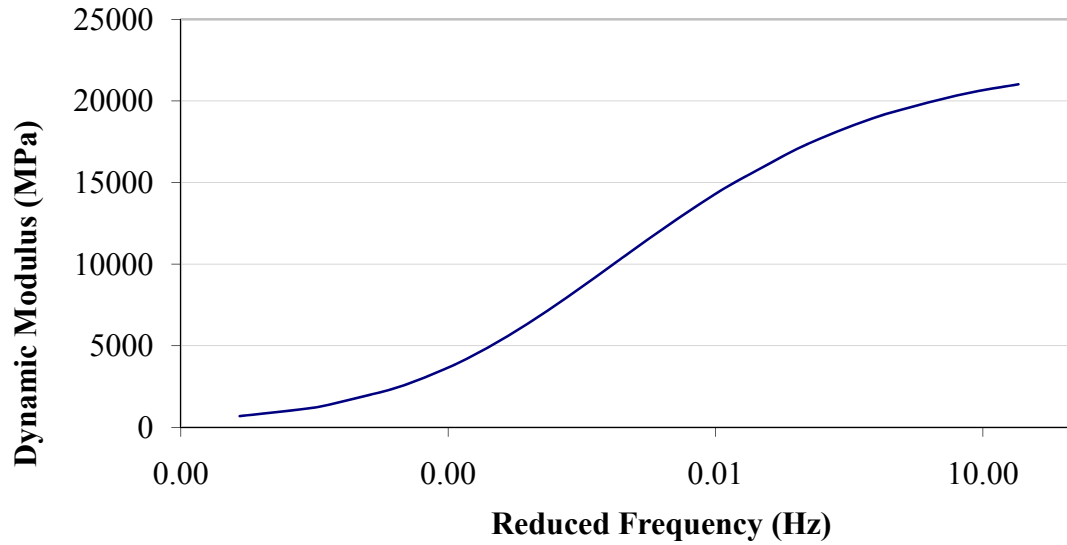


Figure 69 Master Curve for Minimum Required Dynamic Modulus of 5E10 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.2769
α	2.2372
β	-3.4896
γ	0.5768
a	0.0005
b	-0.1464
c	3.0853

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.8359
55.4	-3.3931
70.34	-4.5822
102.56	-6.3397

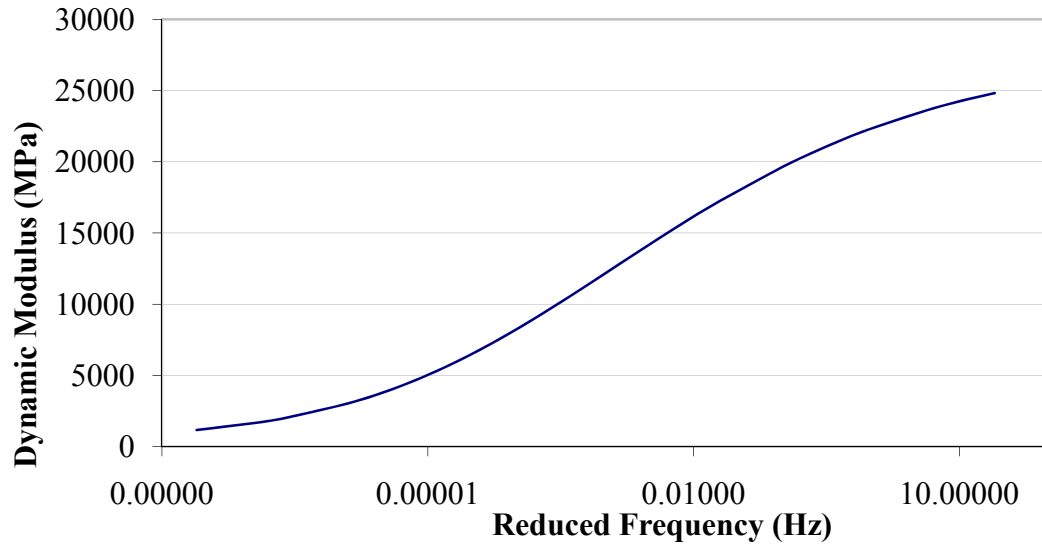


Figure 70 Master Curve for Minimum Required Dynamic Modulus of 5E30 at 4% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.5577
α	2.0472
β	-3.0249
γ	0.4920
a	0.0004
b	-0.1275
c	2.7448

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.7087
55.4	-3.2318
70.34	-4.4719
102.56	-6.6088

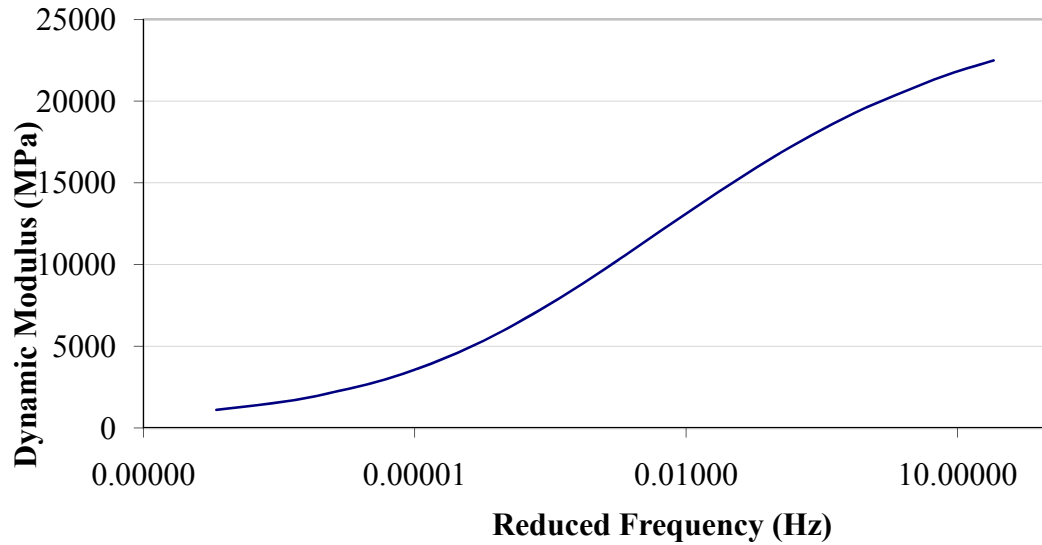


Figure 71 Master Curve for Minimum Required Dynamic Modulus of 5E30 at 7% Air Void Level

Note: Master Curve Parameter:

Constant	Value
δ	4.6226
α	1.9538
β	-2.7080
γ	0.4946
a	0.0003
b	-0.1118
c	2.4291

Temperature (°F)	Log (aT)
23	0.0000
39.2	-1.5389
55.4	-2.9357
70.34	-4.0978
102.56	-6.1924

Development of Trial Flow Number Specification

A similar approach in developing the specification criteria of $|E^*|$ was used in developing the trial Flow number specification. Since not all the flow number tests underwent tertiary flow, the slope of the secondary stage during the flow number test was considered for evaluation. The Actual Life Index was used in this section; incorporating contractor warranty criteria and flow number results to develop the trial SPT specification. Table 20 and Table 21 shows the ranking of mixtures (4% and 7% air void level) based on the flow number slope.

Table 20 Ranking of Mixture with 4% Air Void Level based on Flow Number Slope at 45°C

Descriptors	4% Air Void Level	
	Average	Standard Deviation
5E30 I	0.0401	0.0130
4E30 II	0.2372	0.0833
4E3 II	0.3921	0.2730
3E30 I	0.9782	0.1723
4E10 I	1.3596	0.0181
3E10I	5.7866	1.2779
3E0 II	13.0318	1.4058
5E1 II	24.9128	1.5759
5E3 I	33.2563	9.2458
4E1 I	34.8156	5.2335
5E1 I	40.6422	25.3791

Table 21 Ranking of Mixture with 4% Air Void Level based on Flow Number Slope at 45°C

Descriptors	7% Air Void Level	
	Average	Standard Deviation
5E30 I	0.0374	0.0108
4E30 II	0.8471	0.1429
3E30 I	3.3515	0.5221
4E3 II	4.0470	-
3E10I	12.5223	0.2037
5E1 I	20.0745	24.1038
3E0 II	38.6647	2.1836
5E3 I	64.0833	25.5252
5E1 II	66.6397	29.2130
4E1 I	89.3230	8.7479

Table 15 in the previous section was used as the reference for determining the flow number criteria. Again, a two year warranty period was chosen as the one for the design criteria in the SPT development. A maximum flow number slope was developed based on the Rank index for each mixture type. Flow number was also back-calculated using the equation generated in Figure 49, as shown below:

$$\text{Flow Number} = 31753 \times FN_{\text{slope}}^{-1.081}$$

A summary of maximum flow number slope and minimum flow number criteria are shown in Table 22 and Table 23. It is recommended that all the future mixtures should be tested at a temperature of 45°C.

Table 22 Flow Number Criteria for Mixture with 4% Air Void Level

		Nominal Maximum Aggregate Size		
		Traffic Level	3	4
Maximum Flow Number Slope	E1	n/a	20.00	20.00
	E3	n/a	10.00	10.00
	E10	5.50	5.00	5.00
	E30	1.00	1.00	0.50
Minimum Flow Number	E1	n/a	830	830
	E3	n/a	1600	1600
	E10	2850	3100	3100
	E30	14700	14700	2860

Table 23 Flow Number Criteria for Mixture with 7% Air Void Level

		Nominal Maximum Aggregate Size		
		Traffic Level	3	4
Maximum Flow Number Slope	E1	n/a	40.00	40.00
	E3	n/a	35.00	35.00
	E10	30.00	30.00	30.00
	E30	4.00	4.00	4.00
Minimum Flow Number	E1	n/a	430	430
	E3	n/a	480	480
	E10	560	560	560
	E30	3900	3900	3900

CHAPTER 6: SUMMARY AND RECOMMENDATIONS

The Michigan Department of Transportation (MDOT) has successfully implemented the Superpave volumetric mixture design procedure. Yet, a number of studies have shown that the Superpave volumetric mixture design method alone is insufficient to ensure reliable mixture performance over a wide range of traffic and climatic conditions. The development of an SPT and corresponding performance criteria has been the focus of considerable research efforts in the past several years. In fact, some aspects of the tests have been available for decades, such as the dynamic modulus test of hot mix asphalt. The objectives of this study were:

1. Using the SPT, conduct a laboratory study to measure parameters including the dynamic modulus terms ($E^*/\sin\phi$ and E^*) and the flow number (Fn) for typical Michigan HMA mixtures;
2. Correlate the results of the laboratory study to field performance as they relate to flexible pavement performance (rutting, fatigue, and low temperature cracking); and
3. Make recommendations for the SPT criteria at specific traffic levels (e.g. E3, E10, E30), including recommendations for a draft test specification for use in Michigan.

The current study focuses intensely on rutting performance criteria as no fatigue data was available at the current point due to limited field performance information.

Hence, a summary and recommendations from this preliminary SPT development project are reported as follows:

1. The effective temperature was calculated at each Michigan Department of Transportation region: Superior Region, North Region, Grand Region, Bay Region, Southwest Region, University Region and Metro Region. An average of $T_{\text{eff rutting}}$, 45°C computed from each region was used as the F_N test temperature.
2. It was found that using the traditional σ_{MAAT} calculation was not appropriate for the state of Michigan. In this study, the σ_{MAAT} was calculated based on historical $\text{MAAT}_{\text{Average}}$ from each month in a year.
3. Dynamic modulus values within the range of 50-100 micro-strains are lower as compared to 100-150 micro-strain level. The literature reviews suggested that the strain level should be controlled between 50 to 100 micro-strains so it would not affect the material's viscoelastic behavior.
4. Based on the test results, the dynamic modulus increases with a decrease in asphalt content, a decrease in air voids, and a decrease in compaction effort. The dynamic modulus increases when the temperature is decreased and the frequency is increased. Additionally, the dynamic modulus increases when the asphalt viscosity increases.
5. The dynamic modulus is higher at a higher design traffic level. This also indicates that a mixture with a higher modulus is able to better resist rutting than a mixture with a lower modulus value.

6. For $|E^*|/\sin\phi$, it is noticed that this trend (traffic level increased, $|E^*|/\sin\phi$ increased) is not consistent for the 0.1 hertz and 0.5 hertz test results. However, the difference was not significant.
7. Based on the dynamic modulus test results, $|E^*|$ alone was found to be more suitable in developing the draft specification because it is more consistent in terms of traffic level when compared to $|E^*|/\sin\phi$ values.
8. Most of the mixtures used in this project were from the construction/maintenance of resurfacing, overlaying and milling projects and are representative of mixtures placed in the state of Michigan.
9. The Rank Index was used in this project to determine the perfection in terms of construction and maintenance of a pavement. Overall, all the mixtures could be accepted and used in developing the draft specification for the Simple Performance Test.
10. In this project, the draft specifications for dynamic modulus were developed based field rutting performance and contractor warranty criteria. A 2-year of warranty period was chosen as the design criteria in the SPT development. The minimum dynamic modulus values were selected at each frequency at each temperature based on the test results developed for this study. The sigmoidal master curve technique was used to develop minimum criteria for single master curve criteria for the various mix sizes and trafficking levels. All the master curves, including mixtures with 4% and 7% air void levels, were constructed

using the reference temperature of -5°C . These master curves will be used as the preliminary dynamic modulus criteria for the state of Michigan.

11. It is recommended that all the future mixtures should test at 3 different temperatures (range from -5°C to 40°C) and 5 different frequencies (range from 0.1Hz to 25Hz). A sigmoidal master curve should be constructed and compared with the master curve using the minimum E^* criteria suggested. Additionally, It is suggested that all the master curves should be constructed using the reference temperature of -5°C and the curves constructed should be higher than the desired master curve using the minimum E^* criteria in this project.
12. For flow number testing, a simple stepwise approach to determine flow number was developed. The stepwise approach provides a practical and consistent method to determine the initiation of tertiary flow. This approach used a smoothing technique to give a stepwise increasing trend. The flow number was defined as the minimum point of strain rate versus load cycle number using the new modified data point.
13. In order to validate the applicability of the proposed approach, this method was also compared with existing methods: the Three-Stage model [79], the FNest method [95], and the mathematical product of creep stiffness times cycles versus cycles approach [111]. The R-square ≥ 0.98 was derived from these comparisons and indicated that these methods have shown an excellent correlation with the proposed stepwise method. A comparison of the stepwise method and the traditional method were performed as well. The results show that the correlation

between stepwise and traditional methods was fair ($R\text{-square}=0.64$). However, it was noteworthy that the traditional method may provide a misleading flow number due to some deceptive data points.

14. In this project, flow number and flow number slope were used to evaluate the trial SPT criteria based field rutting performance and contractor warranty criteria. It is recommended that 45°C should be used as test temperature. The maximum flow number slope and minimum flow number were developed for each mixture type. These values will be used as the preliminary flow number criteria for the state of Michigan.
15. The rate of deformation was also evaluated and compared with the flow number. An excellent relationship ($R\text{-square}=0.96$) was found between rate of deformation and flow number. The result also indicated that the rate of deformation from the modified data set using a stepwise approach can be used to compute the flow number.

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APPENDIX 1: PROJECT'S JOB MIX FORMULA

Project: Michigan Avenue, Dearborn

Project Information	
Project No.	34519A
Location:	US-23/M-59 Interchange
Traffic Level:	E10
Agg. Type:	Limestone
Mix Size:	3
Gradation:	Coarse

Specific Gravities	
Gmm	2.485
Gmb	2.41
Gb	1.027
Gse	2.718
Gsb	2.652

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	99.9
1/2 (12.5)	88.2
3/8 (9.5)	72.6
#4 (4.75)	49.1
#8 (2.36)	31.8
#16 (1.18)	20.7
#30 (.60)	14.5
#50 (.30)	9.9
#100 (.15)	6.3
#200 (.075)	4.6
1/2 * 3/8	33
3/4 * 1/2	25
Man. Sand	15
Man. Sand	12
RAP	15

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	58-22
Asphalt Content:	5.7
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	45.5
Dust Corr.:	0.4
1 Face Crush (%):	98.1
2 Face Crush (%):	97.7
Volumetric	
VMA:	14.3
VFA:	78.9
AV:	3
F/Pbe:	0.96
Pbe:	4.79

Project: US-23/ M- 59 Brighton

Project Information	
Project No.	47064 A
Location:	Michigan Ave.
Traffic Level:	E10
Agg. Type:	N/A
Mix Size:	3
Gradation:	Coarse

Specific Gravities	
Gmm	2.496
Gmb	2.419
Gb	1.025
Gse	2.725
Gsb	2.634

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	85.3
3/8 (9.5)	71
#4 (4.75)	43.8
#8 (2.36)	25.9
#16 (1.18)	17.5
#30 (.60)	13.3
#50 (.30)	9.6
#100 (.15)	6.8
#200 (.075)	5.3
#4's	33
1/2"	25
Man. Sand	15
Man. Sand Sora	12
RAP	15

Asphalt Information		
Asphalt Source(PG):	Marathon Det.	
Asphalt Grade (PG):	58-22	
Asphalt Content:	5.6	
Asphalt Additives:	None	
Asphalt Additives (%):	N/A	
SuperPave Consensus Properties		
Angularity (%):	45.4	
Dust Corr.:	0	
1 Face Crush (%):	99.3	
2 Face Crush (%):	98.8	
Volumetric		
VMA:	13.3	
VFA:	76.7	
AV:	3.1	
F/Pbe:	1.2	
Pbe:	4.42	

Project: Vandyke, Detroit

Project Information	
Project No.	46273A
Location:	M 53/28 Mi to 31 Mi Rd.
Traffic Level:	E30
Agg. Type:	N/A
Mix Size:	3
Gradation:	Coarse

Specific Gravities	
Gmm	5.577
Gmb	2.495
Gb	1.031
Gse	2.81
Gsb	2.769

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	98.9
1/2 (12.5)	90
3/8 (9.5)	83.9
#4 (4.75)	66.6
#8 (2.36)	43.7
#16 (1.18)	30.5
#30 (.60)	21.2
#50 (.30)	11
#100 (.15)	6.2
#200 (.075)	4.3
2NS	15
HL3	8
Otr	43
Mfg. Sand	15
6A	19
RAP	N/A

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	64-22
Asphalt Content:	5.2
Asphalt Additives:	None
Asphalt Additives (%)	N/A
SuperPave Consensus Properties	
Angularity (%):	45.5
Dust Corr.:	0.4
1 Face Crush (%):	98.4
2 Face Crush (%):	98.4
Volumetric	
VMA:	14.6
VFA:	78.2
AV:	3.2
F/Pbe:	0.86
Pbe:	5

Project: M - 26 Trimountain

Project Information	
Project No.	53244A
Location:	Hancock
Traffic Level:	E1
Agg. Type:	N/A
Mix Size:	4
Gradation:	N/A

Specific Gravities	
Gmm	2.496
Gmb	2.396
Gb	1.025
Gse	2.718
Gsb	2.674

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	93.9
3/8 (9.5)	85
#4 (4.75)	64.8
#8 (2.36)	51
#16 (1.18)	36.2
#30 (.60)	26.7
#50 (.30)	15.4
#100 (.15)	6.9
#200 (.075)	4.7
Crushed 1 Face	90.5

Asphalt Information	
Asphalt Source(PG):	Murphy Oil
Asphalt Grade (PG):	52-34
Asphalt Content:	4.4
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	43.6
Dust Corr.:	0.4
1 Face Crush (%):	90.5
2 Face Crush (%):	N/A
Volumetric	
VMA:	15.2
VFA:	73.7
AV:	4
F/Pbe:	1
Pbe:	N/A

Project: M – 52, Lansing

Project Information	
Project No.	60476A
Location:	Lansing, Michigan
Traffic Level:	E3
Agg. Type:	N/A
Mix Size:	4
Gradation:	N/A

Specific Gravities	
Gmm	2.489
Gmb	2.39
Gb	1.031
Gse	2.716
Gsb	2.651

Sieve Size	Gradation Percent
1 1/2" (37.5)	100
1" (25)	100
3/4" (19)	100
1/2" (12.5)	98.7
3/8" (9.5)	86.6
#4 (4.75)	71.8
#8 (2.36)	51.4
#16 (1.18)	36.1
#30 (.60)	25.5
#50 (.30)	14.7
#100 (.15)	7.7
#200 (.075)	5.4
Crushed 1 Face	89.1
Crushed 2 Face	85.9

Asphalt Information	
Asphalt Source(PG):	ABS8505
Asphalt Grade (PG):	64-28
Asphalt Content:	5.57
Asphalt Additives:	N/A
Asphalt Additives (%)	4.9
SuperPave Consensus Properties	
Angularity (%):	44.9
Dust Corr.:	N/A
1 Face Crush (%):	89.1
2 Face Crush (%):	85.9
Volumetric	
VMA:	14.3
VFA:	14.9
AV:	73.1
F/Pbe:	1.1
Pbe:	N/A

Project: M - 90, Lexington

Project Information	
Project No.	45440A
Location:	Port Huron
Traffic Level:	E3
Agg. Type:	N/A
Mix Size:	4
Gradation:	N/A

Specific Gravities	
Gmm	2.474
Gmb	2.349
Gb	N/A
Gse	2.719
Gsb	2.658

Sieve Size	Gradation Percent
1 1/2" (37.5)	100
1" (25)	100
3/4" (19)	100
1/2" (12.5)	99.1
3/8" (9.5)	89.6
#4 (4.75)	74.9
#8 (2.36)	56.2
#16 (1.18)	38.6
#30 (.60)	26.8
#50 (.30)	16.5
#100 (.15)	8.7
#200 (.075)	5.6
Crushed 1 Face	96.5
Crushed 2 Face	N/A
Asphalt	6
3/8 * 0	18
5/8 * 3/8	18
MFG Sand	64

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	64-28
Asphalt Content:	N/A
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	48.1
Dust Corr.:	0.5
1 Face Crush (%):	96.5
2 Face Crush (%):	N/A
Volumetric	
VMA:	16
VFA:	75
AV:	4
F/Pbe:	1.1
Pbe:	N/A

Project: M - 53 Detroit, 8 Mile Road, Detroit

Project Information	
Project No.	52804A/52805A
Location:	M-53/M-3 to M-102
Traffic Level:	E10
Agg. Type:	N/A
Mix Size:	4
Gradation:	Coarse

Specific Gravities	
Gmm	2.553
Gmb	2.451
Gb	1.035
Gse	2.796
Gsb	2.738

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	98.6
3/8 (9.5)	86.7
#4 (4.75)	51.1
#8 (2.36)	29.3
#16 (1.18)	19.7
#30 (.60)	14
#50 (.30)	9.5
#100 (.15)	6.1
#200 (.075)	4.5
1/2"	33
4 * 3/8"	25
Otr Sand	15
HL3	12
RAP	4

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	70-22
Asphalt Content:	5.6
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	45.9
Dust Corr.:	N/A
1 Face Crush (%):	95.6
2 Face Crush (%):	92.8
Volumetric	
VMA:	15.5
VFA:	74.2
AV:	4
F/Pbe:	0.99
Pbe:	4.55

Project: 8 mile Road, Detroit Michigan

Project Information	
Project No.	45164A
Location:	Utica(Detroit)
Traffic Level:	E30
Agg. Type:	N/A
Mix Size:	4
Gradation:	N/A

Specific Gravities	
Gmm	2.554
Gmb	2.439
Gb	N/A
Gse	2.785
Gsb	2.728

Sieve Size	Gradation Percent
1 1/2" (37.5)	100
1" (25)	100
3/4" (19)	100
1/2" (12.5)	99
3/8" (9.5)	87.3
#4 (4.75)	55.7
#8 (2.36)	29
#16 (1.18)	18.8
#30 (.60)	14
#50 (.30)	10
#100 (.15)	6.6
#200 (.075)	4.8
Crushed 1 Face	96.7
Crushed 2 Face	94
Asphalt	5.3
3/8 CLEAR	17
1/2" x 3/8"	21
Otr Sand	23
Mfg. Sand	21
1/2 "	18

Asphalt Information		
Asphalt Source(PG):	Marathon Det.	
Asphalt Grade (PG):	70-22	
Asphalt Content:	5.3	
Asphalt Additives:	None	
Asphalt Additives (%):	N/A	
SuperPave Consensus Properties		
Angularity (%):	47.1	
Dust Corr.:	0	
1 Face Crush (%):	96.7	
2 Face Crush (%):	94	
Volumetric		
VMA:	15.3	
VFA:	70.6	
AV:	4.5	
F/Pbe:	1	
Pbe:	N/A	

Project: M-26, Kearsarge St., Calumet

Project Information	
Project No.	53244A
Location:	Houghton, Mi
Traffic Level:	E1
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	2.484
Gmb	2.385
Gb	1.029
Gse	2.66
Gsb	2.729

Sieve Size	Gradation Percent
1 1/2" (37.5)	100
1" (25)	100
3/4" (19)	100
1/2" (12.5)	100
3/8" (9.5)	95.2
#4 (4.75)	73.7
#8 (2.36)	54.7
#16 (1.18)	43.7
#30 (.60)	32.4
#50 (.30)	18.1
#100 (.15)	8.1
#200 (.075)	5.2
Crushed 1 Face	91.9
Crushed 2 Face	N/A

Asphalt Information	
Asphalt Source(PG):	ABS4510
Asphalt Grade (PG):	52-34
Asphalt Content:	4.85
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	42.5
Dust Corr.:	N/A
1 Face Crush (%):	91.9
2 Face Crush (%):	N/A
Volumetric	
VMA:	15.68
VFA:	74.5
AV:	4
F/Pbe:	1.03
Pbe:	N/A

Project: Mathy M38

Project Information	
Project No.	80168A
Location:	M-38
Traffic Level:	E1
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	2.523
Gmb	2.422
Gb	1.026
Gse	2.768
Gsb	2.73

Sieve Size	Gradation Percent
1 1/2" (37.5)	100
1" (25)	100
3/4" (19)	100
1/2" (12.5)	100
3/8" (9.5)	93.6
#4 (4.75)	66.9
#8 (2.36)	54.4
#16 (1.18)	45.1
#30 (.60)	36.1
#50 (.30)	17.9
#100 (.15)	9
#200 (.075)	5.6
Crushed 1 Face	96.9
Crushed 2 Face	N/A

Asphalt Information	
Asphalt Source(PG):	ABS4510
Asphalt Grade (PG):	58-34
Asphalt Content:	5.73
Asphalt Additives:	None
Asphalt Additives (%)	N/A
SuperPave Consensus Properties	
Angularity (%):	45.1
Dust Corr.:	N/A
1 Face Crush (%):	96.9
2 Face Crush (%):	N/A
Volumetric	
VMA:	16.38
VFA:	75.6
AV:	4
F/Pbe:	1.07
Pbe:	N/A

Project: US 2 Bessemer, MI

Project Information	
Project No.	488344A
Location:	Bessemer, MI
Traffic Level:	E3
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	5.517
Gmb	2.416
Gb	1.027
Gse	2.769
Gsb	2.703

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	100
3/8 (9.5)	95.2
#4 (4.75)	72
#8 (2.36)	57.2
#16 (1.18)	40.9
#30 (.60)	25.4
#50 (.30)	11.8
#100 (.15)	7
#200 (.075)	4.4
#4's	86.8
1/2 x1/4"	25
Nat. Sand	39
3/8 Dense Washed	19
Man. Sand	22

Asphalt Information	
Asphalt Source(PG):	Murphy Oil
Asphalt Grade (PG):	58-34
Asphalt Content:	5.91
Asphalt Additives:	None
Asphalt Additives (%)	N/A
SuperPave Consensus Properties	
Angularity (%):	43.9
Dust Corr.:	0
1 Face Crush (%):	86.8
2 Face Crush (%):	N/A
Volumetric	
VMA:	15.9
VFA:	74.8
AV:	4
F/Pbe:	1.08
Pbe:	N/A

Project: Auburn Hill

Project Information	
Project No.	84049A
Location:	Auburn Hills, Mi
Traffic Level:	E10
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	2.473
Gmb	2.374
Gb	1.032
Gse	2.739
Gsb	2.637

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	99.5
3/8 (9.5)	97.4
#4 (4.75)	67.4
#8 (2.36)	37.5
#16 (1.18)	23.5
#30 (.60)	17.1
#50 (.30)	12
#100 (.15)	7.9
#200 (.075)	8.4
Crushed 1 Face	97.3
Crushed 2 Face	96.7
Man. Sand	30
Man. Sand #6	19
3/8x#4	25
31A	10

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	64-22
Asphalt Content:	5.66
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	45.8
Dust Corr.:	0
1 Face Crush (%):	97.3
2 Face Crush (%):	96.7
Volumetric	
VMA:	15.83
VFA:	74.73
AV:	4
F/Pbe:	1.25
Pbe:	N/A

Project: Brighton

Project Information	
Project No.	83707A
Location:	Brighton, Mi
Traffic Level:	E10
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	2.469
Gmb	2.37
Gb	1.032
Gse	2.749
Gsb	2.619

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	99.7
3/8 (9.5)	98.2
#4 (4.75)	88.2
#8 (2.36)	48.8
#16 (1.18)	26.5
#30 (.60)	17.4
#50 (.30)	11.8
#100 (.15)	7.6
#200 (.075)	6.2
Crushed 1 Face	98.2
Crushed 2 Face	98.1
RockWood Man. Sand	18
Sora Man. Sand	33
Sora 3/8x#4	29
3/8 4 Blasst Fumed	10

Asphalt Information	
Asphalt Source(PG):	Marathon Det.
Asphalt Grade (PG):	64-22
Asphalt Content:	6.31
Asphalt Additives:	None
Asphalt Additives (%):	N/A
SuperPave Consensus Properties	
Angularity (%):	45.2
Dust Corr.:	0.4
1 Face Crush (%):	98.2
2 Face Crush (%):	98.1
Volumetric	
VMA:	15.68
VFA:	74.43
AV:	4
F/Pbe:	1.2
Pbe:	N/A

Project: I - 75 Clarkston, Flint

Project Information	
Project No.	45446A
Location:	Clarkston, MI
Traffic Level:	E30
Agg. Type:	N/A
Mix Size:	5
Gradation:	N/A

Specific Gravities	
Gmm	2.564
Gmb	2.463
Gb	N/A
Gse	2.828
Gsb	2.746

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	100
3/8 (9.5)	97.5
#4 (4.75)	70.6
#8 (2.36)	42.6
#16 (1.18)	27.3
#30 (.60)	18.1
#50 (.30)	12.7
#100 (.15)	8.2
#200 (.075)	5.3
Crushed 1 Face	25
Crushed 2 Face	15
Man. Sand	20
HL1	10
3/8x4	10
Fish Lake	10
Lime Sand	15
Trap Sand	35

Asphalt Information		
Asphalt Source(PG):	t and M Oil	
Asphalt Grade (PG):	70-22	
Asphalt Content:	6	
Asphalt Additives:	None	
Asphalt Additives (%):	N/A	
SuperPave Consensus Properties		
Angularity (%):	48.2	
Dust Corr.:	0	
1 Face Crush (%):	25	
2 Face Crush (%):	15	
Volumetric		
VMA:	15.7	
VFA:	74.7	
AV:	4	
F/Pbe:	N/A	
Pbe:	N/A	

Project: I-75 Toledo

Project Information	
Project No.	74577A
Location:	Jan-75
Traffic Level:	E30
Agg. Type:	N/A
Mix Size:	5
Gradation:	Coarse

Specific Gravities	
Gmm	2.51
Gmb	2.409
Gb	1.029
Gse	2.737
Gsb	2.711

Sieve Size	Gradation Percent
1 (25)	100
3/4 (19)	100
1/2 (12.5)	100
3/8 (9.5)	95.4
#4 (4.75)	64.5
#8 (2.36)	36.4
#16 (1.18)	22.4
#30 (.60)	16.5
#50 (.30)	11.6
#100 (.15)	7.4
#200 (.075)	5.4
3/8x4	10
Man Sand	28
Fine Crush	10
Man. Sand	32
1/4 Chip	10
1/2 Clear	10

Asphalt Information	
Asphalt Source(PG):	6505 MPM Oil
Asphalt Grade (PG):	70-22
Asphalt Content:	5.4
Asphalt Additives:	None
Asphalt Additives (%)	N/A
SuperPave Consensus Properties	
Angularity (%):	46
Dust Corr.:	0.4
1 Face Crush (%):	98
2 Face Crush (%):	96.1
Volumetric	
VMA:	15.9
VFA:	74.9
AV:	4
F/Pbe:	1.07
Pbe:	5.05

APPENDIX 2: MIXTURE'S VOLUMETRIC PROPERTIES

Mixture Type: 3E10
Project Location: US-23/M-59, Brighton
Maximum Specific Gravity, Gmm: 2.492

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-EST	2.447	1.80%
4-2	2.427	2.63%
4-3	2.431	2.44%
7-1	2.372	4.81%
7-2	2.361	5.25%
7-3	2.350	5.70%
10-1	2.284	8.37%
10-2	2.283	8.41%
10-3	2.296	7.89%

Mixture Type: 3E10
Project Location: Michigan Avenue, Dearborn
Maximum Specific Gravity, Gmm: 2.499

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-4	2.437	2.47%
4-7	2.419	3.19%
4-9	2.416	3.31%
7-2	2.338	6.43%
7-4	2.334	6.61%
7-8	2.342	6.26%
10-1	2.266	9.34%
10-7	2.265	9.37%
10-9	2.241	10.31%

Mixture Type: 3E30
Project Location: Vandyke, Detroit
Maximum Specific Gravity, Gmm: 2.606

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.489	4.50%
4-2	2.485	4.65%
4-3	2.478	4.94%
7-1	2.409	7.57%
7-2	2.394	8.16%
7-3	2.408	7.59%

Mixture Type: 4E1
 Project Location: M-26 Trimountain
 Maximum Specific Gravity, Gmm: 2.494

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.423	2.85%
4-2	2.424	2.78%
4-3	2.428	2.63%
7-1	2.371	4.91%
7-2	2.359	5.40%
7-3	2.362	5.29%
10-1	2.285	8.38%
10-2	2.286	8.34%
10-3	2.304	7.59%

Mixture Type: 4E3

Project Location: M-52, Lansing

Maximum Specific Gravity, Gmm: 2.493

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-A	2.395	3.91%
4-B	2.394	3.95%
4-C	2.395	3.91%
7-A	2.329	6.56%
7-B	2.325	6.74%
7-C	2.295	7.94%
10-A	2.255	9.54%
10-B	2.255	9.53%
10-C	2.254	9.57%

Mixture Type: 4E3
Project Location: M-90, Lexington
Maximum Specific Gravity, Gmm: 2.432

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-2	2.417	0.61%
4-6	2.393	1.57%
4-8	2.381	2.07%
7-3	2.353	3.24%
7-4	2.348	3.44%
7-9	2.329	4.22%
10-1	2.247	7.59%
10-5	2.251	7.41%
10-8	2.240	7.87%

Mixture Type: 4E10
 Project Location: M-53/M-3 to M-102, Detroit
 Maximum Specific Gravity, Gmm: 2.576

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.485	3.54%
4-2	2.494	3.19%
4-3	2.488	3.42%
4-4	2.474	3.98%
4-5	2.470	4.14%
4-6	2.493	3.22%
4-7	2.470	4.12%
4-8	2.492	3.28%
4-9	2.497	3.09%
7-2	2.430	5.67%
7-3	2.434	5.54%
7-4	2.445	5.11%
10-4	2.327	9.70%
10-3	2.361	8.35%
10-2	2.359	8.45%

Mixture Type: 4E30

Project Location: 8 Mile Road, Detroit

Maximum Specific Gravity, Gmm: 2.570

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.468	4.00%
4-2	2.474	3.77%
4-3	2.491	3.11%
7-1	2.409	6.28%
7-3	2.406	6.40%
7-4	2.404	6.49%
10-1	2.266	11.82%
10-2	2.268	11.77%
10-3	2.261	12.04%

Mixture Type: 5E1
 Project Location: M-26, Kearsarge St., Calumet
 Maximum Specific Gravity, Gmm: 2.487

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-2	2.370	4.71%
4-3	2.381	4.26%
4-4	2.389	3.93%
7-1	2.338	5.99%
7-3	2.330	6.30%
7-4	2.331	6.27%
10-2	2.247	9.64%
10-3	2.246	9.69%
10-4	2.256	9.27%

Mixture Type: 5E1
Project Location: M-38, Mathy
Maximum Specific Gravity, Gmm: 2.527

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-2	2.446	3.23%
4-4	2.424	4.10%
4-8	2.430	3.82%
7-1	2.367	6.32%
7-5	2.375	6.01%
7-7	2.371	6.19%
10-2	2.301	8.94%
10-4	2.302	8.93%
10-6	2.253	10.84%

Mixture Type: 5E3
Project Location: US-2 Bessemer
Maximum Specific Gravity, Gmm: 2.565

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.415	5.89%
4-2	2.409	6.11%
4-3	2.418	5.76%
7-3	2.353	8.29%
7-4	2.360	8.02%
7-7	2.354	8.23%
10-2	2.284	10.96%
10-6	2.284	10.99%
10-7	2.262	11.82%

Mixture Type: 5E10

Project Location: Auburn Hill

Maximum Specific Gravity, Gmm: 2.48

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
A4	2.368	4.53%
B4	2.369	4.49%
C4	2.367	4.57%
A7	2.308	6.94%
B7	2.299	7.30%
C7	2.297	7.36%
A10	2.244	9.53%
B10	2.238	9.75%
C10	2.235	9.87%

Mixture Type: 5E10

Project Location: Brighton

Maximum Specific Gravity, Gmm: 2.4696

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
A4	2.365	4.24%
B4	2.376	3.80%
C4	2.365	4.22%
A7	2.293	7.15%
B7	2.300	6.88%
C7	2.294	7.10%
A10	2.130	13.75%
B10	2.231	9.68%
C10	2.248	8.96%

Mixture Type: 5E30

Project Location: I-75, Clarkston/Flint

Maximum Specific Gravity, Gmm: 2.581

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-1	2.454	4.93%
4-2	2.458	4.76%
4-6	2.451	5.01%
7-2	2.365	8.37%
7-7	2.379	7.82%
7-8	2.367	8.28%
10-1	2.313	10.38%
10-4	2.303	10.76%
10-7	2.294	11.12%

Mixture Type: 5E30

Project Location: I-75 Toledo

Maximum Specific Gravity, Gmm: 2.506

Sample ID	Bulk Specific Gravity, Gmb	Measure Air Void Level
4-2	2.408	3.92%
4-3	2.402	4.15%
4-4	2.401	4.19%
7-1	2.321	7.37%
7-2	2.333	6.89%
7-6	2.309	7.86%
10-1	2.269	9.45%
10-3	2.265	9.63%
10-6	2.242	10.55%

APPENDIX 3: DYNAMIC MODULUS TEST RESULTS

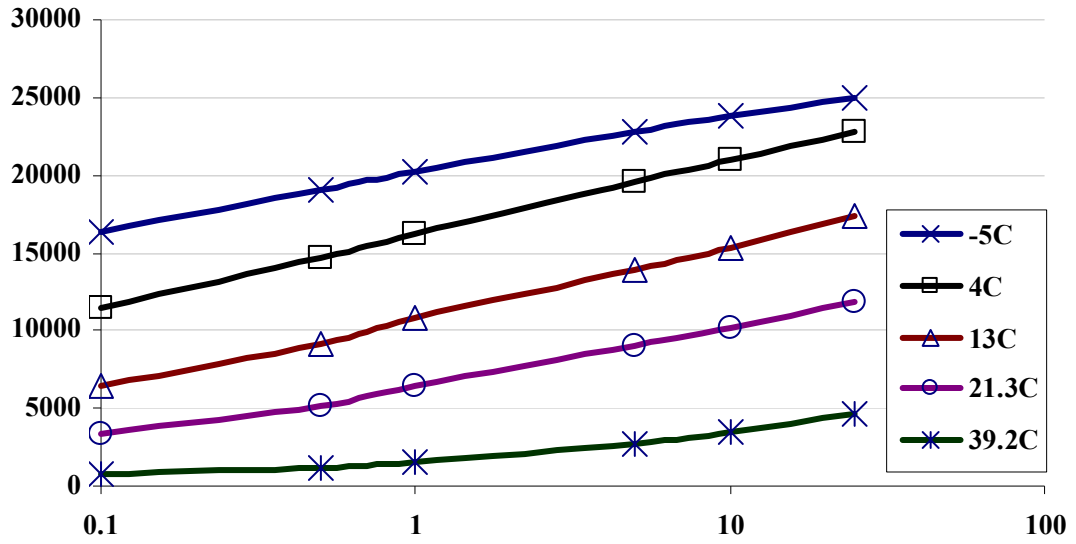
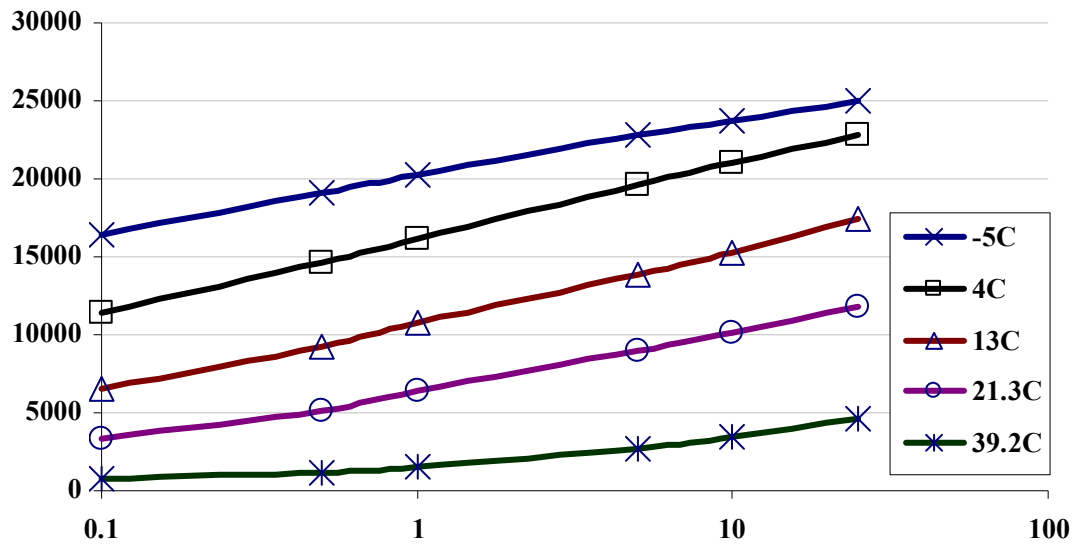
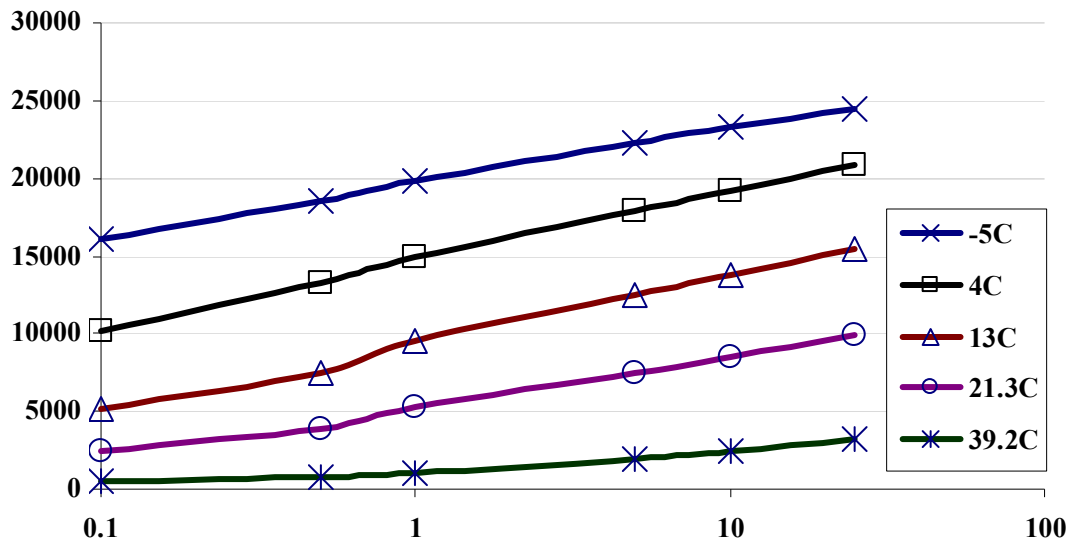


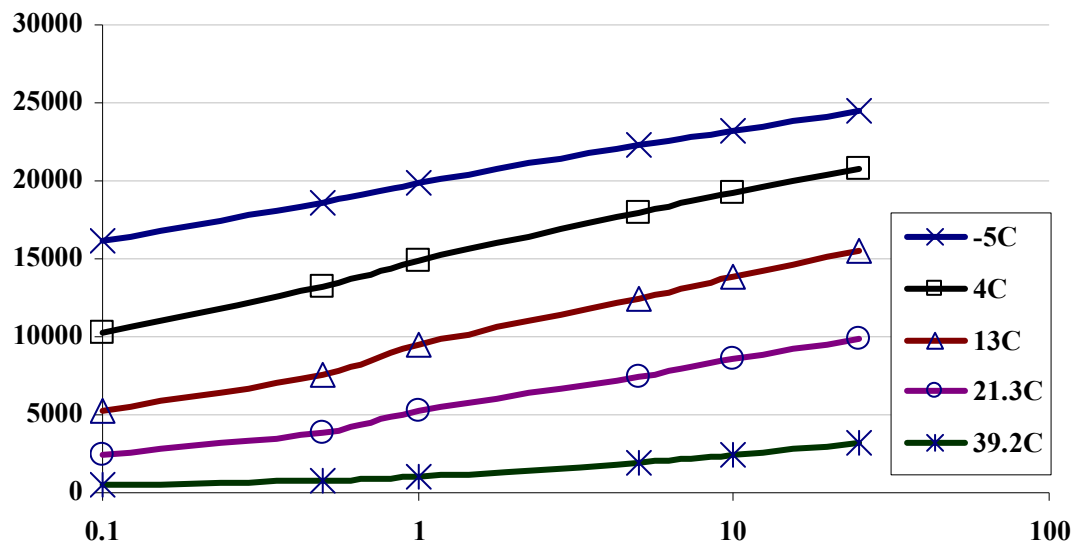
Figure 72 Dynamic Modulus for 3E10 I (Project Location: M-59 Brighton) at 4%
Air Void Level



**Figure 73 Dynamic Modulus for 3E10 I (Project Location: M-59 Brighton) at 7%
Air Void Level**



**Figure 74 Dynamic Modulus for 3E10 II (Project Location: Michigan Ave,
Dearborn) at 4% Air Void Level**



**Figure 75 Dynamic Modulus for 3E10 II (Project Location: Michigan Ave,
Dearborn) at 7% Air Void Level**

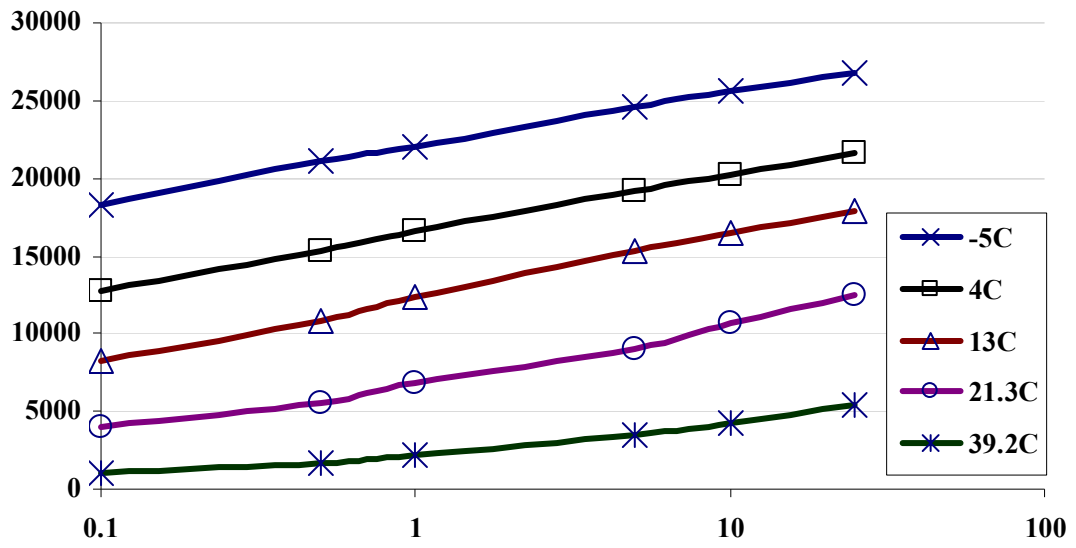
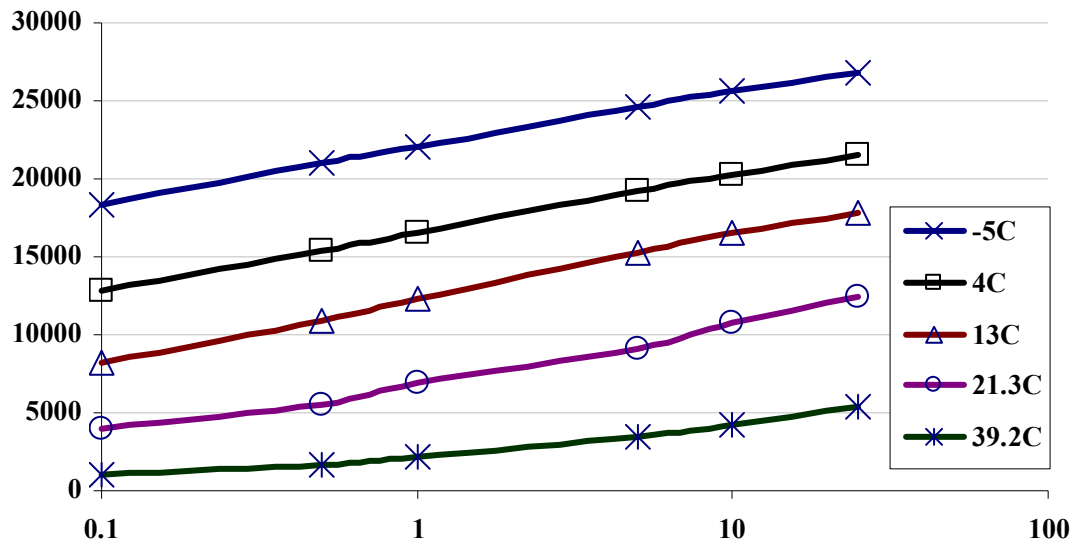
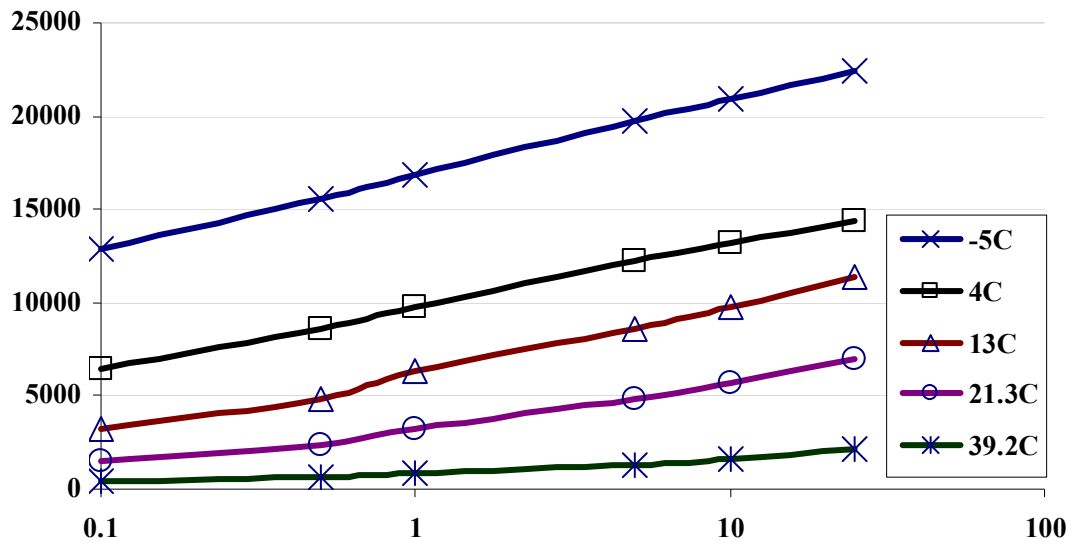


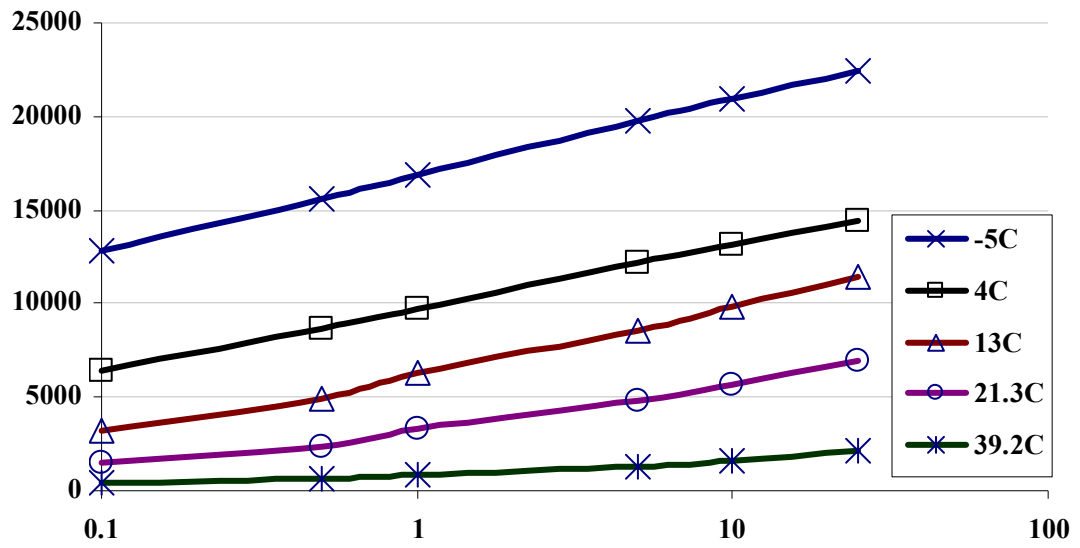
Figure 76 Dynamic Modulus for 3E30 I (Project Location: Vandyke, Detroit) at 4% Air Void Level



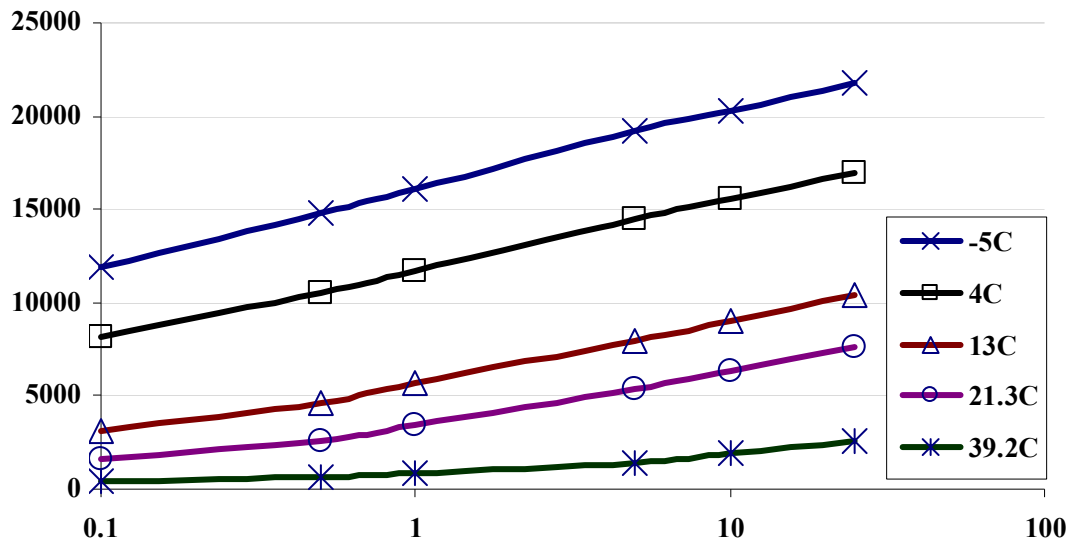
**Figure 77 Dynamic Modulus for 3E30 I (Project Location: Vandyke, Detroit) at 7%
Air Void Level**



**Figure 78 Dynamic Modulus for 4E1 I (Project Location: Tri Mt., Hancock) at 4%
Air Void Level**



**Figure 79 Dynamic Modulus for 4E1 I (Project Location: Tri Mt., Hancock) at 7%
Air Void Level**



**Figure 80 Dynamic Modulus for 4E3 I (Project Location: Lansing, MI) at 4% Air
Void Level**

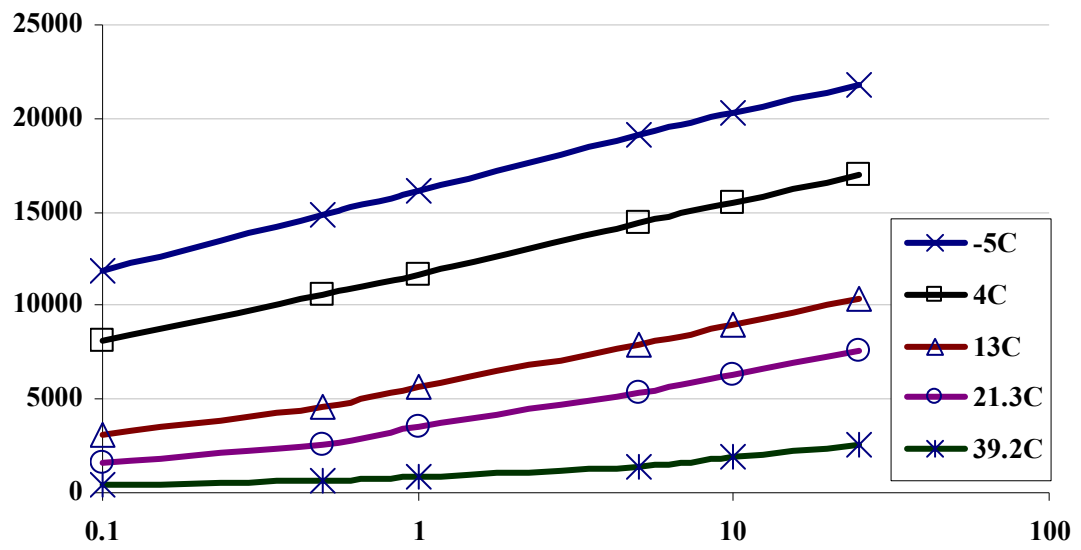


Figure 81 Dynamic Modulus for 4E3 I (Project Location: Lansing, MI) at 7% Air
Void Level

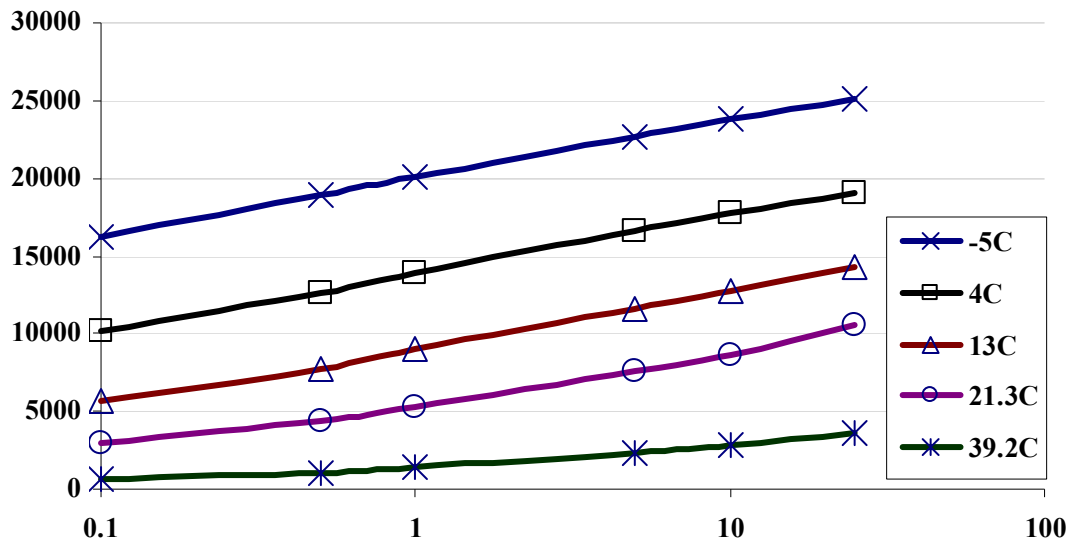


Figure 82 Dynamic Modulus for 4E3 II (Project Location: Lexington) at 4% Air
Void Level

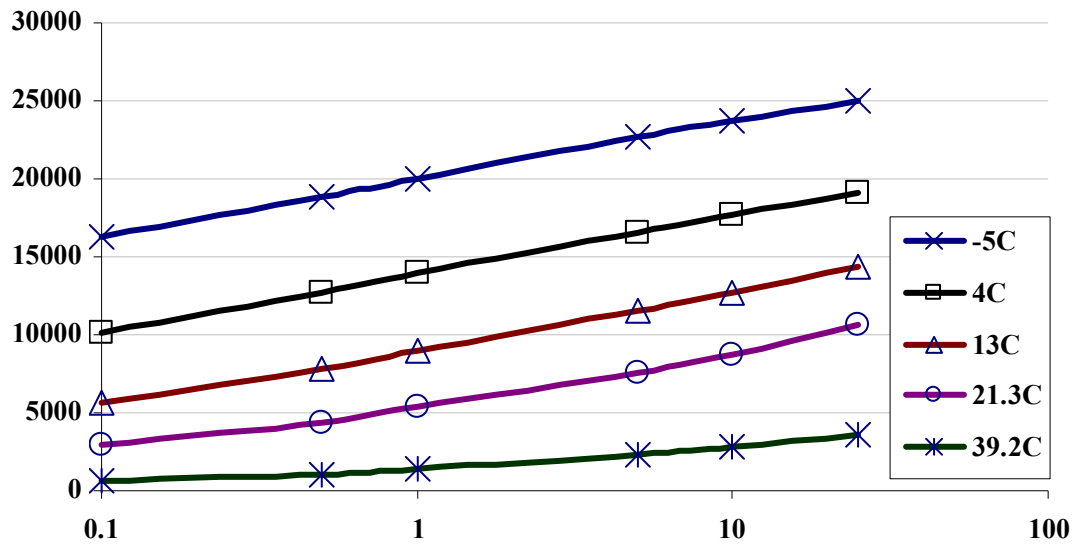


Figure 83 Dynamic Modulus for 4E3 II (Project Location: Lexington) at 7% Air
Void Level

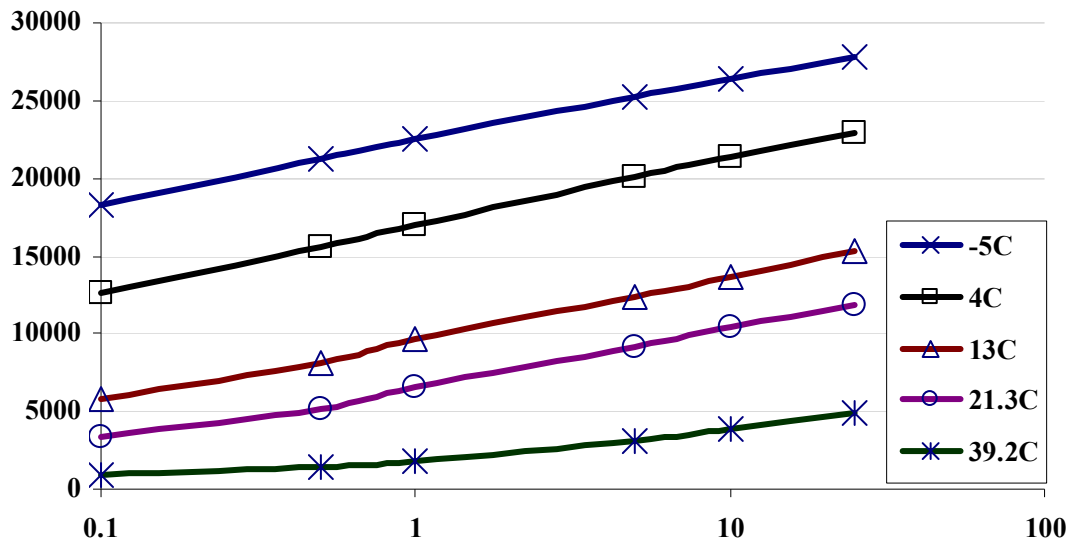
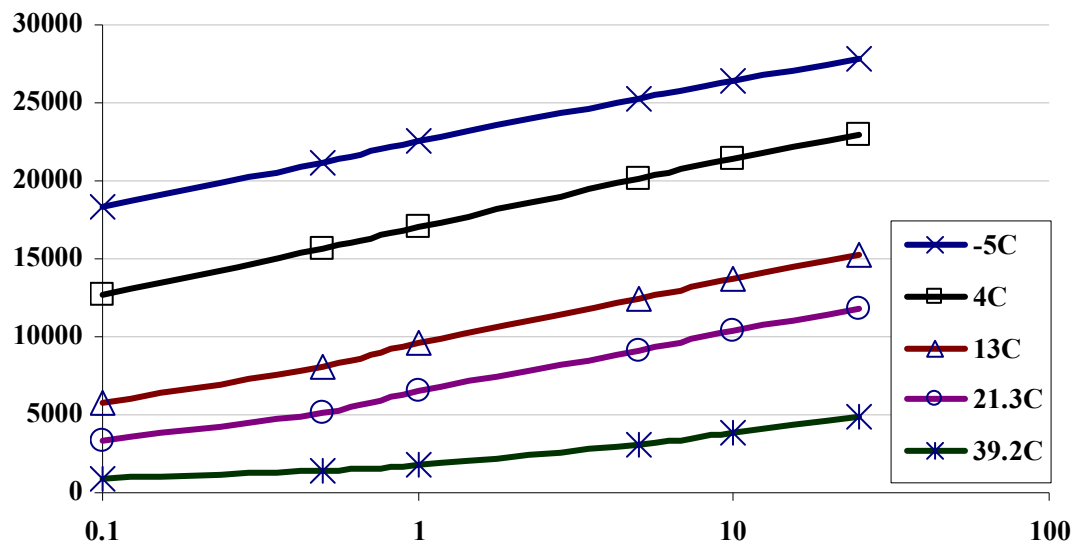


Figure 84 Dynamic Modulus for 4E10 I (Project Location: M-53 Detroit) at 4% Air
Void Level



**Figure 85 Dynamic Modulus for 4E10 I (Project Location: M-53 Detroit) at 7% Air
Void Level**

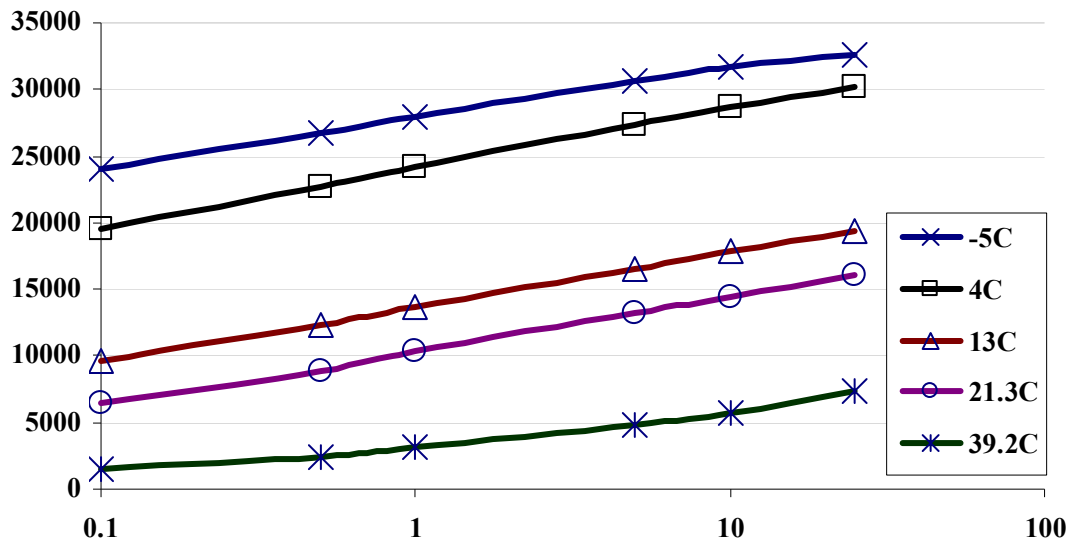


Figure 86 Dynamic Modulus for 4E30 II (Project Location: 8 Mile Road) at 4% Air
Void Level

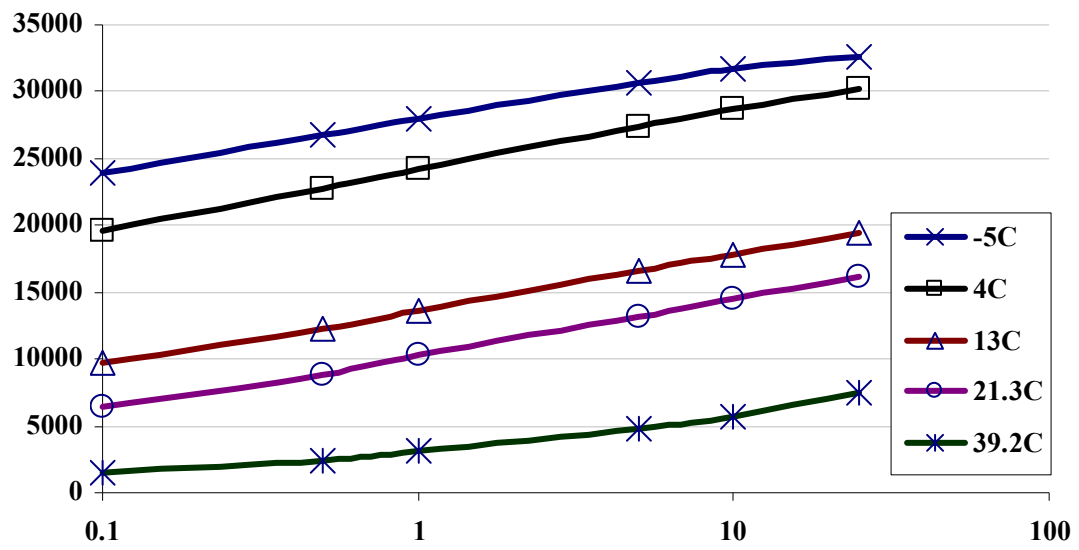
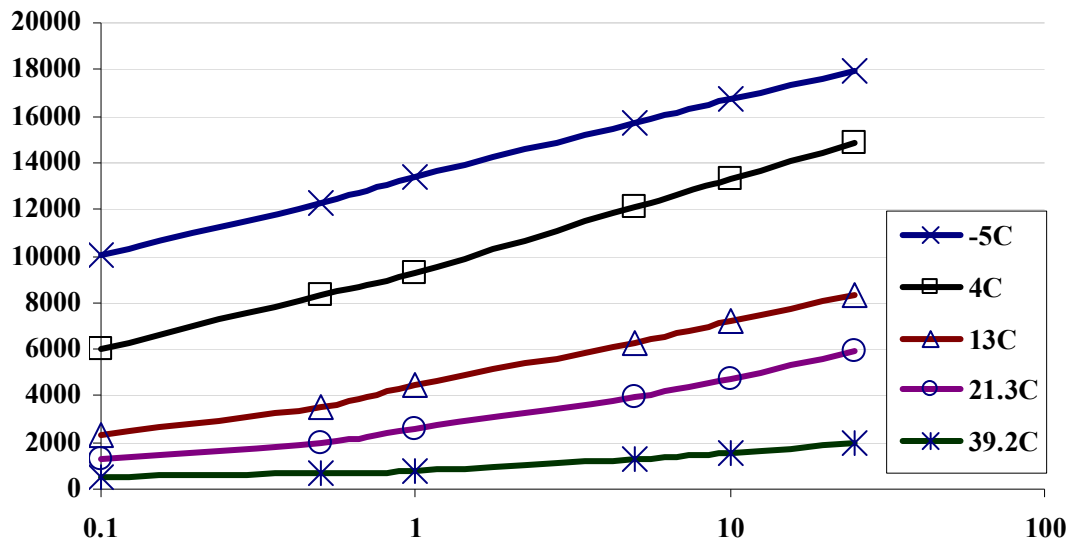
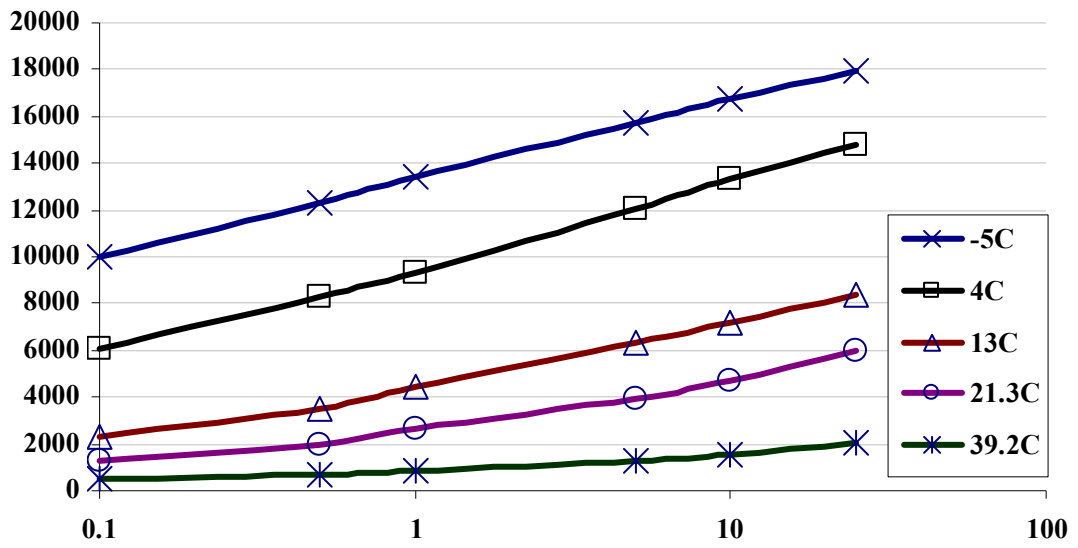


Figure 87 Dynamic Modulus for 4E30 II (Project Location: 8 Mile Road) at 7% Air
Void Level



**Figure 88 Dynamic Modulus for 5E1 I (Project Location: M-26, Kearsarge St.) at 4%
Air Void Level**



**Figure 89 Dynamic Modulus for 5E1 I (Project Location: M-26, Kearsarge St.) at 7%
Air Void Level**

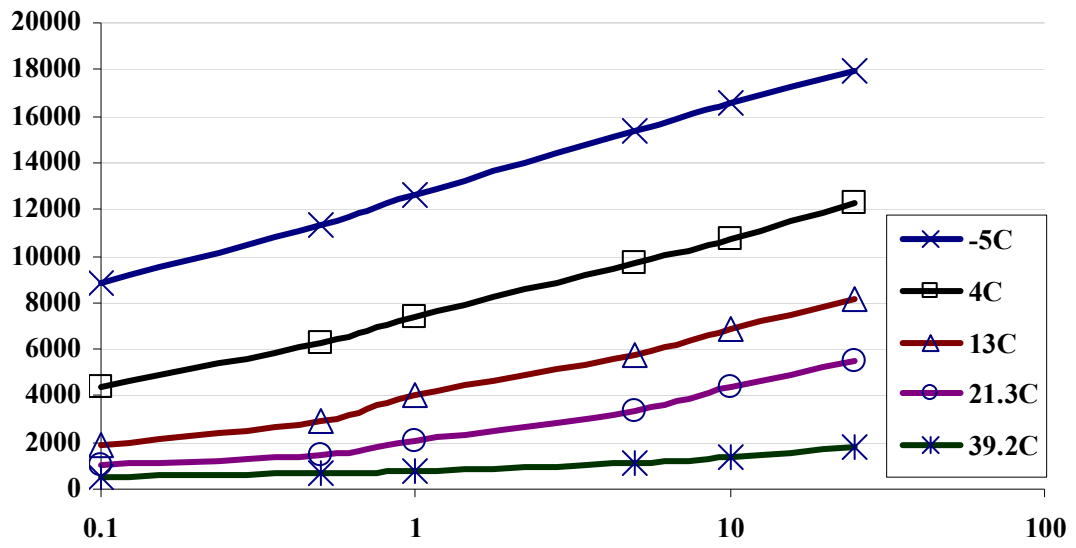


Figure 90 Dynamic Modulus for 5E1 II (Project Location: M-38) at 4% Air Void
Level

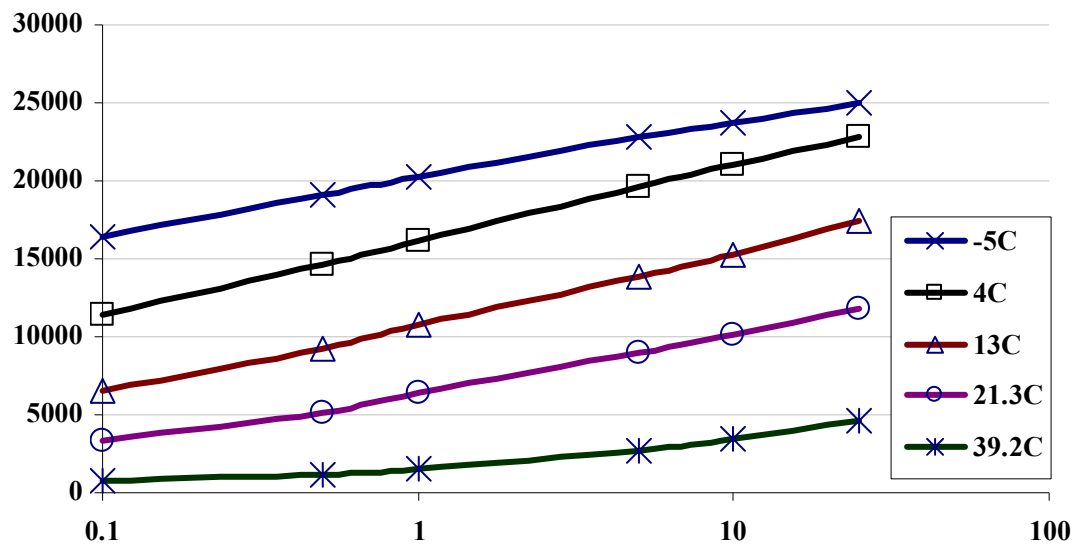


Figure 91 Dynamic Modulus for 5E1 II (Project Location: M-38) at 7% Air Void
Level

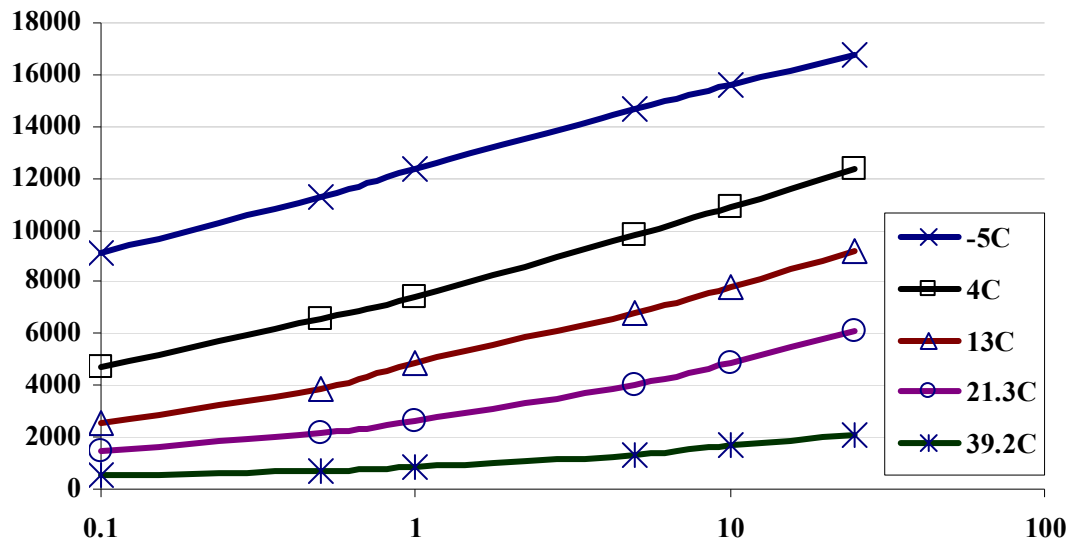


Figure 92 Dynamic Modulus for 5E3 I (Project Location: Bessemer, MI) at 4% Air
Void Level

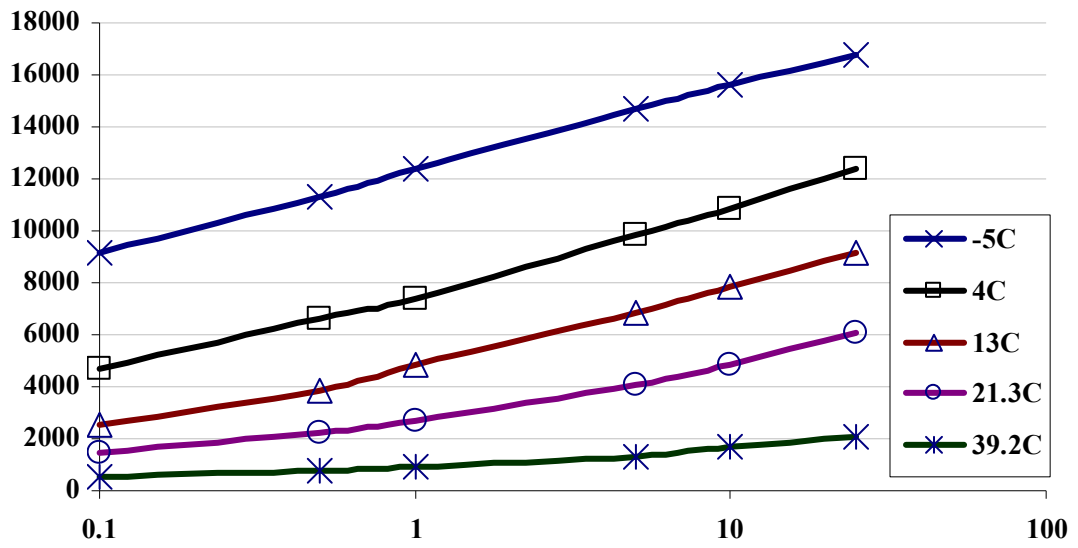


Figure 93 Dynamic Modulus for 5E3 I (Project Location: Bessemer, MI) at 7% Air
Void Level

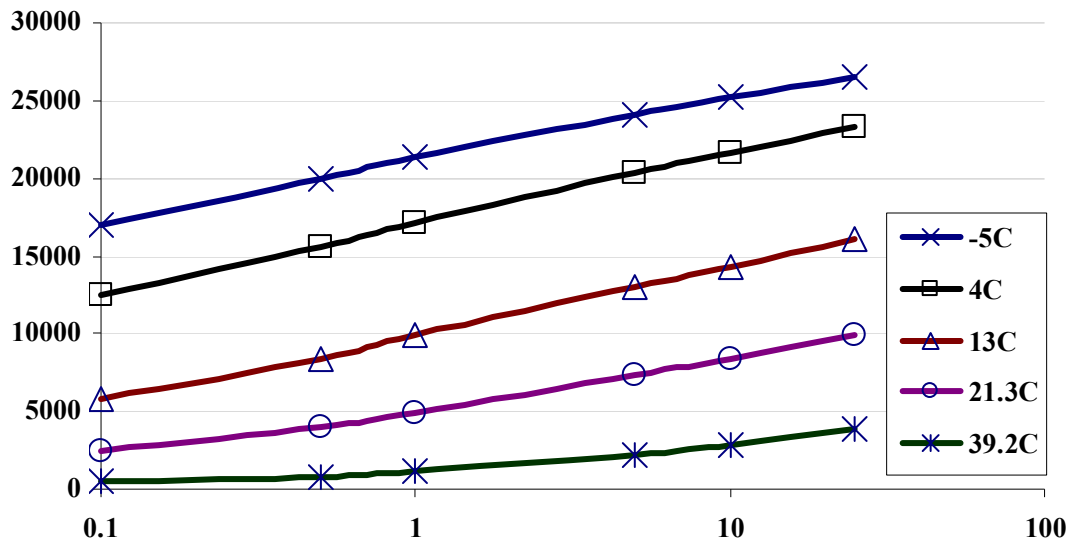


Figure 94 Dynamic Modulus for 5E10 I (Project Location: Auburn Hill) at 4% Air
Void Level

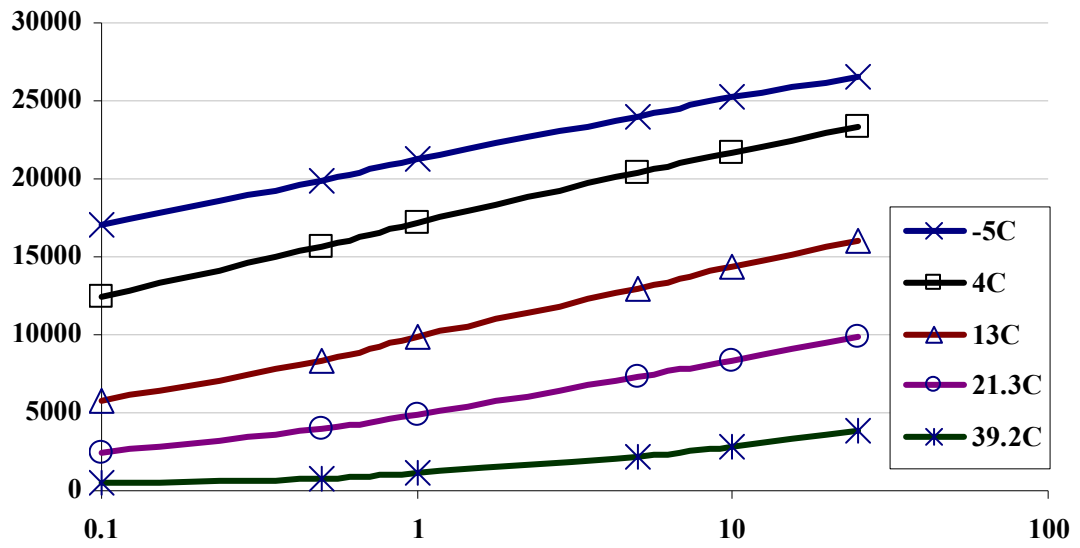


Figure 95 Dynamic Modulus for 5E10 I (Project Location: Auburn Hill) at 7% Air
Void Level

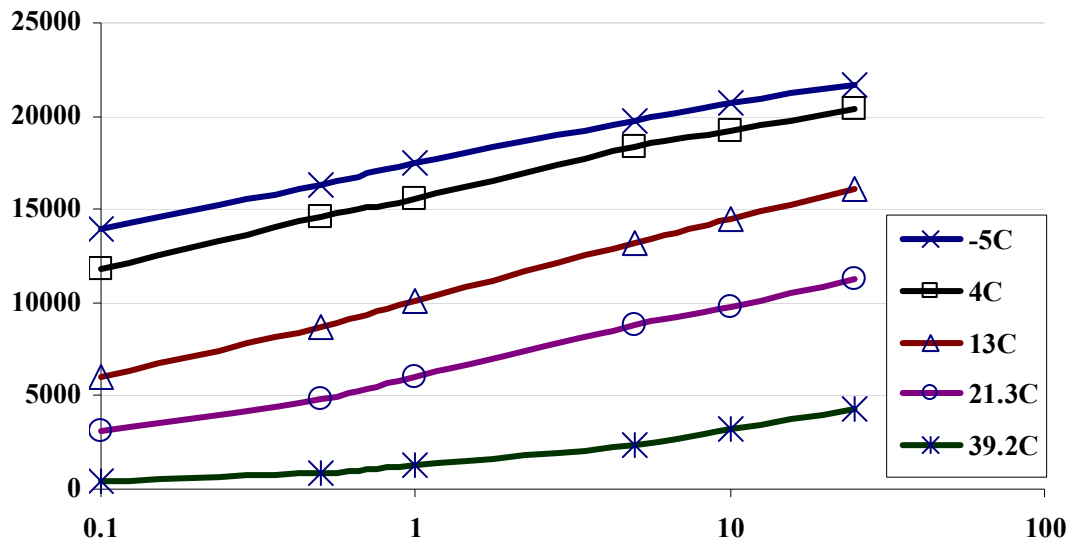


Figure 96 Dynamic Modulus for 5E10 II (Project Location: Oregon, OH) at 4% Air
Void Level

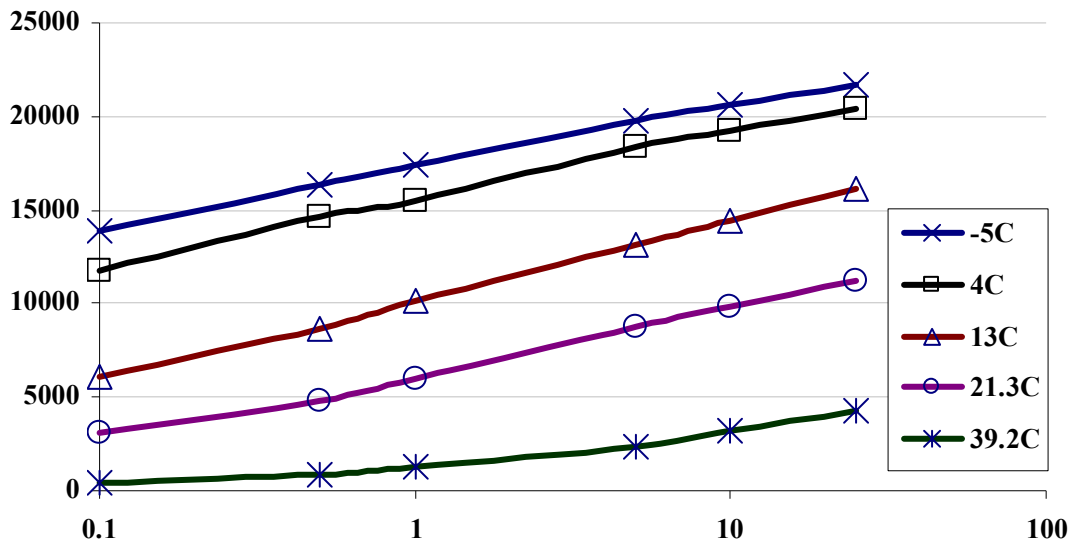
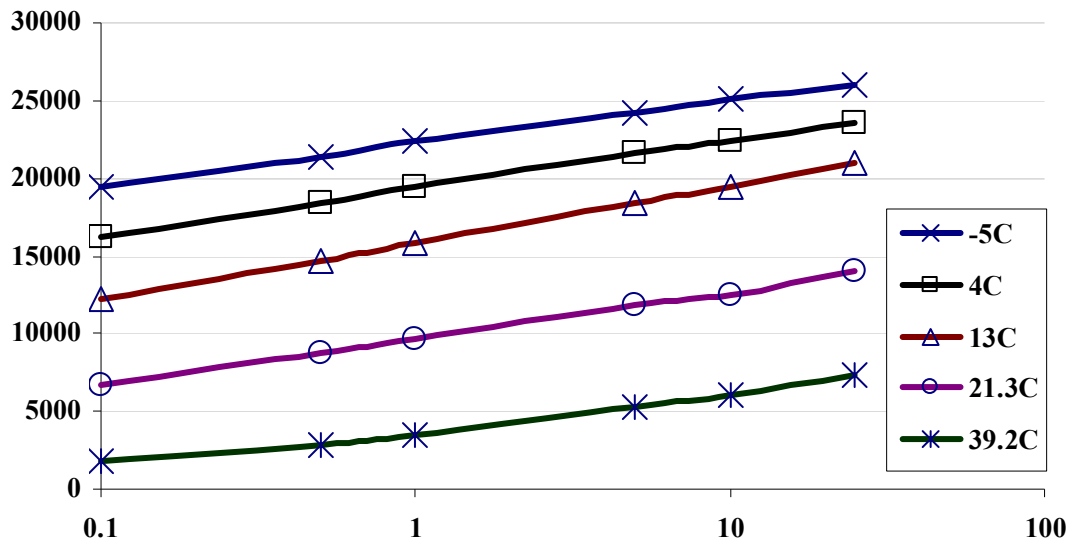
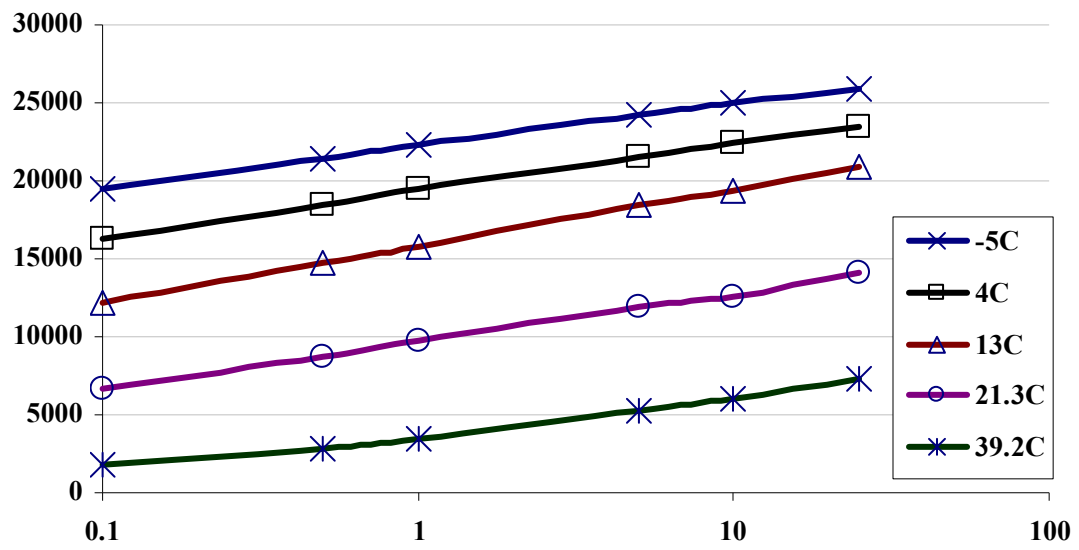


Figure 97 Dynamic Modulus for 5E10 II (Project Location: Oregon, OH) at 7% Air
Void Level



**Figure 98 Dynamic Modulus for 5E30 I (Project Location: I-75 Clarkston) at 4%
Air Void Level**



**Figure 99 Dynamic Modulus for 5E30 I (Project Location: I-75 Clarkston) at 7%
Air Void Level**

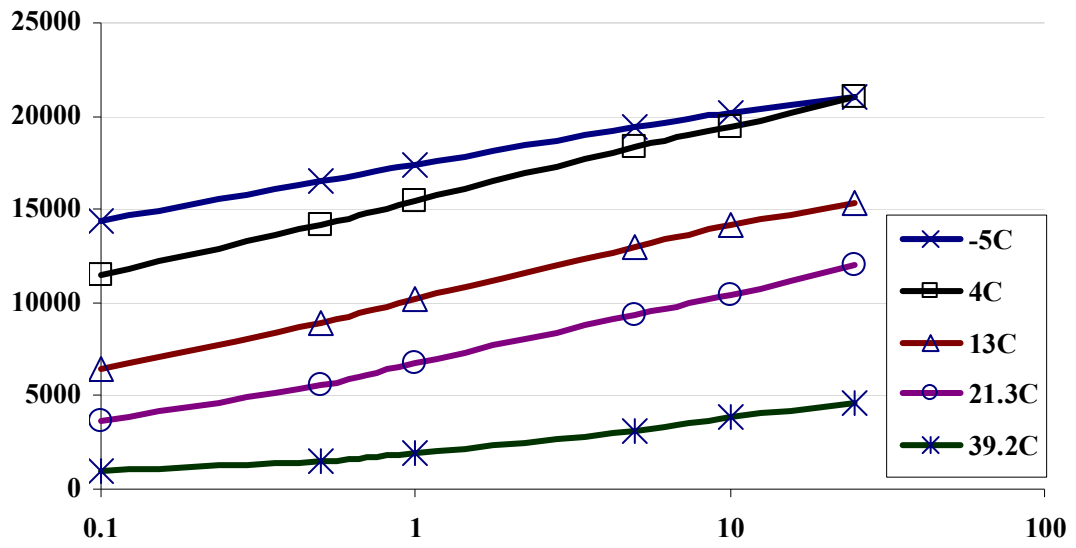


Figure 100 Dynamic Modulus for 5E30 II (Project Location: I-75 Toledo) at 4% Air
Void Level

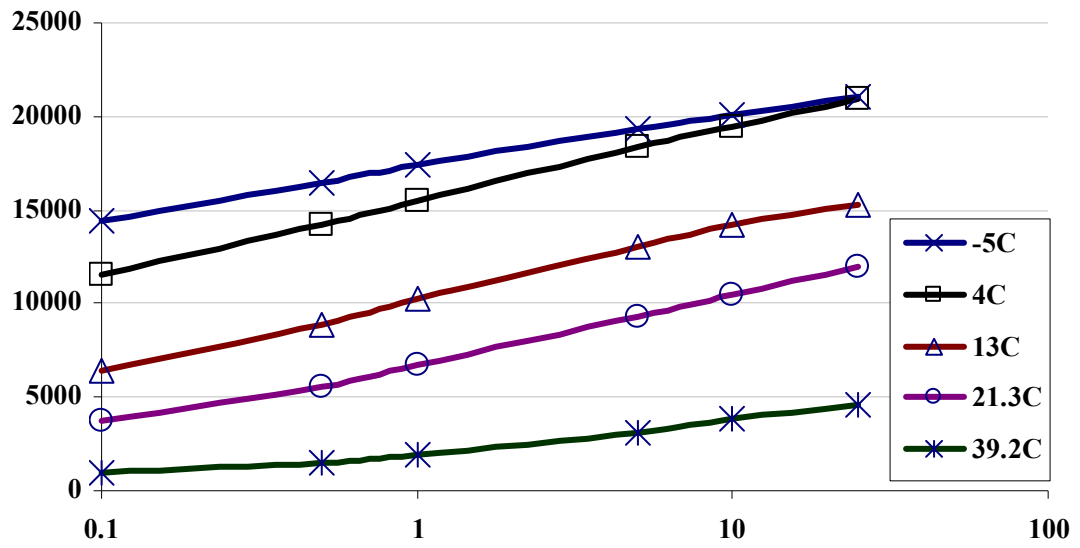


Figure 101 Dynamic Modulus for 5E30 II (Project Location: I-75 Toledo) at 7% Air
Void Level

APPENDIX 4: DYNAMIC MODULUS MASTER CURVES

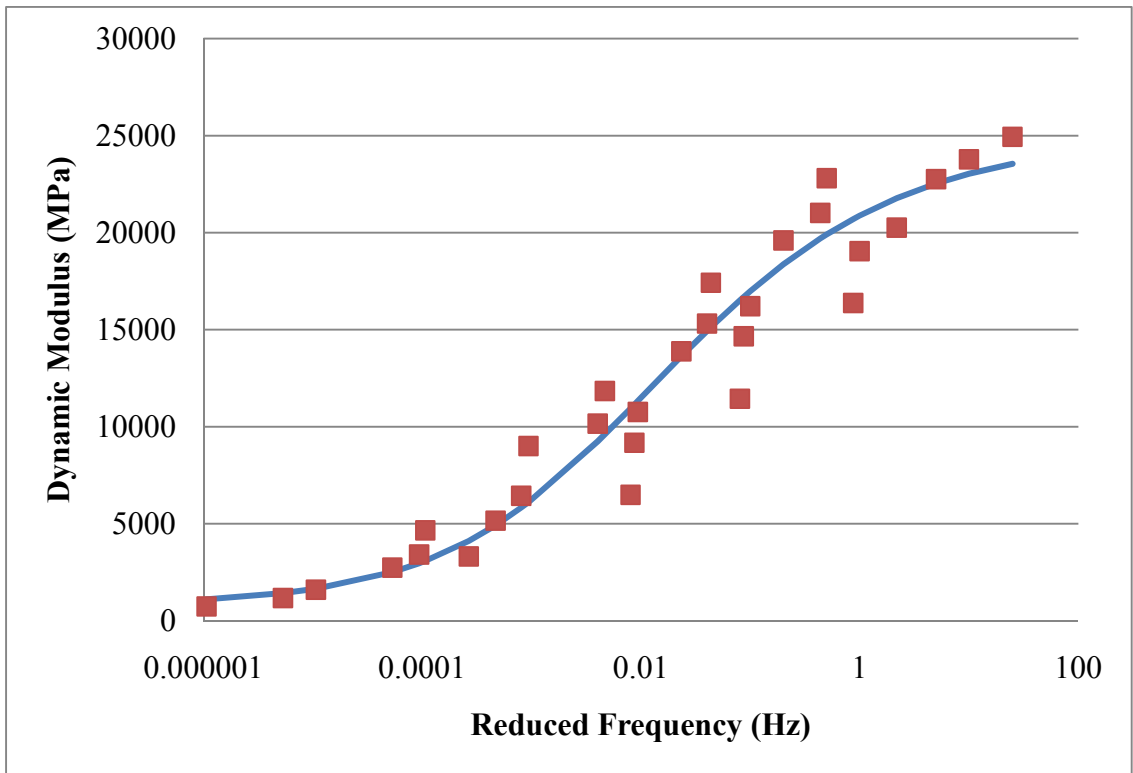


Figure 102 Master Curve of Dynamic Modulus for 3E10 I (Project Location: M-59 Brighton) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

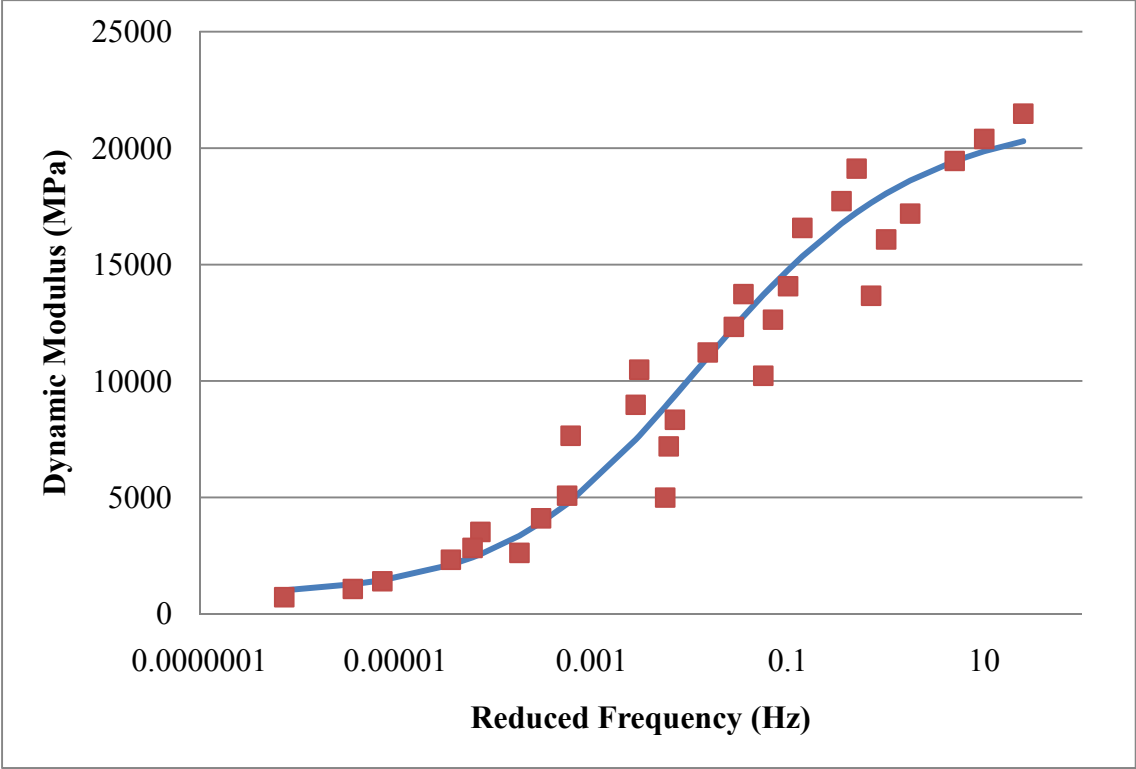


Figure 103 Master Curve of Dynamic Modulus for 3E10 I (Project Location: M-59 Brighton) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

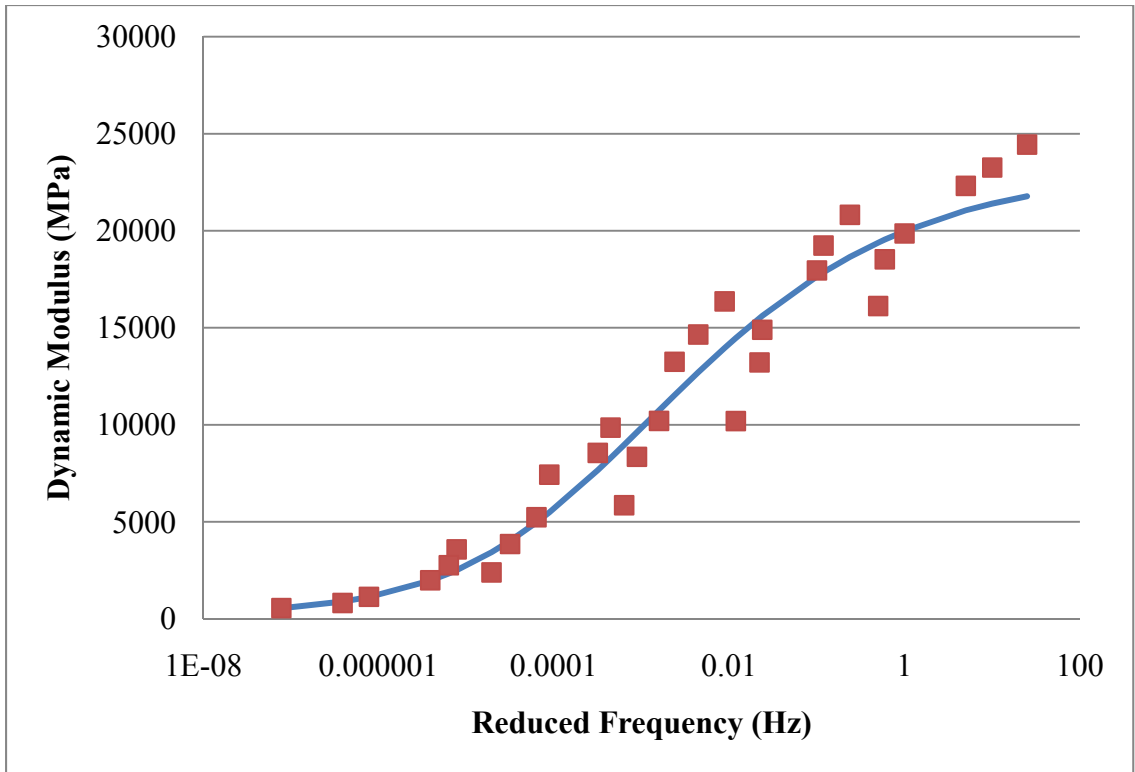


Figure 104 Master Curve of Dynamic Modulus for 3E10 II (Project Location: Michigan Ave, Dearborn) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

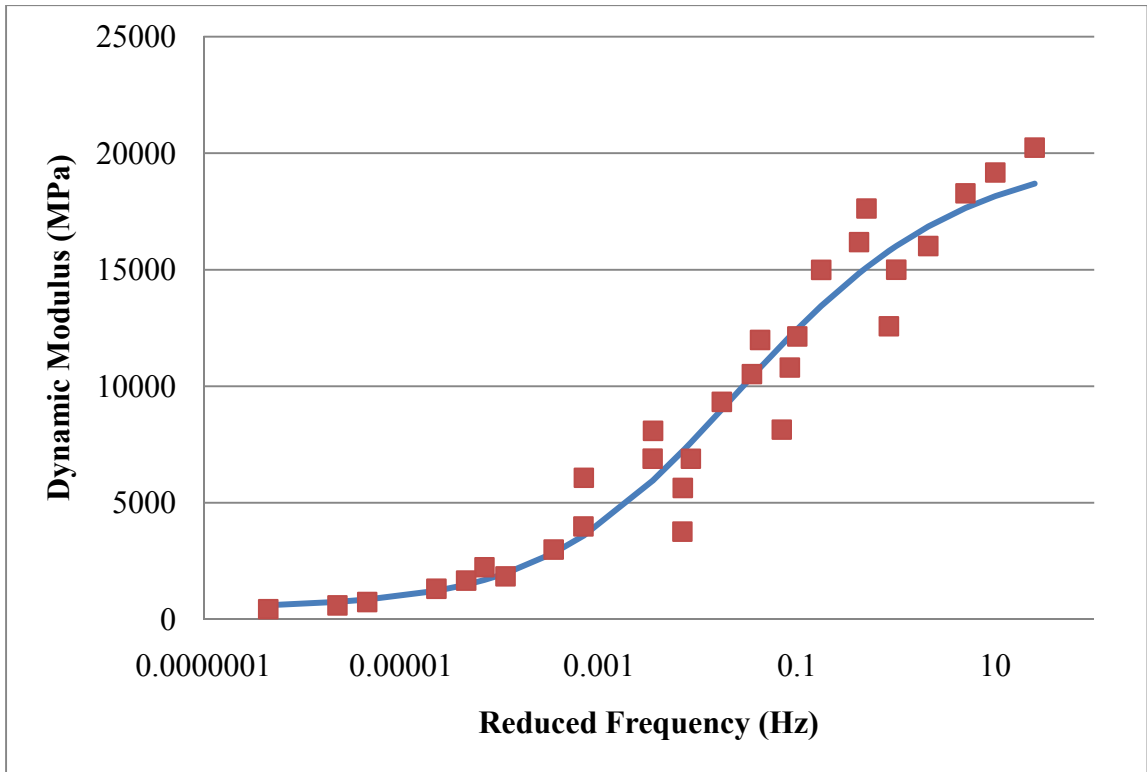


Figure 105 Master Curve of Dynamic Modulus for 3E10 II (Project Location: Michigan Ave, Dearborn) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

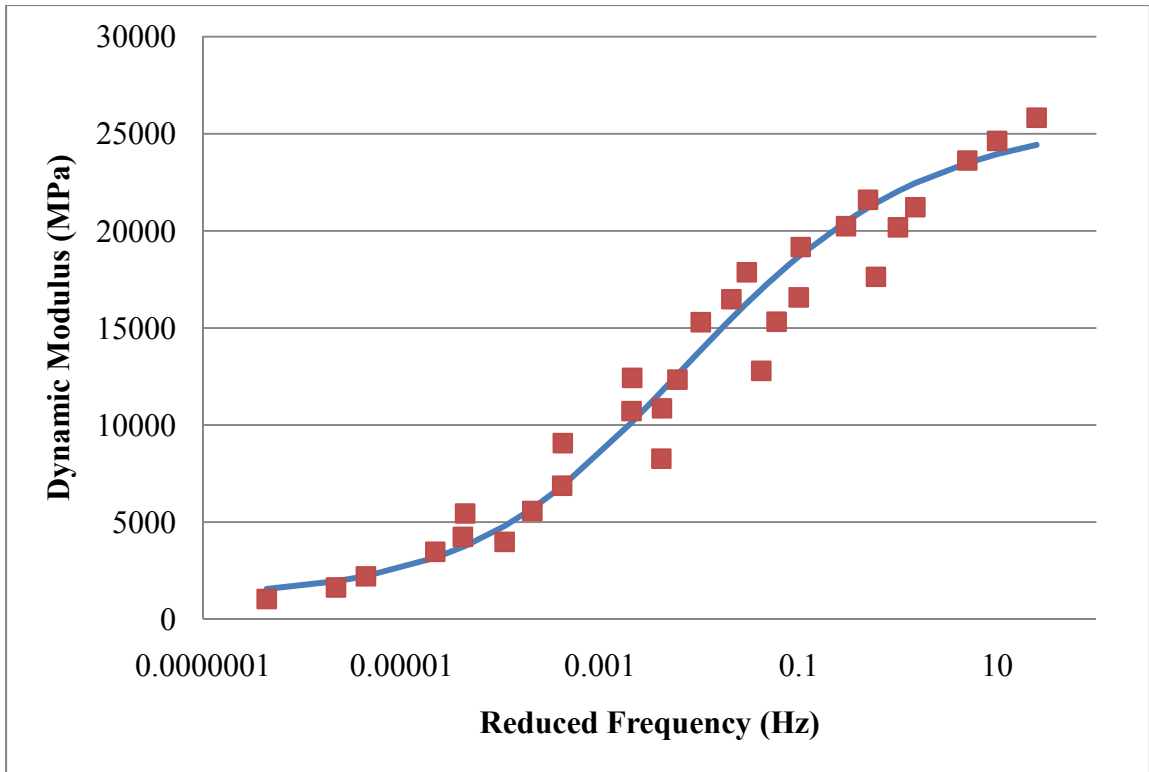


Figure 106 Master Curve of Dynamic Modulus for 3E30 I (Project Location: Vandyke, Detroit) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

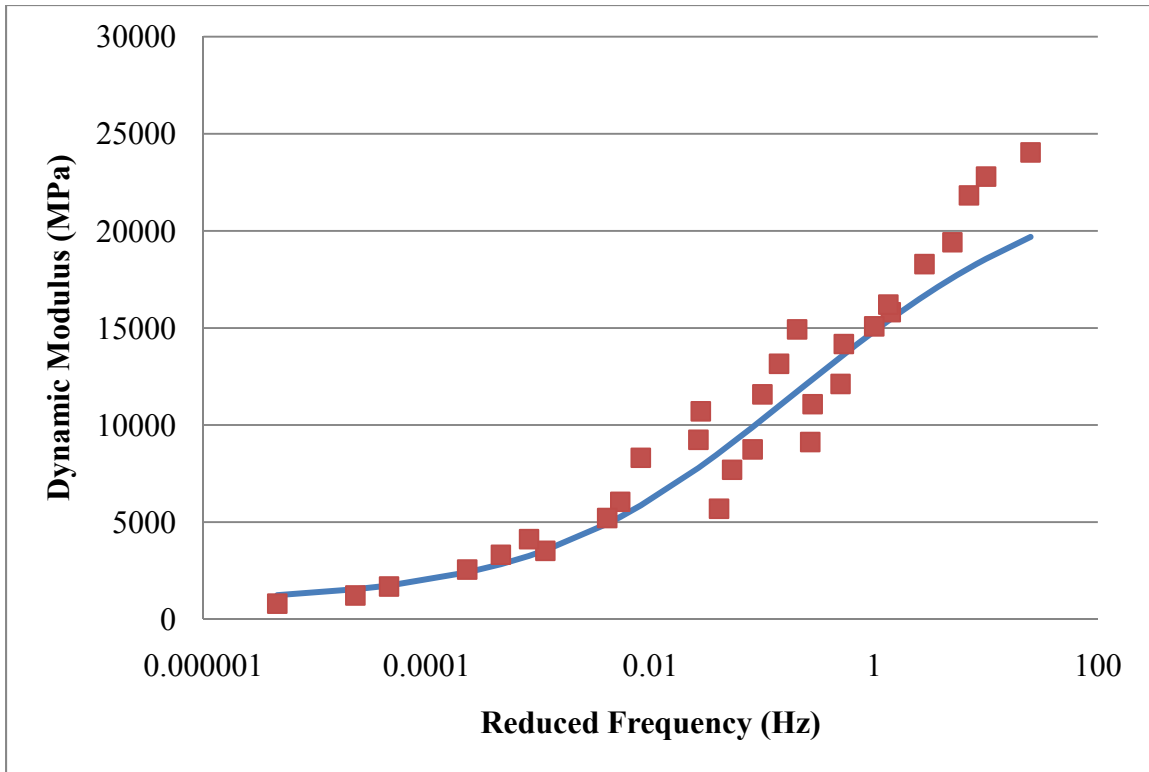


Figure 107 Master Curve of Dynamic Modulus for 3E30 I (Project Location: Vandyke, Detroit) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

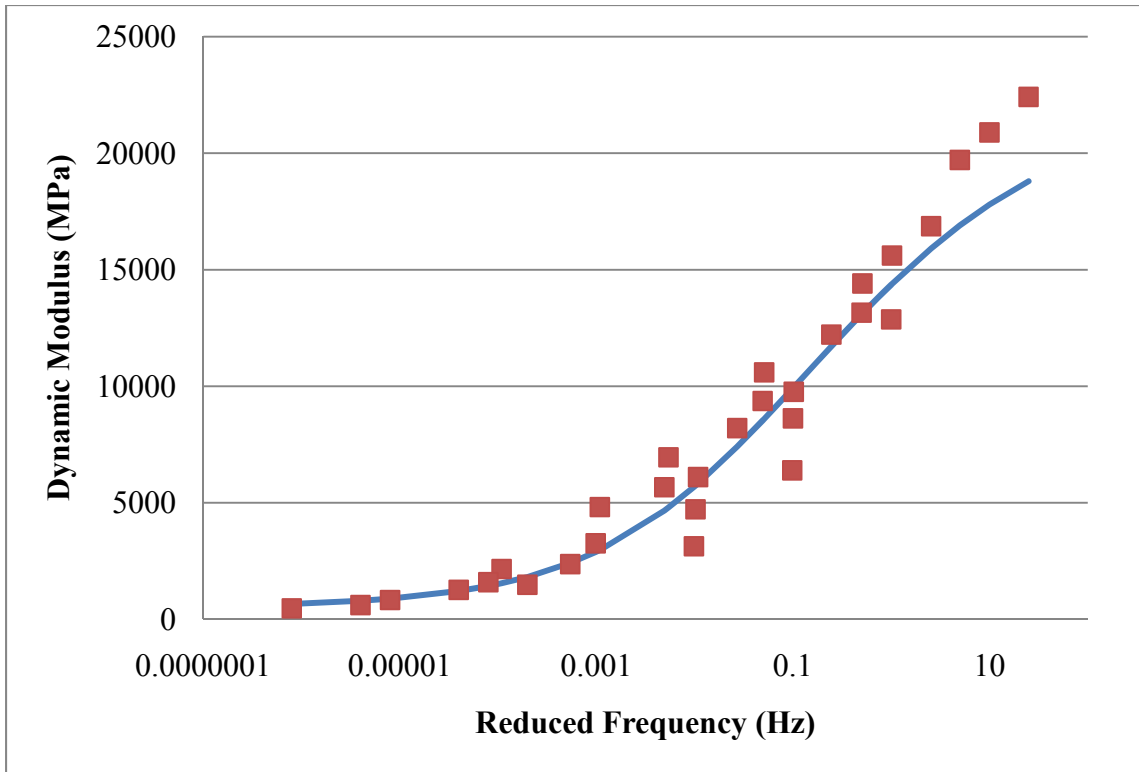


Figure 108 Master Curve of Dynamic Modulus for 4E1 I (Project Location: Tri Mt., Hancock) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

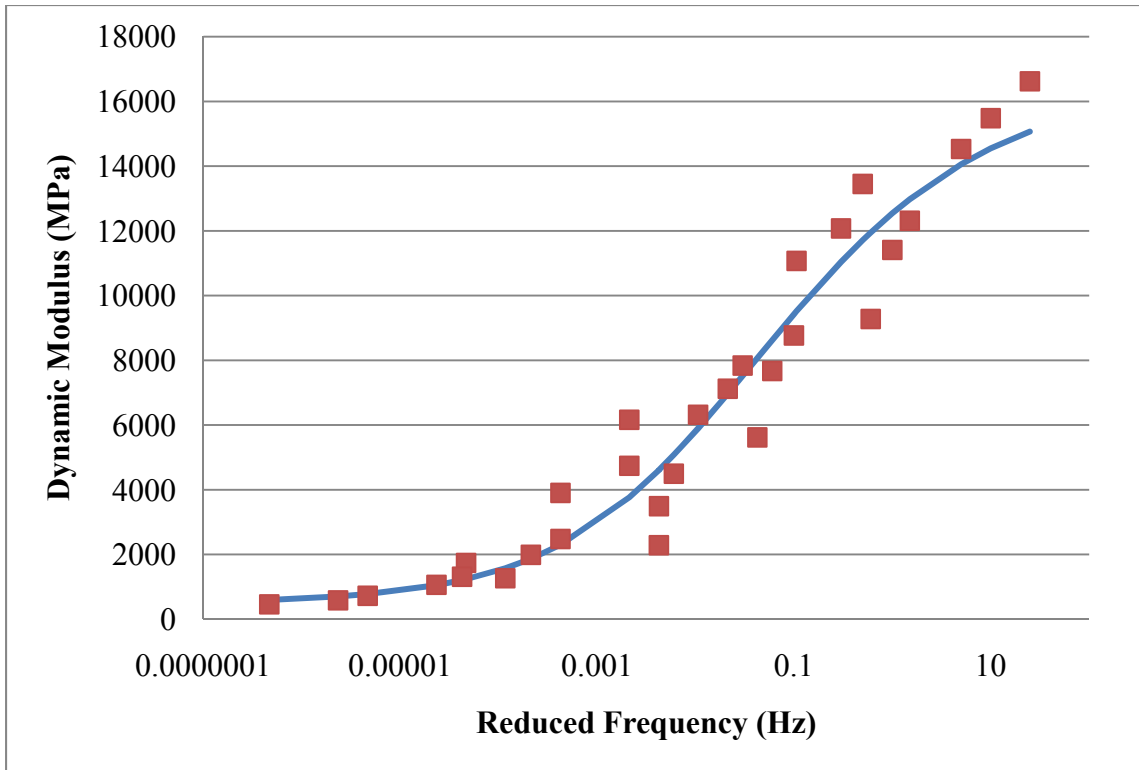


Figure 109 Master Curve of Dynamic Modulus for 4E1 I (Project Location: Tri Mt., Hancock) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

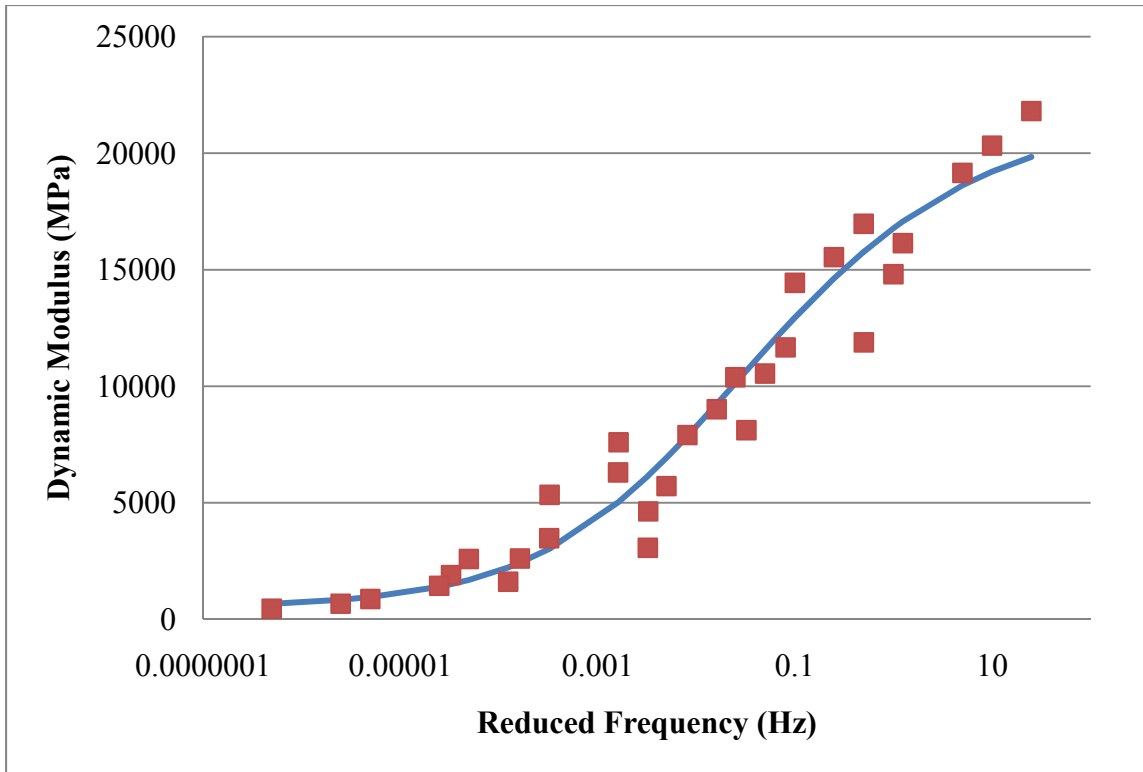


Figure 110 Master Curve of Dynamic Modulus for 4E3 I (Project Location: Lansing, MI)
Mixture with 4% Air Void Level at the Reference Temperature of -5°C

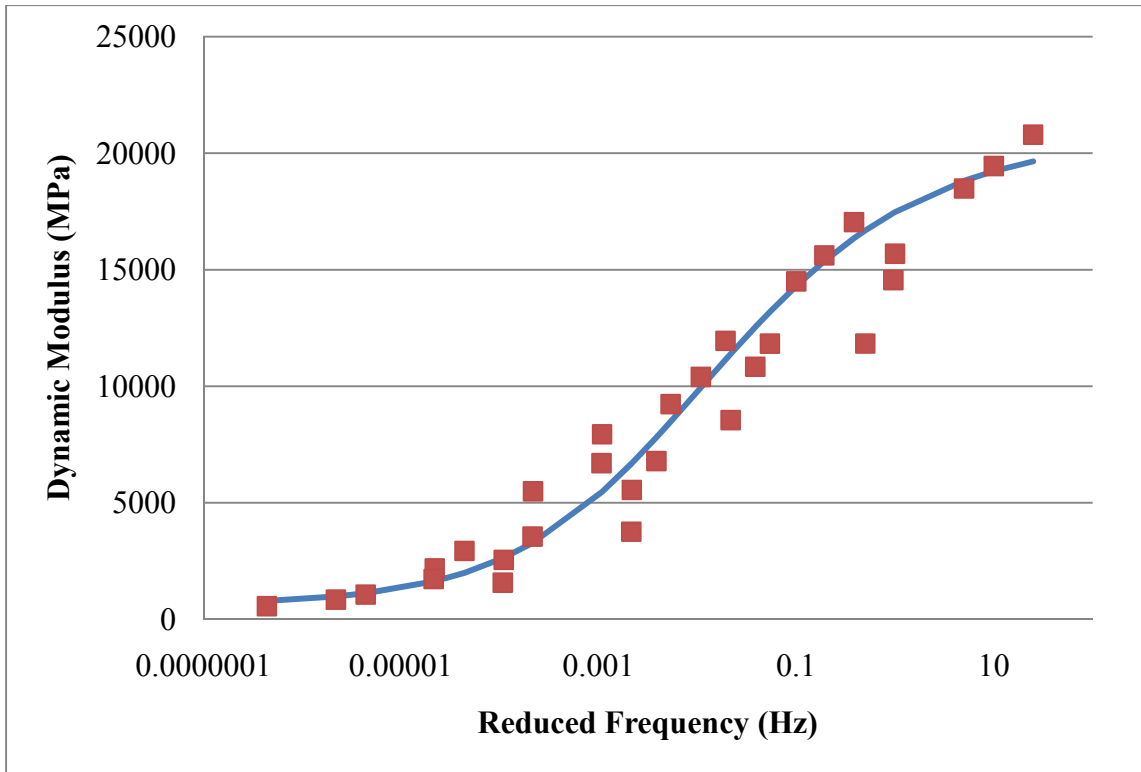


Figure 111 Master Curve of Dynamic Modulus for 4E3 I (Project Location: Lansing, MI)
 Mixture with 7% Air Void Level at the Reference Temperature of -5°C

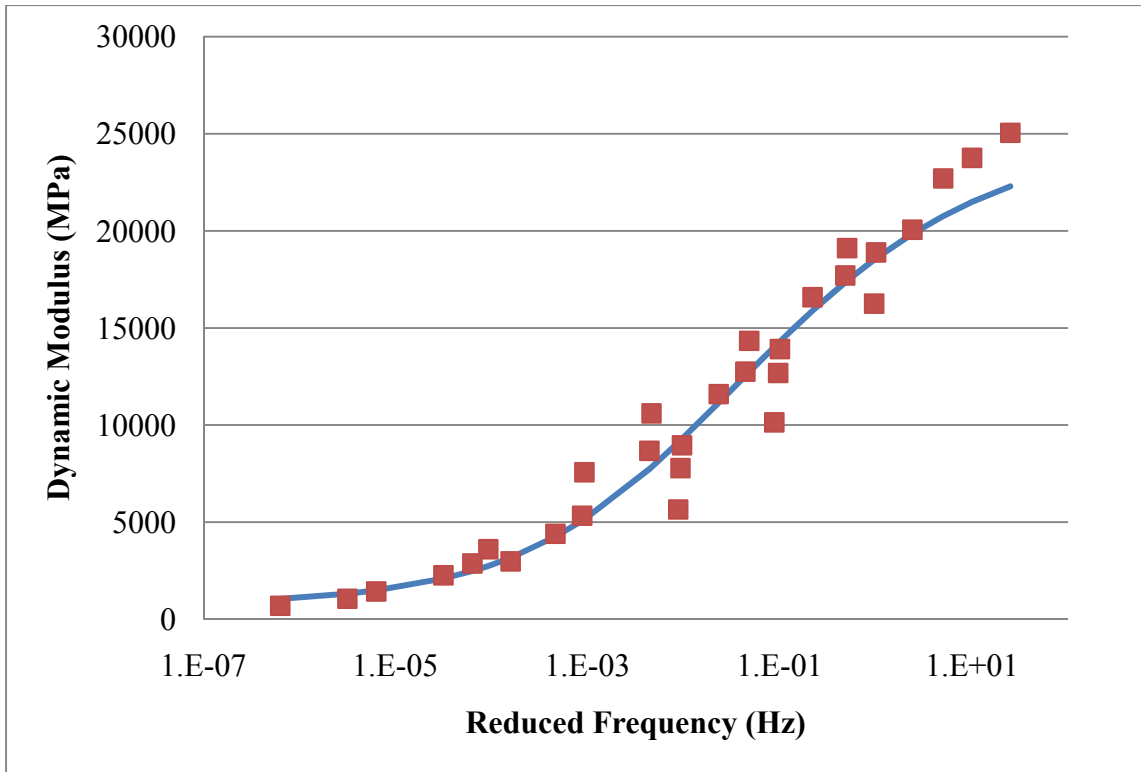


Figure 112 Master Curve of Dynamic Modulus for 4E3 II (Project Location: Lexington)
 Mixture with 4% Air Void Level at the Reference Temperature of -5°C

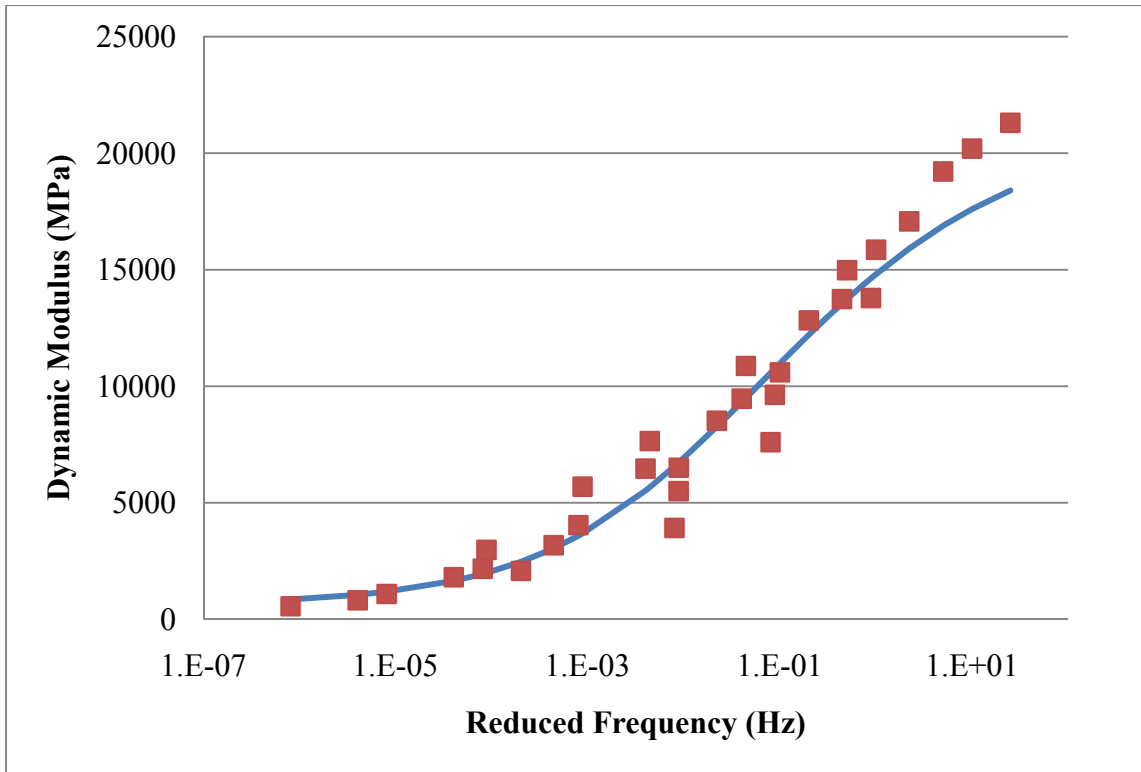


Figure 113 Master Curve of Dynamic Modulus for 4E3 II (Project Location: Lexington)
 Mixture with 7% Air Void Level at the Reference Temperature of -5°C

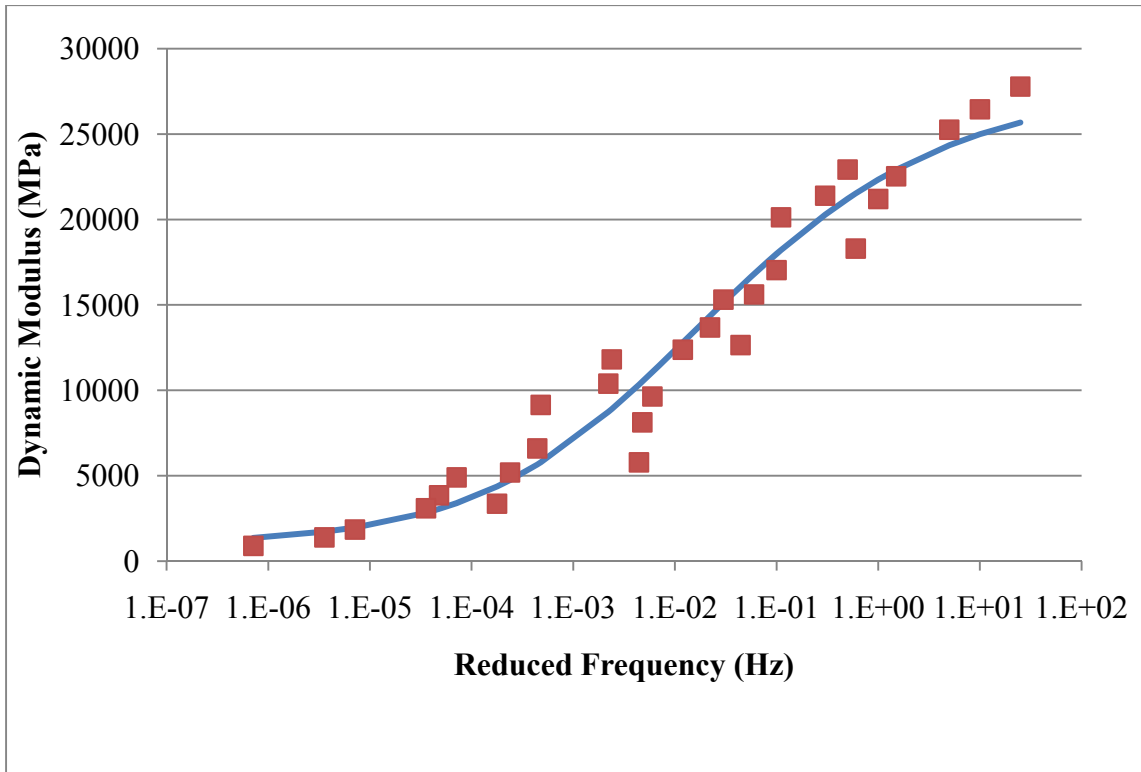


Figure 114 Master Curve of Dynamic Modulus for 4E10 I (Project Location: M-53 Detroit) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

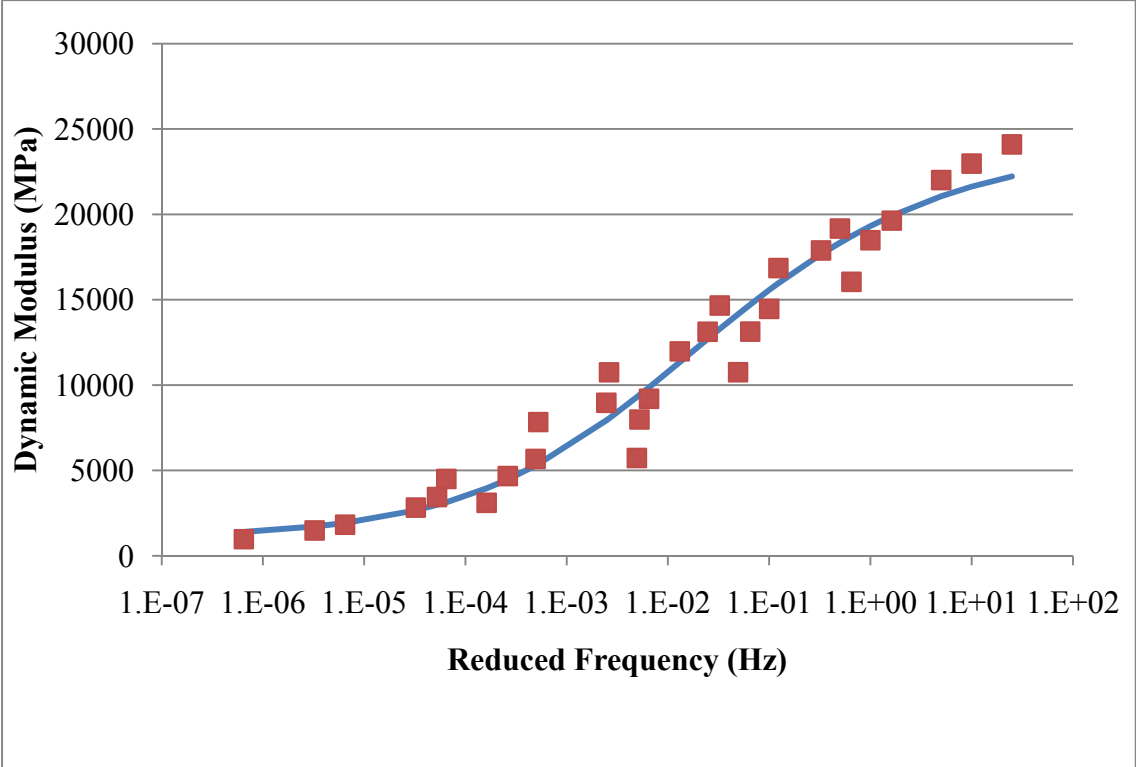


Figure 115 Master Curve of Dynamic Modulus for 4E10 I (Project Location: M-53 Detroit) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

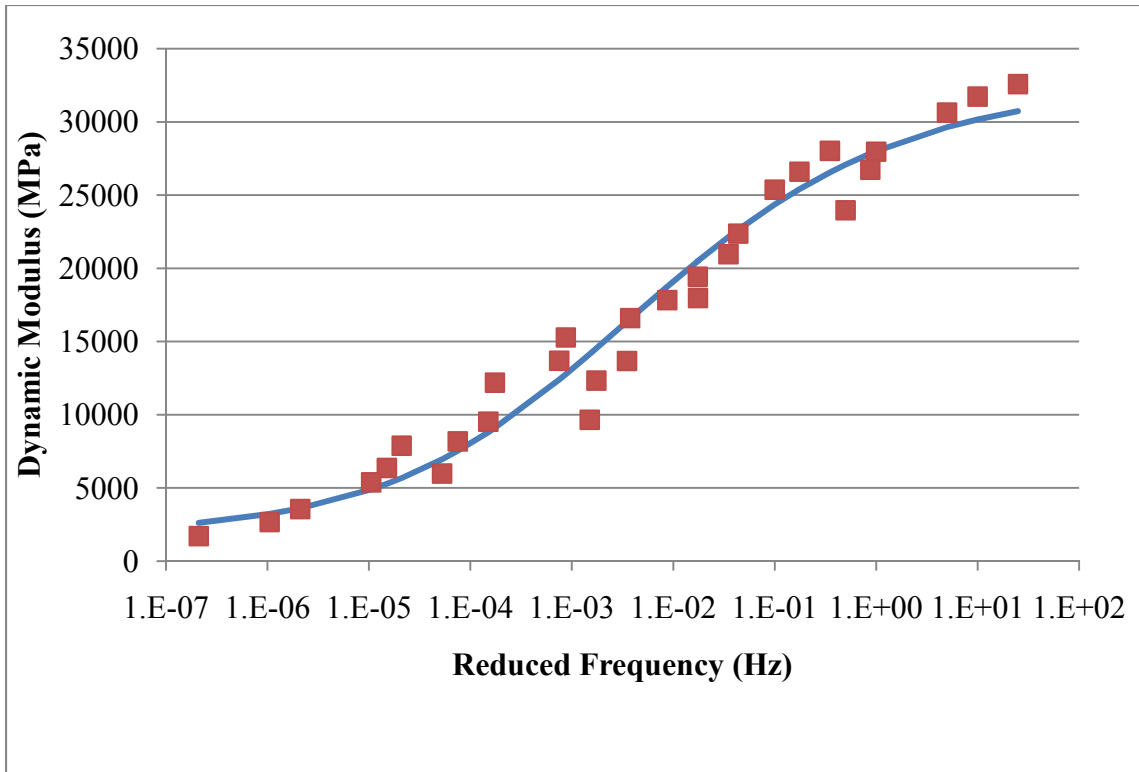


Figure 116 Master Curve of Dynamic Modulus for 4E30 II (Project Location: 8 Mile Rd)
 Mixture with 4% Air Void Level at the Reference Temperature of -5°C

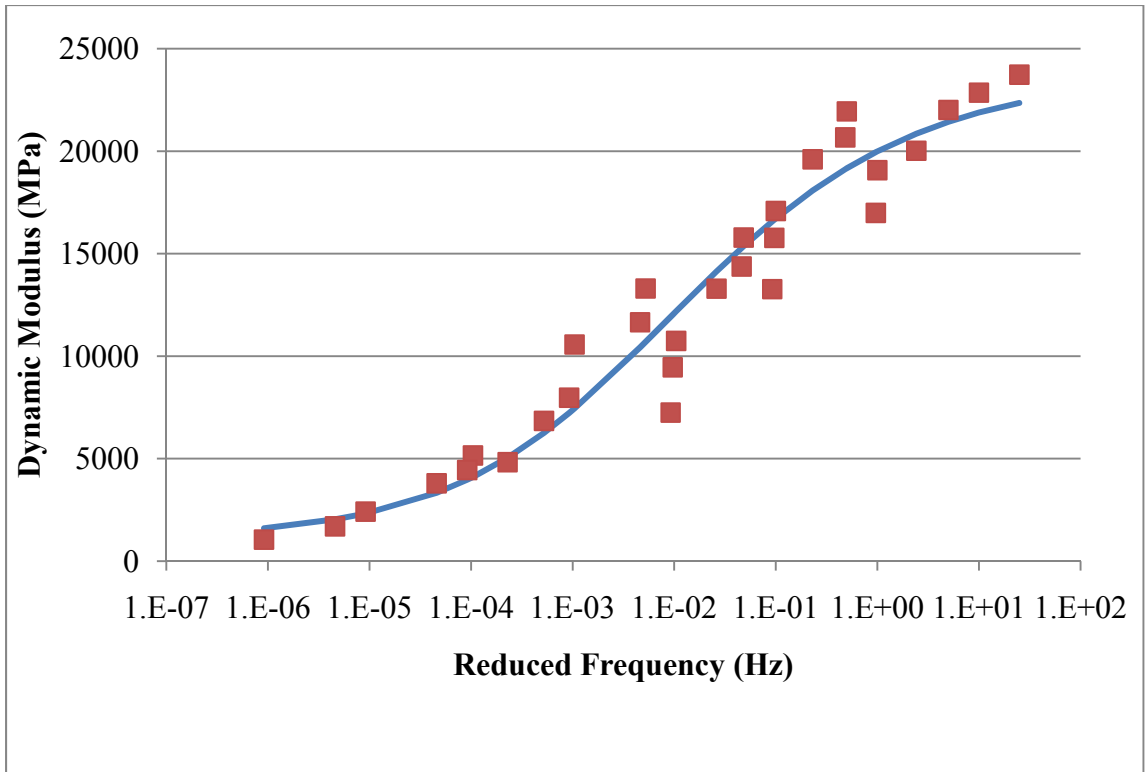


Figure 117 Master Curve of Dynamic Modulus for 4E30 II (Project Location: 8 Mile Rd)
 Mixture with 7% Air Void Level at the Reference Temperature of -5°C

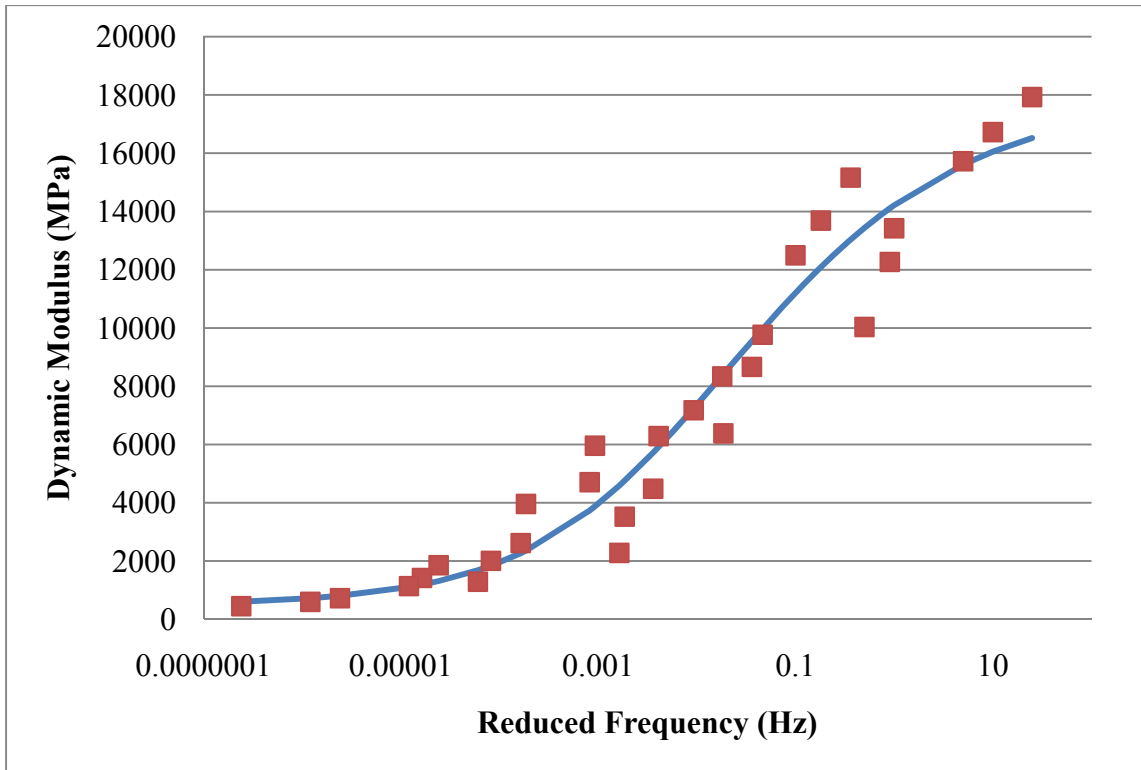


Figure 118 Master Curve of Dynamic Modulus for 5E1 I (Project Location: M-26, Kearsarge St.) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

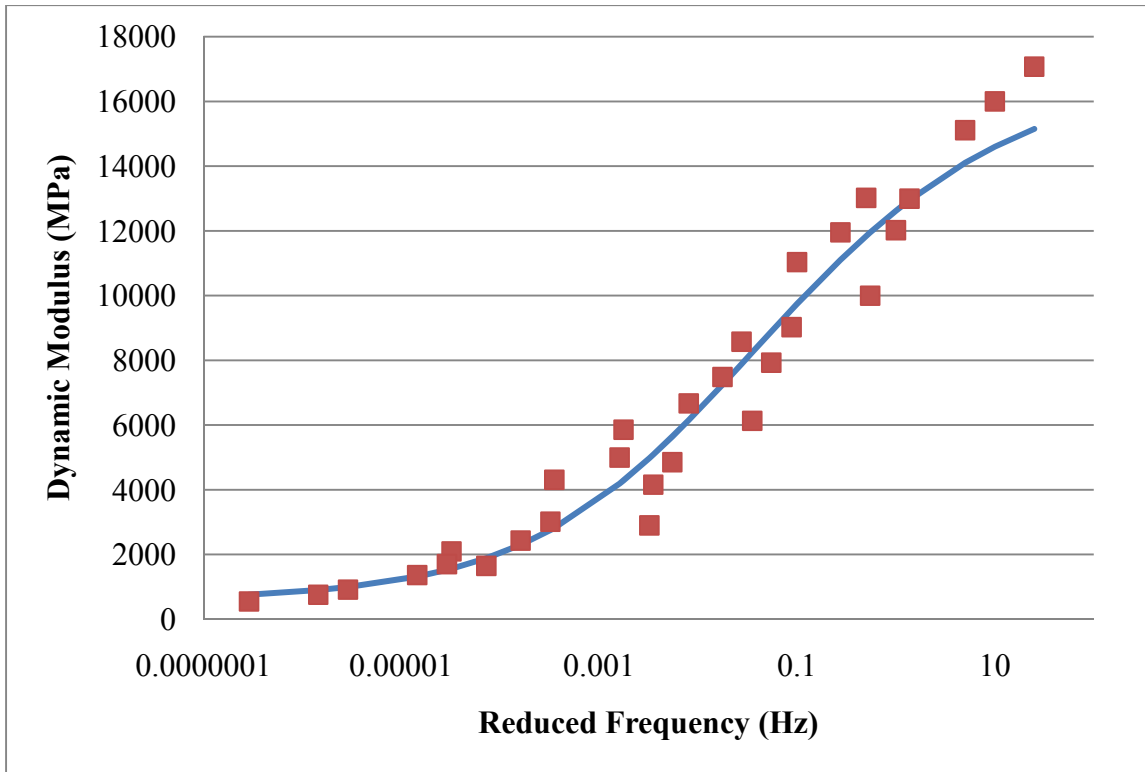


Figure 119 Master Curve of Dynamic Modulus for 5E1 I (Project Location: M-26, Kearsarge St.) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

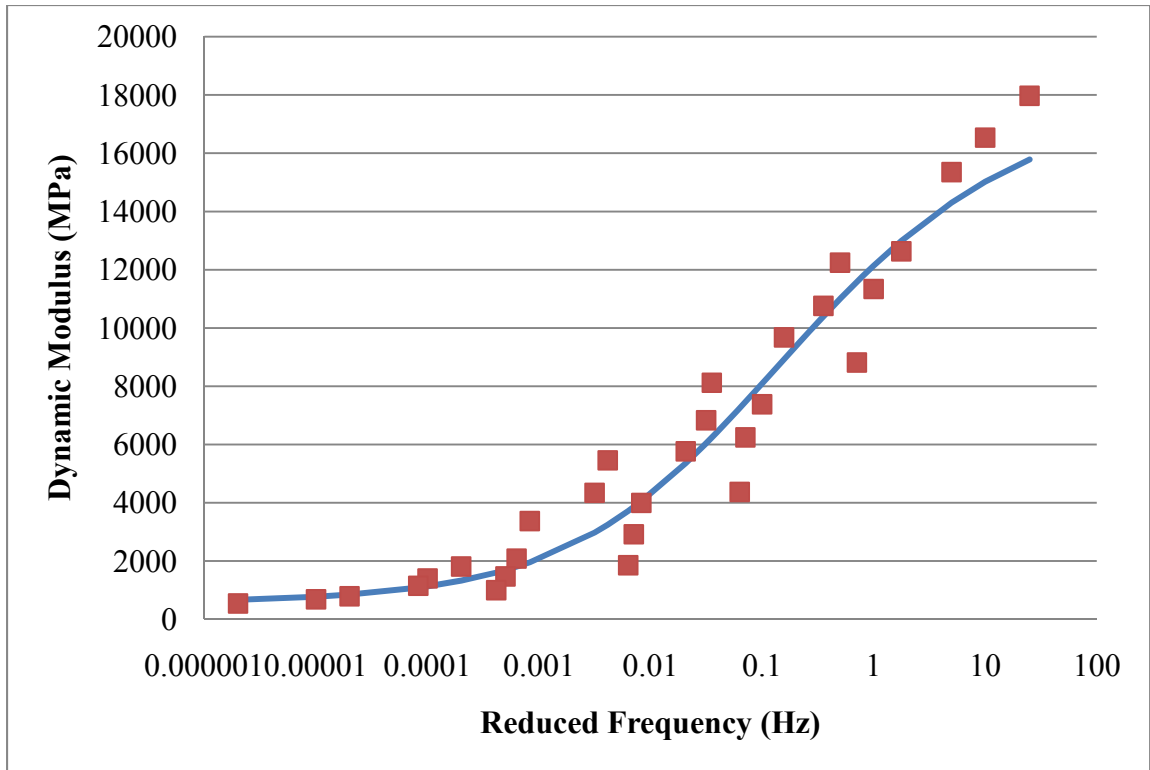


Figure 120 Master Curve of Dynamic Modulus for 5E1 II (Project Location: M-38)
 Mixture with 4% Air Void Level at the Reference Temperature of -5°C

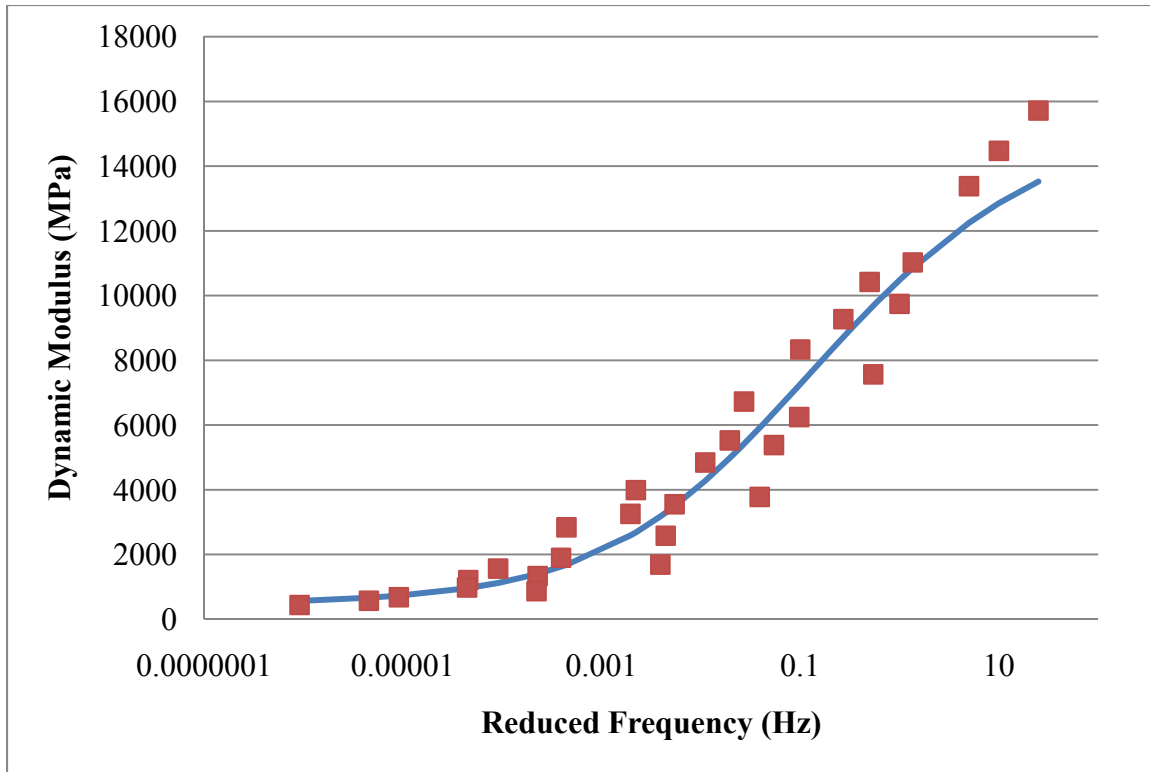


Figure 121 Master Curve of Dynamic Modulus for 5E1 II (Project Location: M-38)
 Mixture with 7% Air Void Level at the Reference Temperature of -5°C

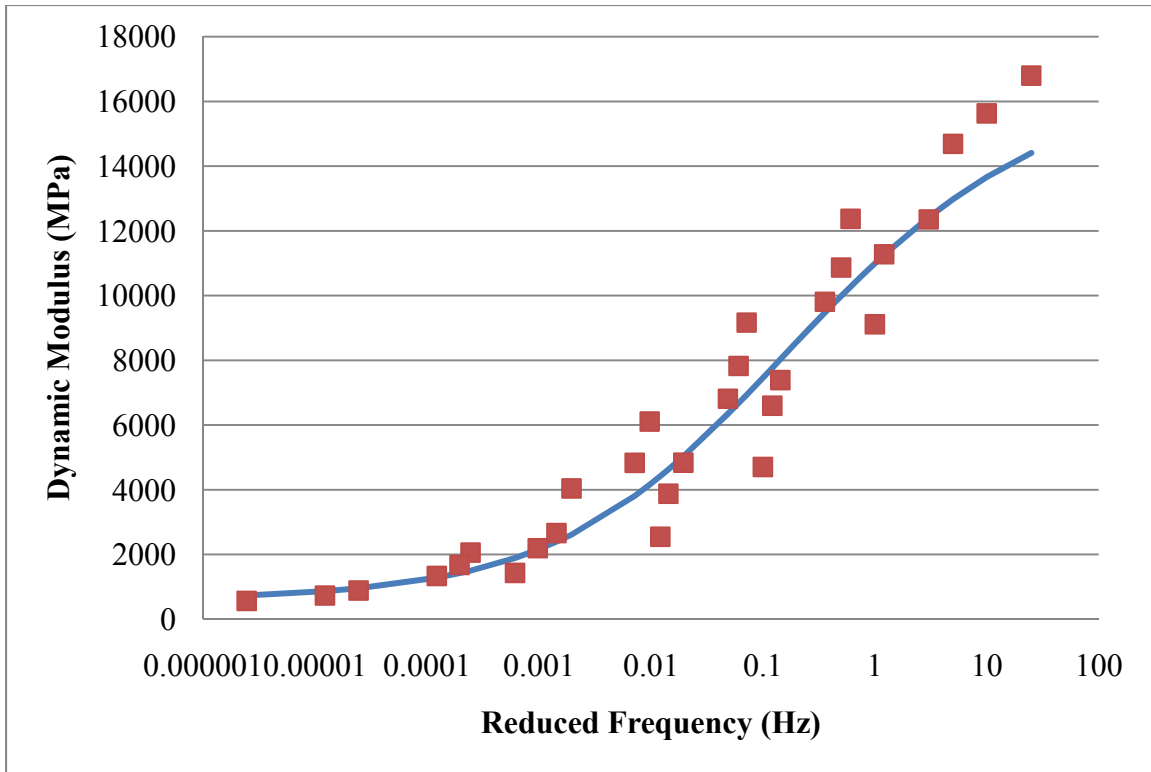


Figure 122 Master Curve of Dynamic Modulus for 5E3 I (Project Location: Bessemer, MI) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

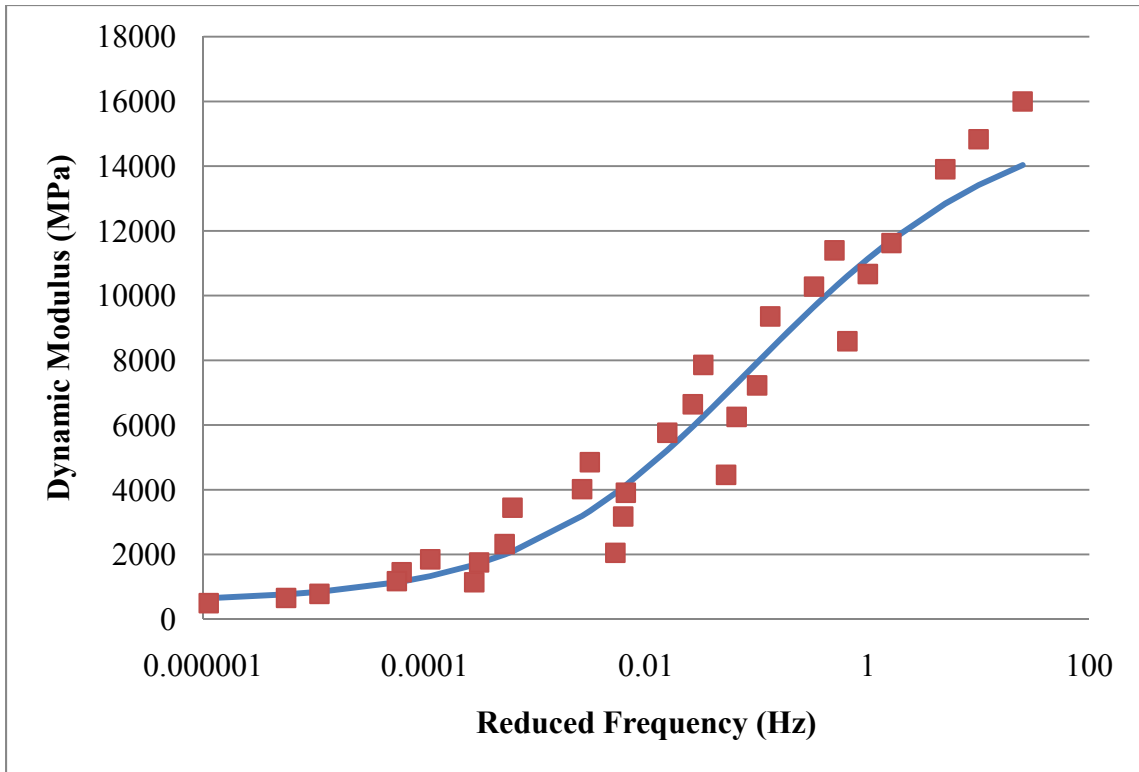


Figure 123 Master Curve of Dynamic Modulus for 5E3 I (Project Location: Bessemer, MI) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

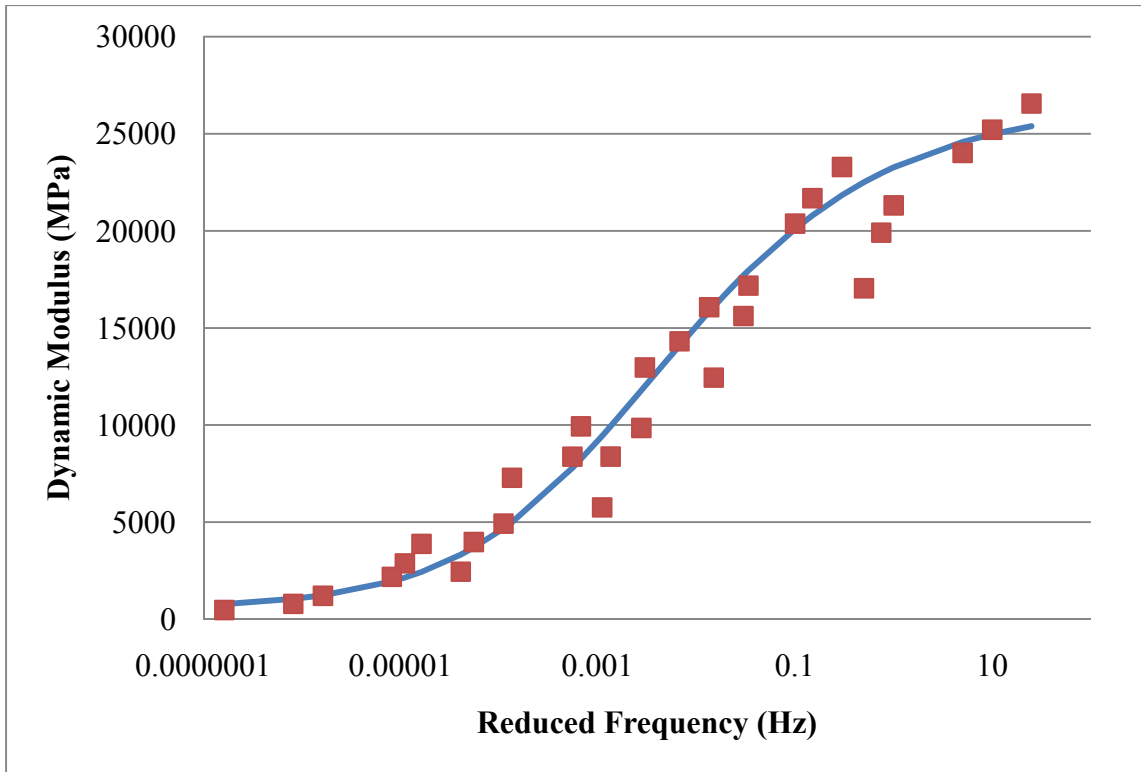


Figure 124 Master Curve of Dynamic Modulus for 5E10 I (Project Location: Auburn Hill) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

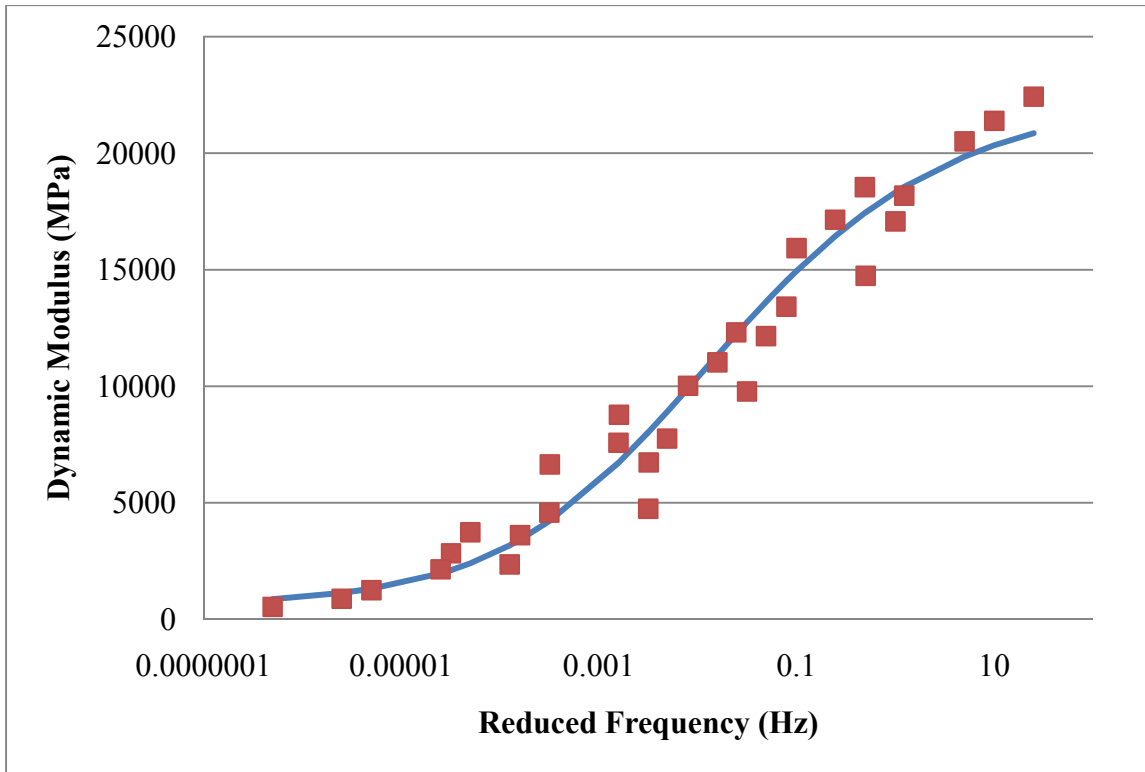


Figure 125 Master Curve of Dynamic Modulus for 5E10 I (Project Location: Auburn Hill) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

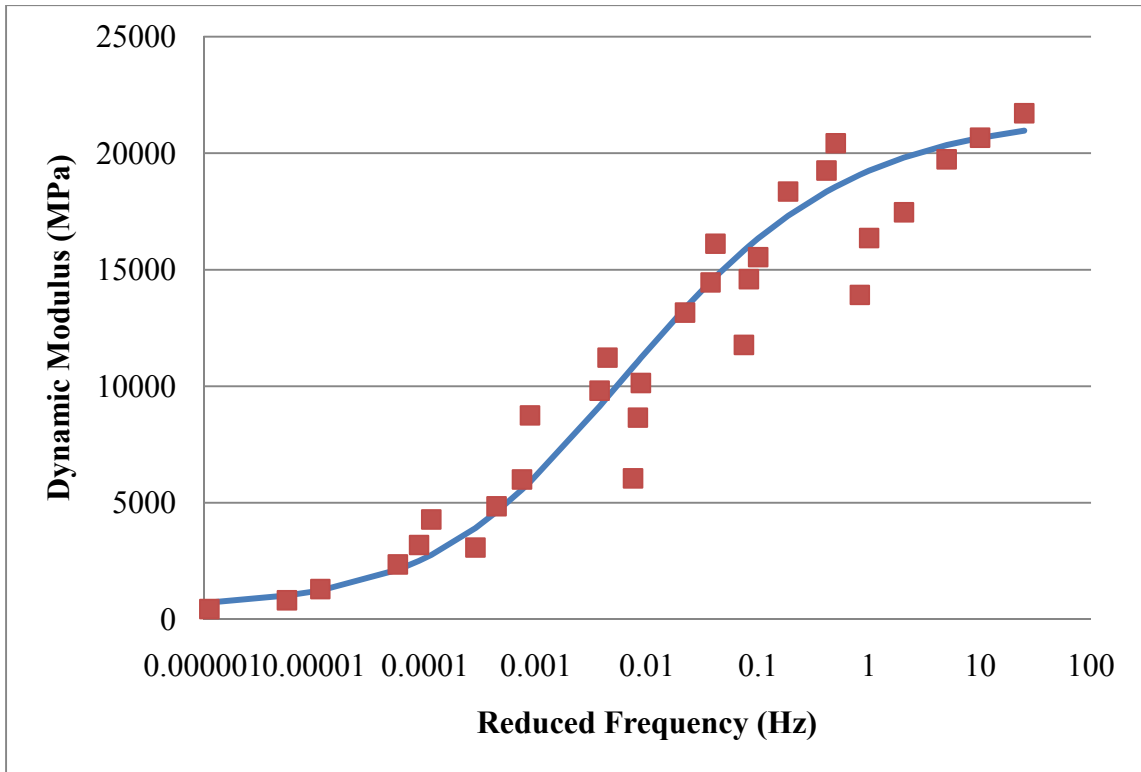


Figure 126 Master Curve of Dynamic Modulus for 5E10 II (Project Location: Oregon, OH) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

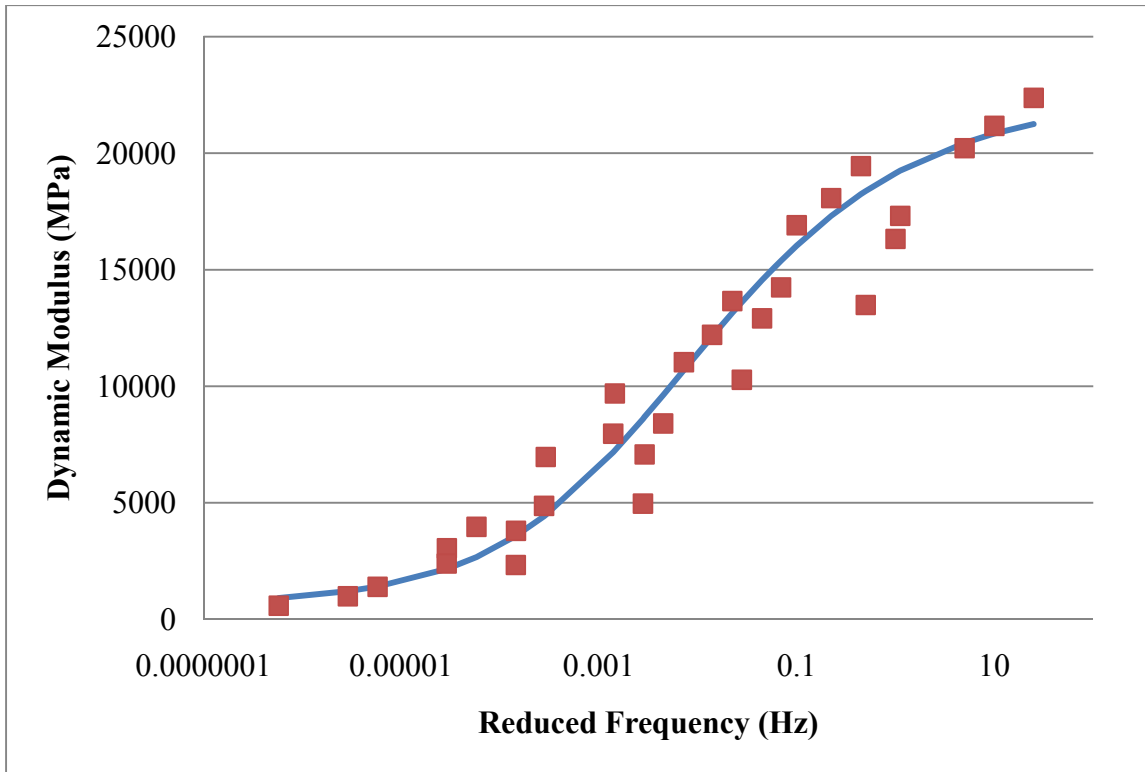


Figure 127 Master Curve of Dynamic Modulus for 5E10 II (Project Location: Oregon, OH) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

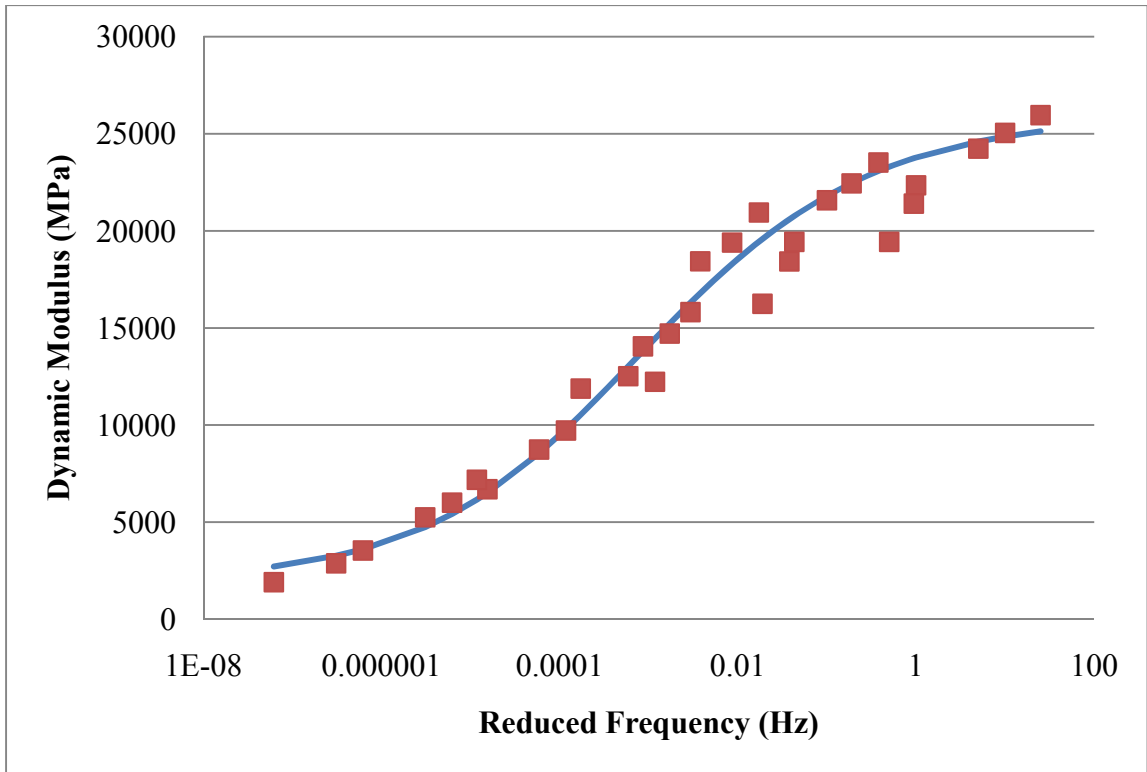


Figure 128 Master Curve of Dynamic Modulus for 5E30 I (Project Location: I-75 Clarkston) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

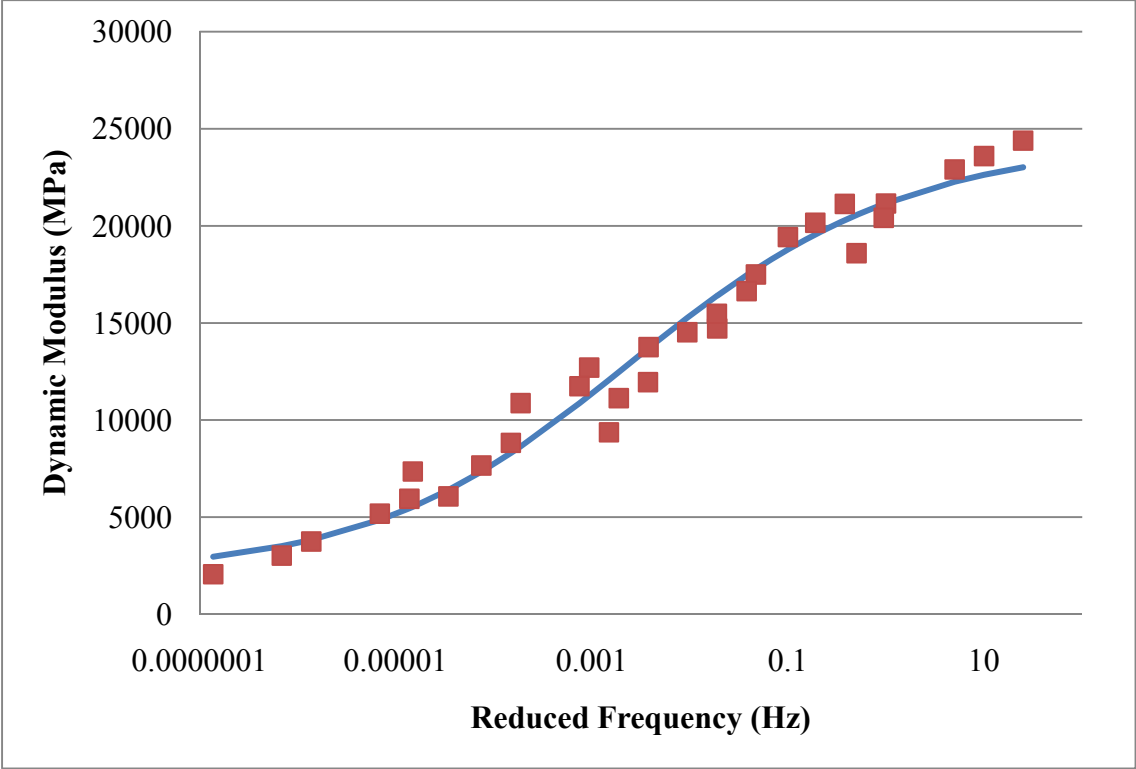


Figure 129 Master Curve of Dynamic Modulus for 5E30 I (Project Location: I-75 Clarkston) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

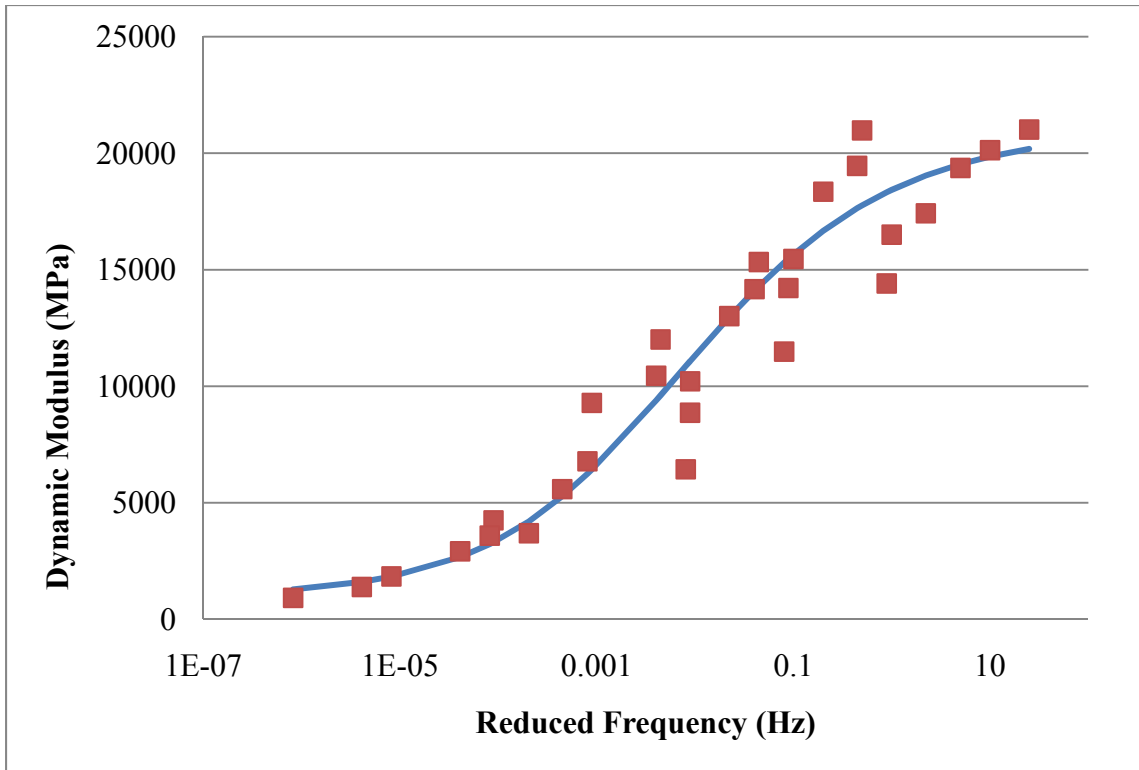


Figure 130 Master Curve of Dynamic Modulus for 5E30 II (Project Location: I-75 Toledo) Mixture with 4% Air Void Level at the Reference Temperature of -5°C

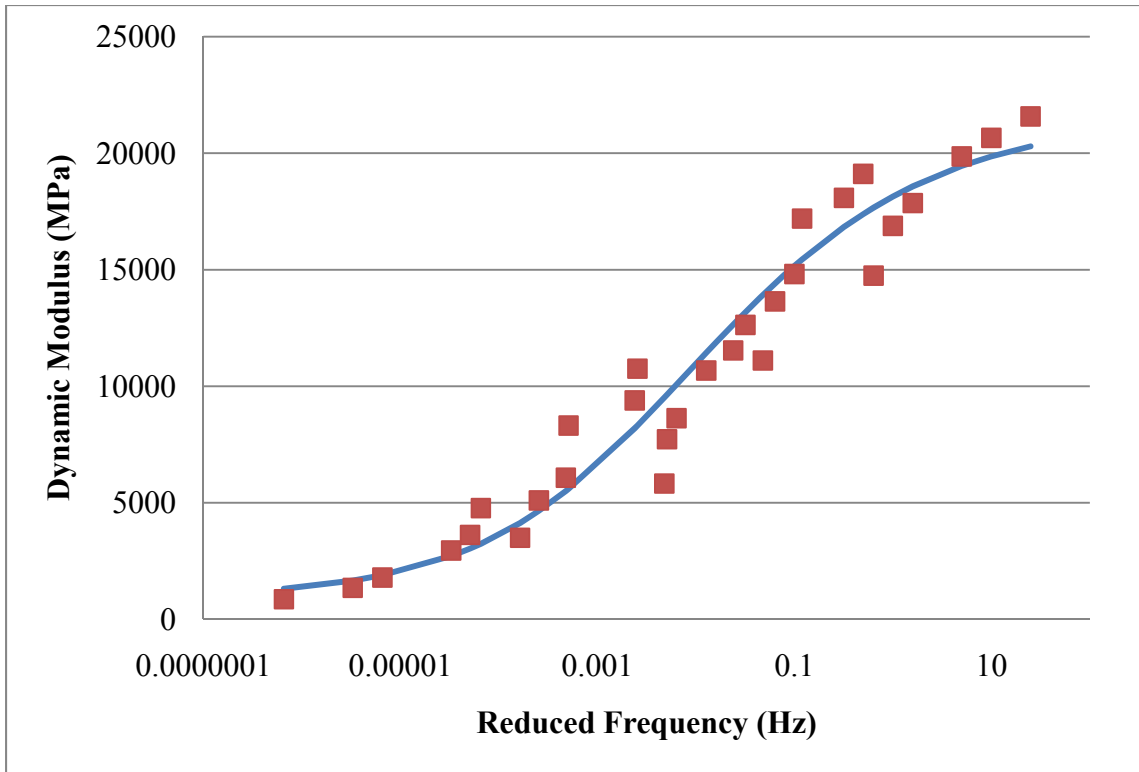


Figure 131 Master Curve of Dynamic Modulus for 5E30 II (Project Location: I-75 Toledo) Mixture with 7% Air Void Level at the Reference Temperature of -5°C

APPENDIX 5: MINIMUM DYNAMIC MODULUS CRITERIA

Table 24 Minimum Dynamic Modulus Criteria for 4% Air Void Level Mixture at -5 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
-5	25	23000	25000	22000	25000	27000	32000	18000	18000	26800	26800
-5	10	21000	23000	19000	21000	25000	28000	17000	17000	25000	25000
-5	5	20000	22000	18000	19500	22000	25000	15500	16000	24500	25000
-5	1	18000	22000	16000	18000	20000	24000	13000	14000	21500	22000
-5	0.5	17000	20000	14000	16000	18000	22000	11500	12000	20000	20000
-5	0.1	16000	18000	12500	13000	17500	17500	13000	14000	18000	19000

Table 25 Minimum Dynamic Modulus Criteria for 4% Air Void Level Mixture at 4 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
4	25	18000	20000	12500	17000	20500	23500	12500	12500	23500	23500
4	10	16000	18000	11000	16000	19500	21000	11000	11000	22000	22000
4	5	15000	17000	10000	14500	16000	18000	10000	10000	20000	20000
4	1	13000	15000	8500	12000	14500	16500	7500	7500	17500	17500
4	0.5	11000	13000	7500	11000	13500	18000	6500	6500	15500	15500
4	0.1	10000	12000	6000	8500	12500	15000	4500	4500	12500	13500

Table 26 Minimum Dynamic Modulus Criteria for 4% Air Void Level Mixture at 13 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
13	25	13000	15000	10000	11500	13500	15500	8500	9000	16500	16500
13	10	11000	13500	9000	10000	12000	14000	7000	7500	14500	14500
13	5	9500	11500	8000	9500	10500	12500	6000	6500	13500	13500
13	1	8000	10000	6000	7500	9000	11500	4000	5000	10500	10500
13	0.5	6500	8000	4500	6500	7500	10000	3500	3500	9000	9500
13	0.1	5000	7000	3000	4000	5000	8000	1900	2500	6500	7500

Table 27 Minimum Dynamic Modulus Criteria for 4% Air Void Level Mixture at 21.3 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
21.3	25	9000	10000	6000	8000	9000	13000	5500	5500	11500	12500
21.3	10	8000	9000	5000	6000	8000	10000	4500	4500	10000	10500
21.3	5	6000	7000	4000	6000	8000	11000	3500	3500	9000	9500
21.3	1	5000	6000	2500	3500	6000	8000	2500	2500	6000	8000
21.3	0.5	3500	5000	2000	3000	4500	6000	1500	2000	5000	6000
21.3	0.1	2000	3000	1000	2000	3000	5000	1000	1000	3500	4000

Table 28 Minimum Dynamic Modulus Criteria for 4% Air Void Level Mixture at 39.2 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
39.2	25	2500	4500	1500	3000	3500	5000	2000	2000	4500	5000
39.2	10	2000	3500	1000	2000	3500	4500	1500	1500	3500	4000
39.2	5	1500	3000	1000	1800	2500	4000	1150	1150	2500	3000
39.2	1	800	1500	700	1000	1500	2000	800	800	1300	2000
39.2	0.5	600	1000	500	700	1000	1500	700	700	800	1500
39.2	0.1	400	600	400	500	700	900	550	550	600	900

Table 29 Minimum Dynamic Modulus Criteria for 7% Air Void Level Mixture at -5 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
-5	25	19000	21000	17000	20500	21000	22000	17000	17000	22500	22500
-5	10	18000	20000	16000	20000	20500	21000	16000	16000	21500	21500
-5	5	16000	19000	14500	18500	20000	20000	14500	15000	20500	20500
-5	1	13000	16000	12000	16000	17000	18000	12000	12000	18500	18500
-5	0.5	12000	15000	11000	15000	16000	17000	11000	11000	16500	17000
-5	0.1	10000	12000	8500	12000	13000	14000	8500	9000	15000	15000

Table 30 Minimum Dynamic Modulus Criteria for 7% Air Void Level Mixture at 4 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
4	25	16000	16000	10500	12000	16000	19000	10500	10500	19500	19500
4	10	14000	14500	9500	11000	14000	17000	9500	10000	18500	18500
4	5	12000	12500	8500	10000	13000	16000	8500	9000	17000	17500
4	1	10000	10500	6500	11500	12500	15500	6500	6500	14500	15000
4	0.5	8000	9000	5500	10500	12000	13500	5500	6000	13000	14000
4	0.1	7000	8000	4000	8500	10000	11000	4000	5000	10500	12000

Table 31 Minimum Dynamic Modulus Criteria for 7% Air Void Level Mixture at 13 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
13	25	10000	12000	6000	8000	12500	13000	7000	7000	14000	14000
13	10	8000	10000	5500	6000	10000	11000	6000	6000	12500	12500
13	5	6500	8500	5000	5500	8500	10000	5000	5000	11000	11000
13	1	5500	6500	4000	6000	7500	8500	4000	4000	9000	9000
13	0.5	4500	6500	3000	5500	6500	7500	3000	3500	7500	8000
13	0.1	3000	4000	2000	4000	4500	6000	1700	2000	5000	6000

Table 32 Minimum Dynamic Modulus Criteria for 7% Air Void Level Mixture at 21.3 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
21.3	25	6500	8000	4000	6500	8500	10000	4000	4000	10000	10500
21.3	10	5500	7000	4000	7000	8000	9500	3000	3000	8000	10000
21.3	5	5000	6500	3500	6000	7000	8000	4000	5000	7000	8500
21.3	1	3000	5000	2000	3500	6000	8000	2000	2500	5000	6500
21.3	0.5	5000	5500	2500	3000	4000	5000	1500	2000	4000	5500
21.3	0.1	1500	3000	1000	1500	2500	4000	1000	1000	2500	3500

Table 33 Minimum Dynamic Modulus Criteria for 7% Air Void Level Mixture at 39.2 °C

Temperature (°C)	Frequency (Hz)	3E10	3E30	4E1	4E3	4E10	4E30	5E1	5E3	5E10	5E30
39.2	25	2000	3500	1500	3000	4000	4500	1600	1600	4000	4500
39.2	10	1500	3000	1000	2200	3000	4000	1250	1250	3050	3500
39.2	5	1000	2000	700	1000	2000	2500	1000	1000	2400	2850
39.2	1	650	1000	600	750	1300	1550	700	800	1400	1800
39.2	0.5	500	800	400	850	1000	1250	600	600	1000	1300
39.2	0.1	400	600	350	600	750	850	450	450	600	850


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Publication: Construction and Building Materials

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Volume number	23
Issue number	11
Pages	8
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Format	Both print and electronic
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Expected publication date	Jan 2010
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