Wisconsin Highway Research Program

Wisconsin Mixture Characterization Using the Asphalt Mixture Performance Tester (AMPT) on Historical Aggregate Structures

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16. Abstract

This research evaluated the stiffness and permanent deformation properties of typical Wisconsin Department of Transportation (WisDOT) asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT) and associated test and analysis procedures. Dynamic modulus master curve and flow number data were collected for 12 different good performing asphalt mixtures representing typical mixture design practice in Wisconsin. The data were analyzed to determine the sensitivity of the AMPT tests to changes in key mixture design factors associated with rutting resistance. A database of dynamic modulus master curve and flow numbers was assembled for use in future mechanistic pavement design related efforts.

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Asphalt Mixture Performance Tester, dynamic modulus, flow number, pavement structural design, asphalt mixture design

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Executive Summary

Project Summary

This research evaluated the stiffness and permanent deformation properties of typical Wisconsin Department of Transportation (WisDOT) asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT) and associated test and analysis procedures. Dynamic modulus master curve and flow number data were collected for 12 different good performing asphalt mixtures representing typical mixture design practice in Wisconsin. The data were analyzed to determine the sensitivity of the AMPT tests to changes in key mixture design factors associated with rutting resistance. A database of dynamic modulus master curve and flow numbers was assembled for use in future mechanistic pavement design related efforts.

Background

The AMPT is a small servo-hydraulic testing device developed specifically for testing asphalt mixtures. The AMPT was developed in National Cooperative Highway Research Program (NCHRP) Project 9-29 to conduct three performance related tests on asphalt concrete that were recommended in NCHRP Project 9-19 to compliment the Superpave volumetric mixture design method. These are dynamic modulus, flow number, and flow time. The dynamic modulus master curves obtained with the AMPT are the primary material property input for asphalt materials in the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG). The MEPDG can be used to predict the amount of rutting and cracking that is expected to occur over the design life of a pavement. The flow number and flow time have been proposed as tests to evaluate the rutting resistance of asphalt mixtures. Criteria for using the flow number test in mixture design were developed in NCHRP Project 9-33. The flow time test was envisioned as an inexpensive alternative to the flow number test; however, interest in the flow time test has faded due to the moderate price of the AMPT.

Process

Dynamic modulus master curve and flow number data were collected for 12 different good performing asphalt mixtures representing typical mixture design practice in Wisconsin. The mixtures represented 4 different sources, two design traffic levels, and two binder grades. The data were analyzed to determine the sensitivity of the AMPT tests to the following key mixture design factors:

- Design traffic level,
- Aggregate angularity,
- Design voids in the mineral aggregate (VMA), and
- Binder grade

The data analysis included statistical analysis of the measured data, comparison of the measured data to available criteria and predictive models, and predictions of pavement rutting using a spreadsheet version of the MEPDG rutting model.

Findings and Conclusions

For a specific aggregate source, the dynamic modulus was generally found to be insensitive to the key mixture design factors, except at the highest test temperatures, where aggregate source was significant. For a traffic level of 10 million equivalent single axle loads (ESAL), the predicted rutting was low and approximately the same for all mixtures for design traffic speeds of 40 and 20 mph. For a design traffic speed of 1 mph, the predicted rutting was higher, but still relatively insensitive to the mixture design traffic level and binder grade. The predicted rutting at 1 mph was affected most by the aggregate source.

Comparisons of measured dynamic moduli with values predicted from mixture composition using available models, showed the Hirsch model provides a reasonable estimate of the dynamic modulus, while the latest version of the Witczak dynamic modulus equation consistently overestimates the dynamic modulus. Both of these models require master curves of binder properties over the range of temperatures and loading rates used in the predictions. An older version of the Witczak dynamic modulus equation that can be used with typical viscosity-temperature susceptibility parameters provides somewhat poorer estimates of the dynamic modulus than the Hirsch model, but does not require binder properties to be measured.

The flow number was found to be sensitive to all of the key mixture design factors. The flow number was found to increase with increasing binder grade, increasing aggregate angularity, and decreasing design VMA. Binder grade had the most significant effect on the flow number. Comparison of the measured flow numbers to the mixture design criteria developed in NCHRP Project 9-33 indicate the NCHRP Project 9-33 criteria are conservative based on the reported field performance of the mixtures tested. Allowable traffic from a rutting model developed in NCHRP Projects 9-25 and 9-31 agreed more closely with the reported performance of the mixtures. This rutting model and the measured flow numbers were used to develop revised flow number criteria for mixture design.

Recommendations

The AMPT equipment and associated testing and analysis procedures provide the capability to rapidly evaluate properties of asphalt mixtures associated with pavement structural design and rutting performance. WisDOT should continue with the planned purchase of this equipment and the collection of data for additional Wisconsin mixtures.

The dynamic modulus master curves developed in this study can be used to further evaluate the MEPDG. Dynamic modulus values for other mixtures can be estimated from mixture composition using the Hirsch model, provided a representative binder modulus master curve is available. If a binder modulus master curve is not available, the Witczak dynamic modulus equation with typical viscosity-temperature susceptibility parameters may be used to estimate dynamic modulus values.

The NCHRP 9-33 criteria for rutting resistance using the flow number test appear to be conservative based on the reported field performance of the mixtures tested. Revised criteria were developed in this project that better represent the field performance of the mixtures tested. Flow number tests should be conducted on additional mixtures with known performance to validate the revised criteria.

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- Ms. Judie Ryan, Mr. Erv Dukatz and the other members of the Technical Oversight Committee for their assistance in finalizing the matrix of aggregate sources, mixtures, and binders to be included in the project, and their review and oversight of the work presented in this report.
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- Mathy Construction Company and Northeast Asphalt, Inc. for providing the aggregate samples and designing the mixtures used in the project.
- Mathy Technology and Engineering Services, Inc. for providing the asphalt binder samples used in the project.

Table of Contents

Table of Figures

Table of Tables

Chapter 1 Introduction and Research Approach

1.1 Background

1.1.1 Asphalt Mixture Performance Tester

The Asphalt Mixture Performance Tester (AMPT) is a small servo-hydraulic testing device developed specifically for testing asphalt concrete mixtures. Figure 1 is a photograph of the AMPT. The AMPT was originally called the Simple Performance Test System when it was developed in National Cooperative Highway Research Program (NCHRP) Project 9-29. The Federal Highway Administration (FHWA) changed the name of the device to the AMPT when it took over implementation efforts for the equipment in 2008.

Figure 1. Photograph of the IPC Global Asphalt Mixture Performance Tester.

The AMPT was developed to conduct three performance related tests on asphalt concrete that were recommended in NCHRP Project 9-19 to compliment the Superpave volumetric mixture design method. These are dynamic modulus, flow number, and flow time. Data from all three tests were shown to correlate well with observed rutting in field pavements (*1*). The dynamic modulus is also the primary material input for asphalt concrete layer characterization in the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic Empirical Pavement Design Guide (MEPDG). Thus, the AMPT can be used to obtain performance related properties of asphalt concrete for both mixture design and pavement structural design.

Substantial development and testing work for the AMPT was completed in NCHRP Project 9-29. (*2,3,4*). This included the development of a detailed equipment specification, the evaluation of three first article devices, ruggedness testing for the dynamic modulus and flow number tests, and the preparation of three draft AASHTO standards for (1) specimen fabrication, (2) testing, and (3) data analysis. There are currently three manufacturers of the AMPT: Interlaken Technology Corporation, IPC Global, Ltd, and Medical Device Testing Services, Inc. Approximately 25 units have been sold to highway agencies, research centers, and asphalt mixture producers in the United States.

1.1.2 AMPT Tests and Criteria

Although the AMPT is capable of performing three performance related tests, only the dynamic modulus and flow number tests have been applied in pavement design and asphalt concrete mixture analysis. The flow time test was envisioned as an inexpensive alternative to the flow number test; however, interest in the flow time test has faded due to the moderate price of the AMPT.

1.1.2.1 Dynamic Modulus Test

In the dynamic modulus test, an asphalt concrete specimen at a specified temperature is subjected to continuous sinusoidal, stress-controlled loading. Both the applied stress and the resulting strain are recorded with time as shown schematically in Figure 2. The dynamic modulus is defined as the peak stress divided by the peak strain. It is the overall stiffness of the asphalt concrete mixture at a particular test temperature and loading frequency.

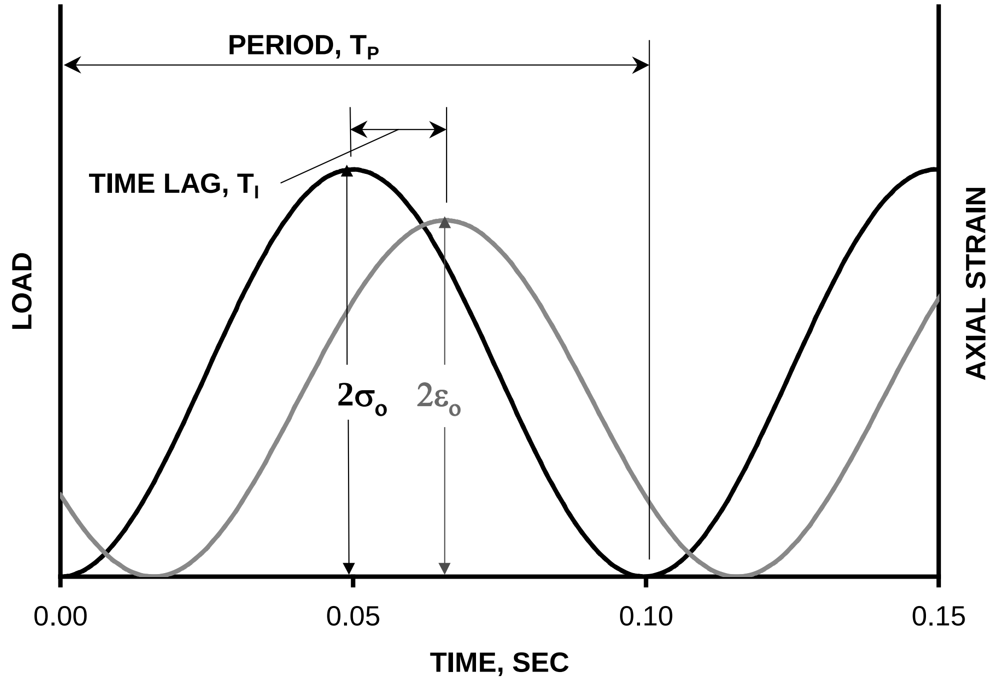

Figure 2. Schematic of Stresses and Strains in the Dynamic Modulus Test.

Dynamic Modulus in Pavement Design

In the MEPDG stresses and strains in the pavement are computed using layered elastic theory. The dynamic modulus of asphalt concrete layers is the material property for use in this analysis. Dynamic moduli for different temperatures and frequencies of loading can be combined using the principle of time-temperature superposition to form a master curve. A typical dynamic modulus master curve obtained from shifting of test data is shown in Figure 3. As part of NCHRP Project 9-29 a practical procedure for developing dynamic modulus master curves for use in structural design was developed (*3*). This procedure involves testing duplicate specimens at three temperatures and four loading rates. The data are then fit to Equation 1 to determine the master curve parameters. The fitting is easily done using the Solver function within Mircrosoft Excel™. A spreadsheet was developed to perform the fitting as part of NCHRP 9-29.

$$\log\left|E^*\right| = \log(Min) + \frac{\left[\log(Max) - \log(Min)\right]}{1 + e^{\beta + \gamma\left[\log\omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right]}} \tag{1}$$

where:

$|E^*|$ = dynamic modulus

ω = applied frequency, Hz

Max = maximum modulus

Min = minimum modulus

β, and γ = fitting parameters

T_r = reference temperature, °K

T = test temperature, °K

ΔE_a = activation energy

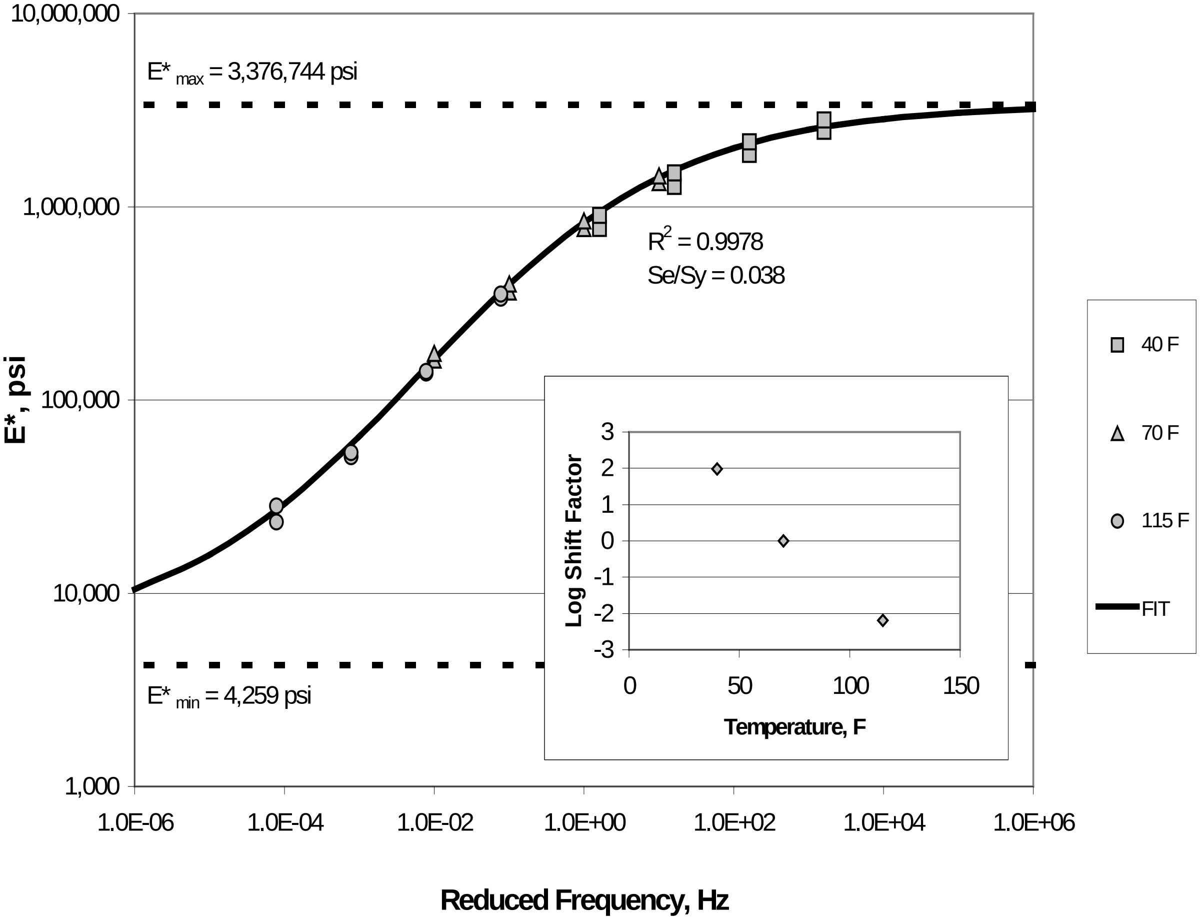

Figure 3. Example Dynamic Modulus Master Curve (*3*).

Dynamic Modulus as a Performance Test

In research conducted in NCHRP Project 9-19, dynamic modulus data at high temperatures correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility *(1)*. Figure 4 shows an example of the relationship between rutting and dynamic modulus obtained in NCHRP Project 9-19 for the FHWA Pavement Testing Facility sections. The rutting resistance of the mixtures increased as the dynamic modulus at high temperatures increased.

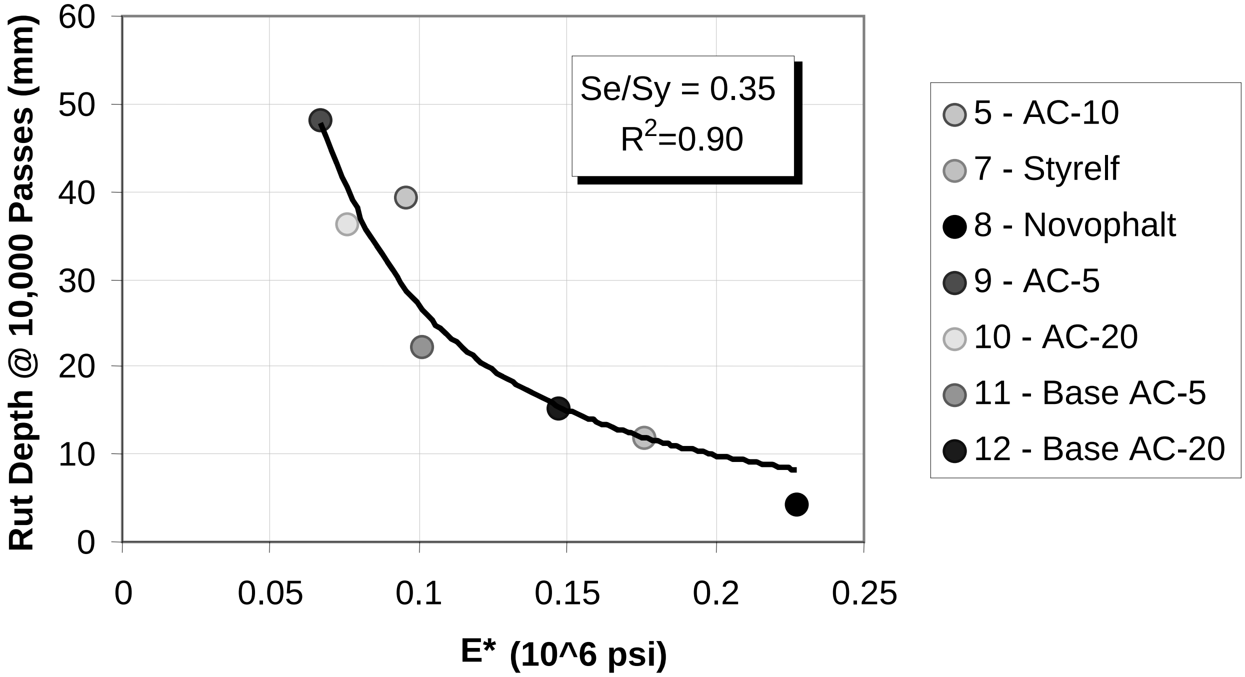

Figure 4. Relationship Between Dynamic Modulus and Rutting for the FHWA Pavement Testing Facility Sections *(1)*.

Recently as part of NCHRP Project 9-19 and NCHRP Project 9-22, researchers at the Arizona State University developed criteria for using the dynamic modulus test to assess rutting resistance (*5*). The criteria are in the form of a Microsoft Excel™ workbook that interpolates a database of predicted rut depths obtained from many runs of the MEPDG. Users have the flexibility to consider up to three asphalt concrete layers and to enter dynamic modulus master curves for each layer. Other inputs include climatic data, traffic volume, and traffic speed. The workbook returns estimated rutting in each of the asphalt concrete layers that are specified.

1.1.2.2 Flow Number Test

In the flow number test, a test specimen, at a specific test temperature, is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured for each load cycle and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent strain. Figure 5 shows example data from the flow number test.

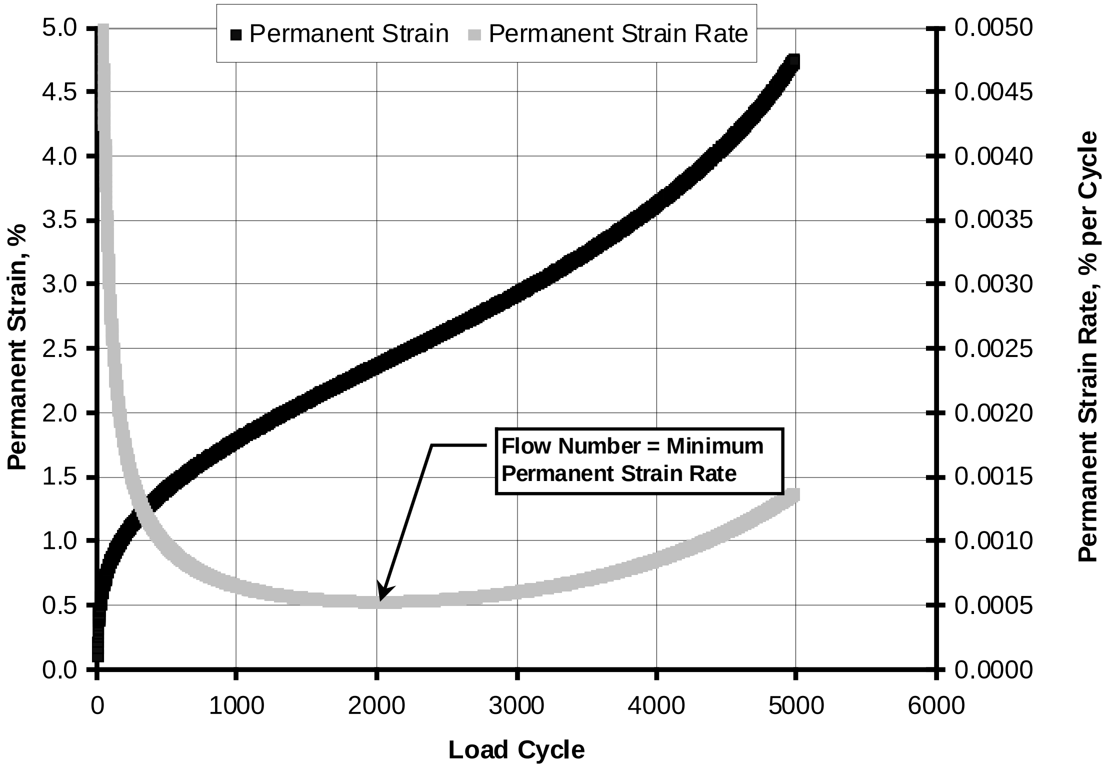

Figure 5. Example Flow Number Test Data.

In research conducted in NCHRP Project 9-19, flow number data at high temperatures correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility *(1)*. Figure 6 shows an example of the relationship between rutting and flow number obtained in the Project 9-19 research for the FHWA Pavement Testing Facility sections. Recently, tentative criteria for the flow number test have been developed in NCHRP Project 9-33. The criteria are shown in Table 1. These are based on flow number test data collected by the FHWA on several field projects and a relationship between mixture volumetric properties and rutting resistance developed in NCHRP Projects 9-25 and 9-31 (*6*). The test is conducted at the 50 percent reliability performance grade temperature obtained from LTPPBind 3.1 at a depth of 20 mm without traffic volume or speed adjustments. The air void content of the specimens is 7.0 ±0.5 percent, and the flow number test is conducted without confinement using an axial stress of 600 kPa. The criteria given in Table 1 are for an average rut depth of 7 mm which corresponds to 95 percent reliability that the rut depth will be less than 12 mm.

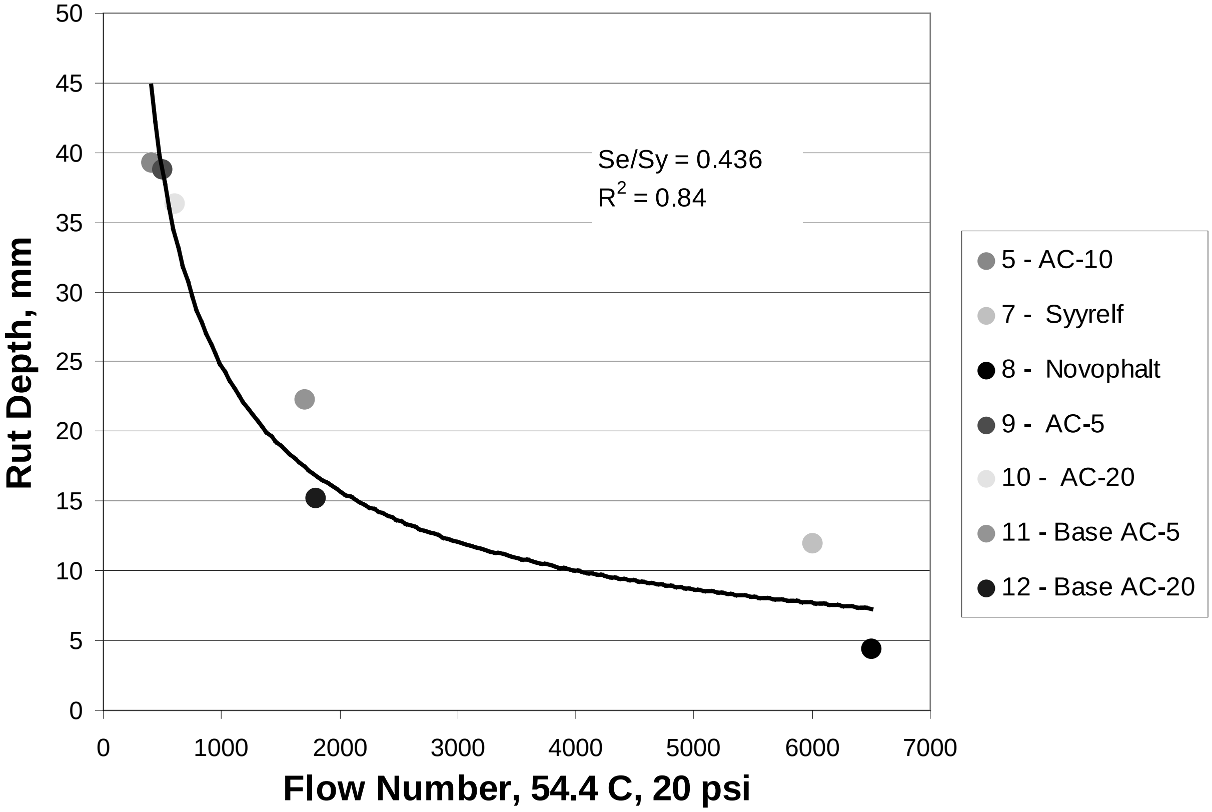

Figure 6. Relationship Between Flow Number and Rutting for the FHWA Pavement Testing Facility Sections *(1)*.

Table 1. Recommended Minimum Flow Number Requirements (*6*).

Traffic Level *Million ESALs*	**Minimum Flow Number** *Cycles*
< 3	---
3 to < 10	53
10 to < 30	190
≥ 30	740

1.1.3 Summary

Substantial effort has been expended in several NCHRP Projects to develop and implement the AMPT. User friendly equipment was developed in NCHRP Project 9-29, and is currently available from three vendors. Dynamic modulus master curves for use with the MEPDG can be generated with the AMPT. Criteria for rutting resistance have been developed for the dynamic modulus test and the flow number test.

1.2 Problem Statement and Objectives

This project addressed an important step in the implementation of mechanistic approaches for pavement structural design and asphalt concrete mixture design by the Wisconsin Department of Transportation (WisDOT). Both the MEPDG and the updated mixture design procedure being assembled in NCHRP Project 9-33 use engineering and performance properties obtained from the AMPT. Information on these properties for mixtures that have been historically used in Wisconsin are needed as WisDOT considers the implementation of new mechanistic pavement and asphalt concrete mixture design methods.

The objectives of this research project were to collect dynamic modulus and flow number data on mixtures currently used by the WisDOT and to compare these properties to the performance of pavements built with similar mixtures. The project and the resulting database of dynamic modulus and flow number properties will serve several purposes including:

- Provide typical dynamic modulus and flow number properties for mixtures used by WisDOT classified by design traffic level, binder grade, and aggregate source.

- Local validation of criteria for rutting resistance developed in major national research efforts.
- Input data for evaluation and initial use of the MEPDG.
- Training of WisDOT staff in the use of AMPT for pavement and asphalt concrete mixture design and evaluation.

1.3 Research Approach

The approach taken in this project was straightforward. In consultation with the Technical Oversight Committee, four aggregate sources that are currently used in Wisconsin were selected. The sources that were selected were Cisler, Christian/Gade, Glenmore, and Wimmie. For each source, approved WisDOT mixture designs for traffic levels E-3 and E-10 were obtained. Laboratory mixtures were prepared using a neat PG 58-28 binder in both the E-3 and E-10 mixtures and a modified PG 70-28 binder in the E-10 mixtures. A total of 12 mixtures were characterized. Table 2 presents a summary of the mixtures that were tested. Detailed information about the mixtures and binders is presented in Chapter 2.

Table 2. Summary of Mixtures Tested.

Source	Nominal Maximum Aggregate Size, mm	E-3 PG 58-28	E-10 PG 58-28	E-10 PG 70-28
Cisler	12.5	**X**	**X**	**X**
Christian/Gade	12.5	**X**	**X**	**X**
Glenmore	19.0	**X**	**X**	**X**
Wimmie	12.5	**X**	**X**	**X**

Dynamic modulus master curves and flow number tests were conducted on each of the 12 mixtures shown in Table 2. Specimens for these tests were prepared to a target air void content of 7.0 ± 0.5 to represent expected in-place air void contents. The specimens were prepared in accordance with AASHTO PP60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)*. The dynamic modulus testing was conducted on duplicate specimens in accordance with AASHTO PP61, *Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Using the Asphalt Mixture Performance Tester (AMPT)* and AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt*

(HMA) Using the Asphalt Mixture Performance Tester (AMPT). The flow number testing was conducted at a temperature of 49.6 °C, which is the 50 percent reliability performance grade temperature at a depth of 20 mm for Madison, Wisconsin obtained from LTPPBind 3.1. Flow number tests were conducted in accordance with AASHTO TP 79 using two stress conditions: (1) unconfined using an axial stress of 600 kPa, and (2) confined using a confining stress of 69 kPa and a deviatoric stress of 483 kPa. The unconfined tests correspond to the stress conditions recommended in NCHRP 9-33 for the criteria given in Table 1. The confined tests use the stress conditions recommended in NCHRP 9-30A for the development of an improved rutting model for the MEPDG (*7*).

Chapter 2 Mixtures and Binders

2.1 Mixtures

The mixtures used in this study were approved WisDOT designs for traffic levels E-3 and E-10. The mixtures were selected by the Technical Oversight Committee and represent aggregate sources that are used extensively in Wisconsin and have good rutting performance. Table 3 summarizes data from the WsiDOT pavement management database for representative roadway segments where three of the mixtures have been used. As shown in Table 3, the average rut depth for the mixtures shown was only 0.11 in after 3 to 5 years of service.   The estimated accumulated ESAL's in Table 3 were obtained from the reported annual average daily truck traffic using a truck factor of 0.9 as recommended in Chapter 14 of the WisDOT Facilities Development Manual. Similar performance was reported for the other mixtures used in the project.

Table 3. Summary of Rutting Performance From the WisDOT Pavement Management Database.

Source	Mix	Year Constructed	Route	Age, yrs	Number of Segments Included	Average Estimated Accumulated ESAL	Average Rut Depth, in
Cisler	E 10	2004	State Highway 13	3	3	424,928	0.14
Christian/Gade	E 3	2002	State Highway 28	5	6	328,089	0.08
Wimmie	E 3	2005	State Highway 54	3	9	302,193	0.11

Tables 4 and 5 present pertinent properties at the design binder content for the E-3 and E-10 mixtures, respectively. Complete WisDOT mixture design reports are included in Appendix A. Figures 7 to 17 compare selected design properties for the eight mixtures.

Table 4. Summary of E-3 Mixture Design Properties.

Property		Cisler	Christian/ Gade	Glenmore	Wimmie
		12.5 mm	12.5 mm	19 mm	12.5 mm
Gradation, % passing	Sieve size, mm	WisDOT Mix ID 250-0056 2005	WisDOT Mix ID 250-0053 2002	WisDOT Mix ID 250-0096 2003	WisDOT Mix ID 250-0048 2005
	25	100.0	100.0	100.0	100.0
	19	100.0	100.0	100.0	100.0
	12.5	95.5	95.7	89.9	94.5
	9.5	84.7	86.0	76.9	83.0
	4.75	63.2	63.8	62.9	63.2
	2.36	46.9	48.4	45.0	47.0
	1.18	35.9	36.0	32.6	35.4
	0.6	26.0	24.7	23.8	23.3
	0.3	13.3	11.7	13.5	11.9
	0.15	5.9	5.4	5.6	6.4
	0.075	4.1	3.5	3.3	3.8
Binder content, wt %		4.9	5.2	4.5	4.8
Design Air Voids, vol %		4.0	4.0	4.0	4.0
Design VMA, vol %		14.3	14.6	13.5	14.6
Design VFA, vol %		72	72.5	70.3	72.6
Maximum Specific Gravity		2.487	2.565	2.592	2.536
Aggregate Bulk Specific Gravity		2.650	2.733	2.747	2.713
Effective binder content, vol %		10.3	10.6	9.5	10.6
Dust/Binder Ratio		0.9	0.9	1.0	1.0
Design Gyrations		75	75	75	75
% Gmm at N_{ini}		89.7	89.0	89.6	89.6
% Gmm at N_{max}		96.9	96.5	96.7	96.8
Tensile Strength Ratio		80.3	87.8	73.9	91.5
Average Gyrations to 7 % Air Voids		20	21	22	NR
Fractured Faces, 1 face, wt %		92.9	95.2	100.0	94.2
Fractured Faces, 2 faces, wt %		92.6	94.2	100.0	92.7
Sand Equivalent, %		83.0	NR	80.0	84.0
Flat and Elongated, wt %		2.2	0.5	0.8	3.0
Fine Aggregate Angularity, %		43.5	43.3	45.7	43.8

Table 5. Summary of E-10 Mixture Design Properties.

Property		Cisler	Christian/ Gade	Glenmore	Wimmie
		12.5 mm	12.5 mm	19 mm	12.5 mm
Gradation, % passing	Sieve size, mm	WisDOT Mix ID 250-0186 2004	WisDOT Mix ID 250-0061 2002	WisDOT Mix ID 250-0055 2004	WisDOT Mix ID 250-0047 2005
	25	100.0	100.0	100.0	100.0
	19	100.0	100.0	99.9	100.0
	12.5	95.1	96.8	89.2	94.8
	9.5	83.3	88.8	76.9	84.3
	4.75	64.7	68.6	58.7	66.7
	2.36	46.3	49.2	41.4	47.7
	1.18	32.4	34.8	29.5	34.2
	0.6	22.7	23.0	21.1	21.9
	0.3	11.2	11.5	11.7	12.8
	0.15	5.6	5.5	4.6	7.1
	0.075	3.7	3.3	2.6	4.1
Binder content, wt %		5.6	5.5	4.4	5.0
Design Air Voids, vol %		4.0	4.0	4.0	4.0
Design VMA, vol %		15.8	15.4	13.2	15.1
Design VFA, vol %		74.7	73.8	69.7	73.5
Maximum Specific Gravity		2.476	2.552	2.595	2.534
Aggregate Bulk Specific Gravity		2.665	2.736	2.745	2.721
Effective binder content, vol %		11.8	11.4	9.2	11.1
Dust/Binder Ratio		0.7	0.7	0.8	0.9
Design Gyrations		100	100	100	100
% Gmm at N_{ini}		88.5	87.9	88.7	88.5
% Gmm at N_{max}		96.9	96.8	96.5	97.2
Tensile Strength Ratio		84.5	78.8	80.7	91.8
Average Gyrations to 7 % Air Voids		34	35	29	43
Fractured Faces, 1 face, wt %		98.1	97.0	99.9	93.9
Fractured Faces, 2 faces, wt %		98	94.7	99.9	92.4
Sand Equivalent, %		85.0	79.0	81.0	84.0
Flat and Elongated, wt %		2.1	0.2	0.8	3.2
Fine Aggregate Angularity, %		45.1	44.9	45.8	46.0

Figures 7 and 8 compare the gradation of the E-3 and E-10 mixtures, respectively. These figures show the control points and 0.45 maximum density line for 12.5 mm mixtures. Although the Glenmore mixtures are 19 mm mixtures because they have slightly less than 90 percent passing the 12.5 mm sieve (89.9 and 89.2, for E-3 and E-10, respectively), they have gradations that are very similar to the 12.5 mm mixtures from the other sources. All mixtures classify as fine-graded based on the AASHTO M323 classification system. Figure 9 compares the percent passing the 2.36 mm sieve which is the control sieve for 12.5 mm mixtures. All mixtures, even the 19.0 mm Glenmore mixtures, have more that 39 percent passing the 2.36 mm sieve; therefore, they classify as fine-graded. There are only minor differences in the gradation between the E-3 and E-10 designs for the 12.5 mm mixtures. The gradation for the E-10 Glenmore 19 mm mixture is somewhat coarser than the E-3 gradation. Figure 10 compares the estimated surface area of the aggregates in each of the mixtures. The surface area of the aggregates can be estimated by summing the percent passing the 0.30, 0.15, and 0.075 mm sieves and dividing the result by 5 (*8*). As shown there is little difference in the estimated surface area of the aggregates in the mixtures. Overall the surface area of all of the mixtures is relatively low due to the low percentage of material passing the 0.075 mm sieve.

The major difference in the aggregate properties for the E-3 and E-10 mixtures is the angularity of the aggregates. Figure 11 compares the coarse aggregate fractured faces for each of the mixtures. The coarse aggregate in the Glenmore 19 mm mixtures had 100 percent fractured faces. For the Cisler and Christian/Gade 12.5 mm mixtures, the coarse aggregate fractured faces were higher for the E-10 mixtures compared to the E-3 mixtures. For the Wimmie 12.5 mm mixtures, the coarse aggregate fractured faces were essentially the same. Figure 11 compares the fine aggregate angularity for the eight mixtures. For the 12.5 mm mixtures, the fine aggregate angularity of the E-10 mixtures was significantly higher than that of the E-3 mixtures. The fine aggregate angularity of the Glenmore 19 mm mixtures was essentially the same for the E-3 and E-10 mixtures.

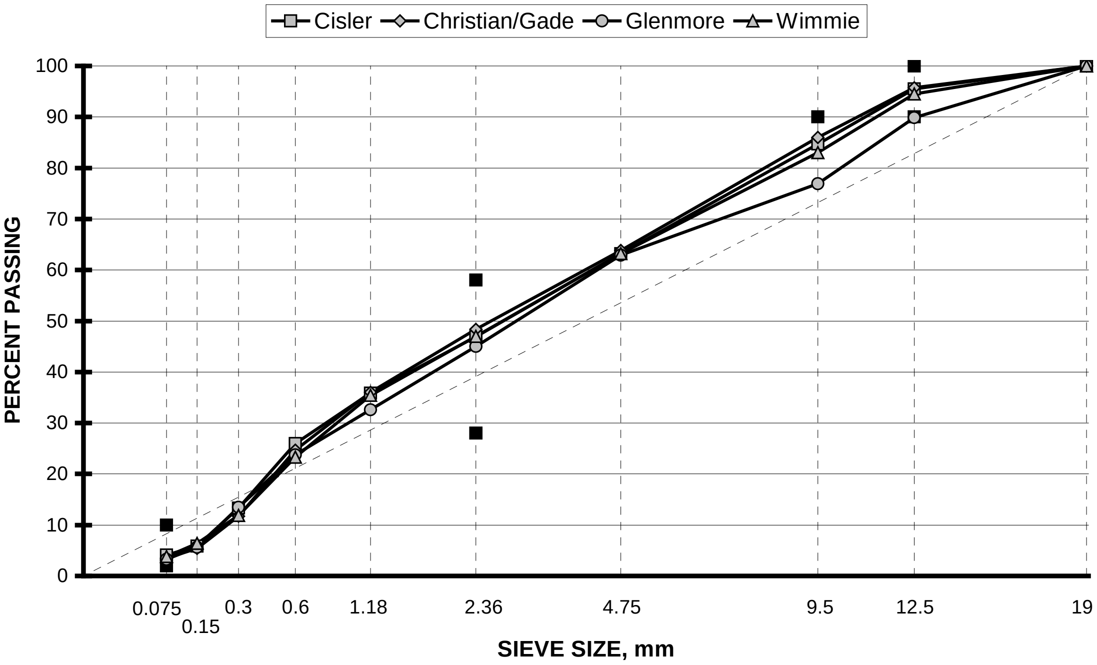

Figure 7. Gradation of E-3 Mixtures.

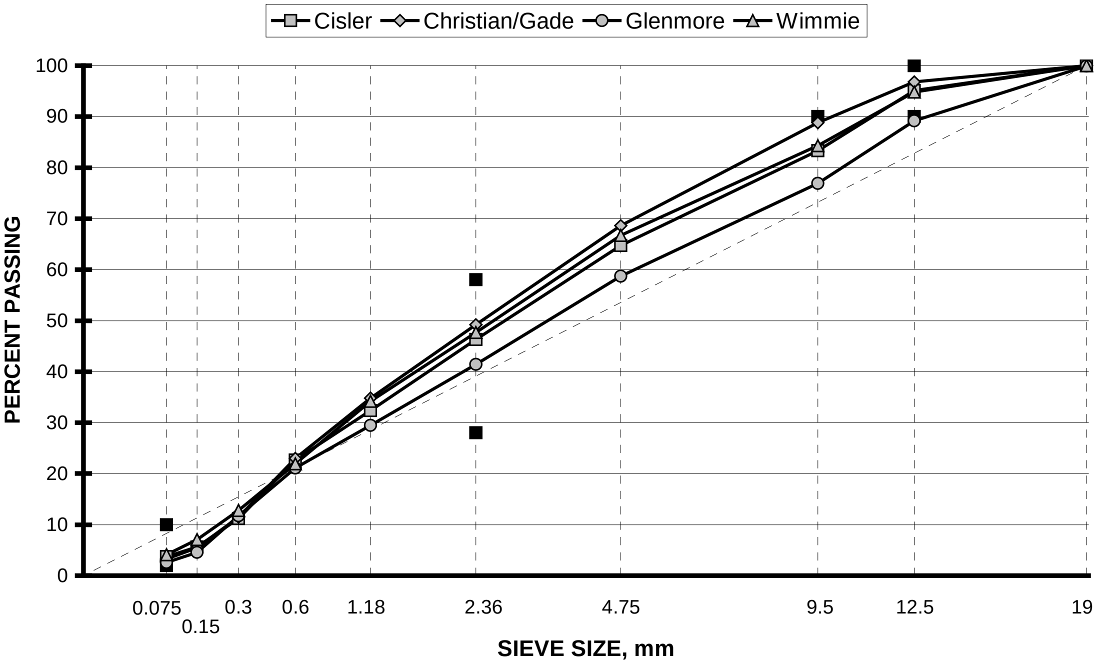

Figure 8. Gradation of E-10 Mixtures.

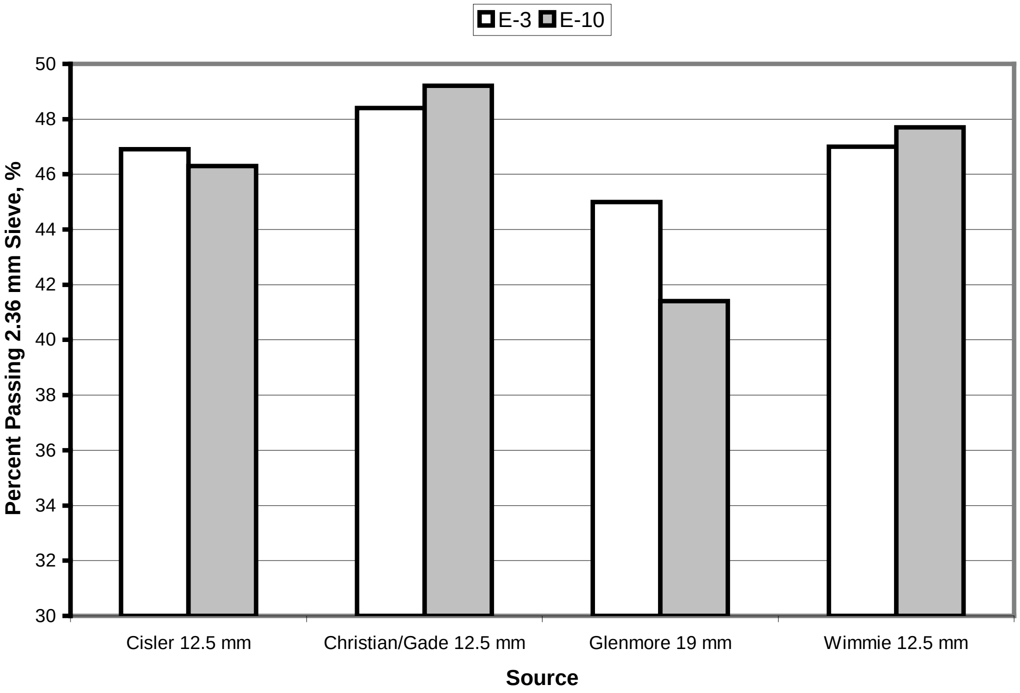

Figure 9. Percent Passing 2.36 mm Sieve (Control Sieve for 12.5 mm Mixtures).

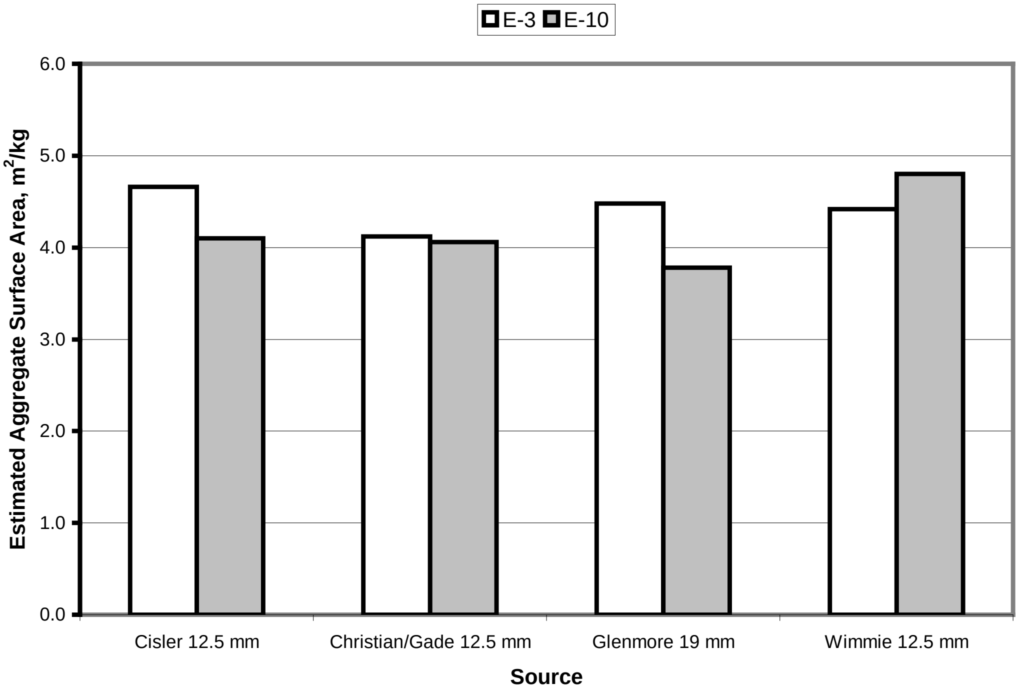

Figure 10. Estimated Aggregate Surface Area.

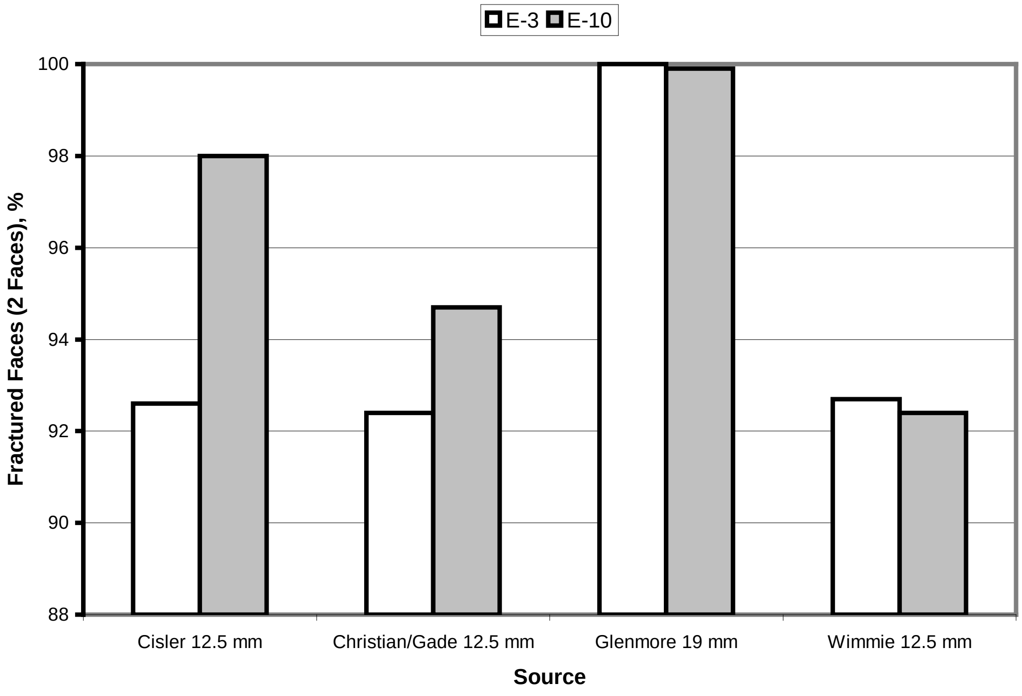

Figure 11. Coarse Aggregate Fractured Faces.

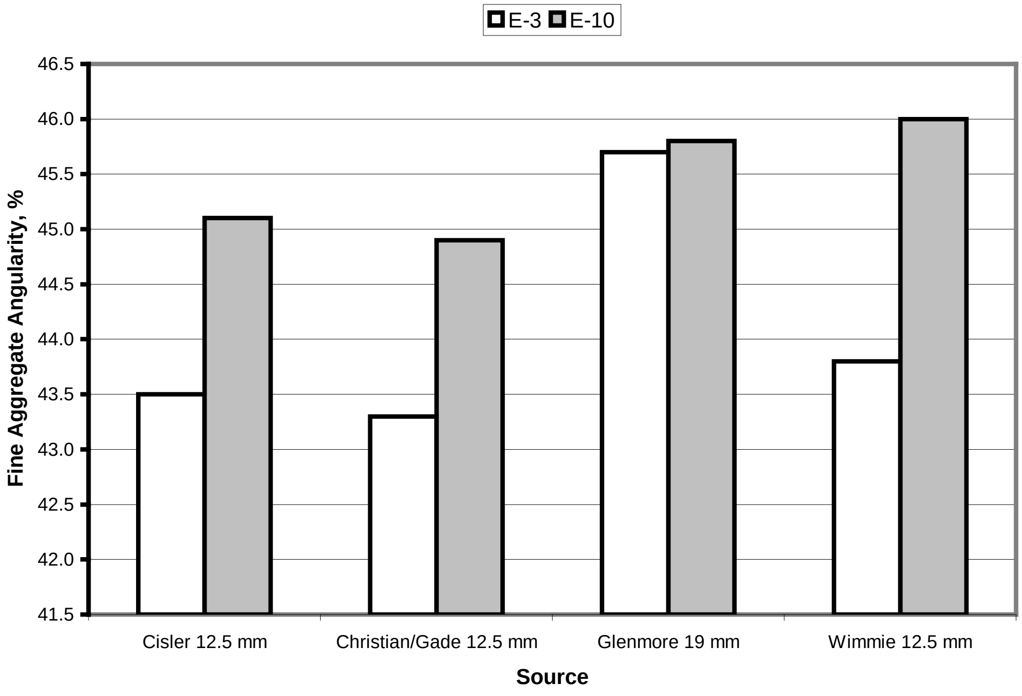

Figure 12. Fine Aggregate Angularity.

Figures 13 through 15 compare selected volumetric properties for the mixtures. Figure 13 compares the design VMA for the mixtures. The design VMA for the Glenmore mixtures is substantially lower than that for the other sources because these mixtures were designed as 19 mm mixtures with a lower minimum design VMA of 13.0 compared to 14.0 for the 12.5 mm mixtures. For the 12.5 mm mixtures where the aggregate angularity increased significantly between the E-3 and E-10 mixtures, the design VMA increased in spite of the increased compactive effort used in the E-10 mixtures. The E-3 mixtures were designed using 75 gyrations while the E-10 mixtures were design using 100 gyrations. This increased design VMA resulted in higher binder contents in the 12.5 mm E-10 mixtures. Figure 14 shows the effective volumetric binder content of the mixtures, which is equal to the VMA minus the design air voids. The design air voids for all mixtures was 4.0 percent. The minimum effective volumetric binder content is 10.0 percent for 12.5 mm mixtures and 9.0 percent for 19 mm mixtures. Figure 15 compares the design binder content for the mixtures.

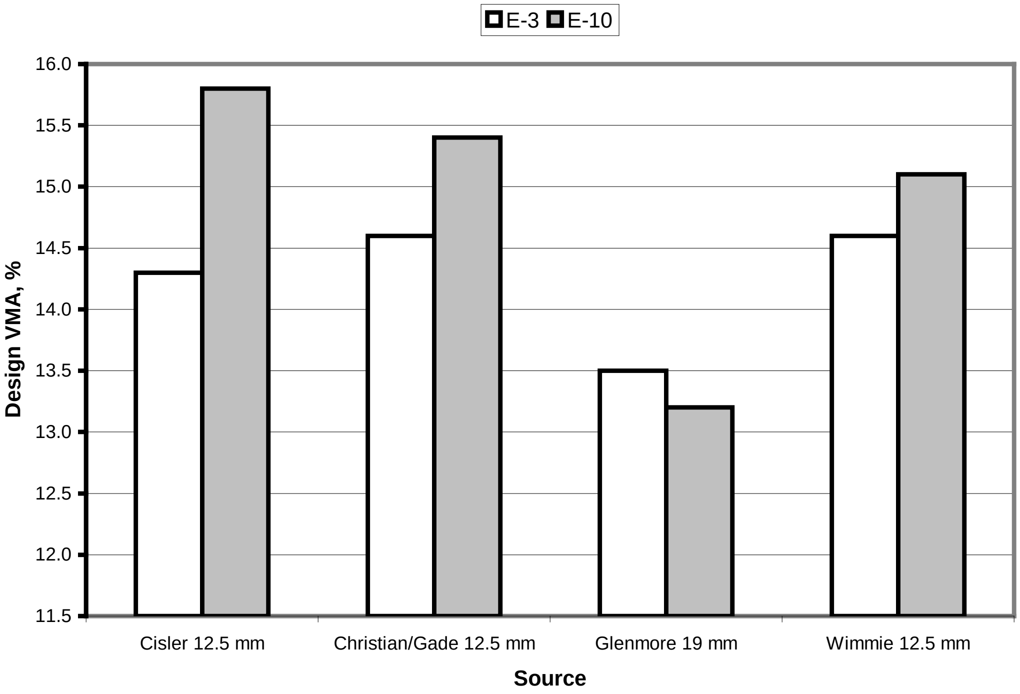

Figure 13. Design VMA.

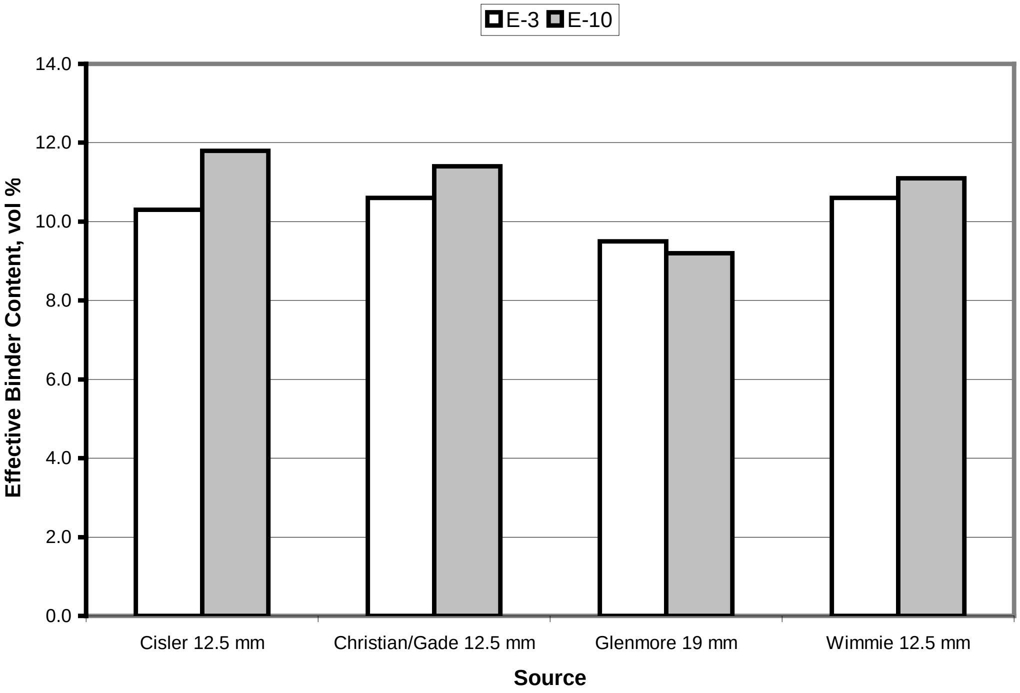

Figure 14. Effective Volumetric Binder Content.

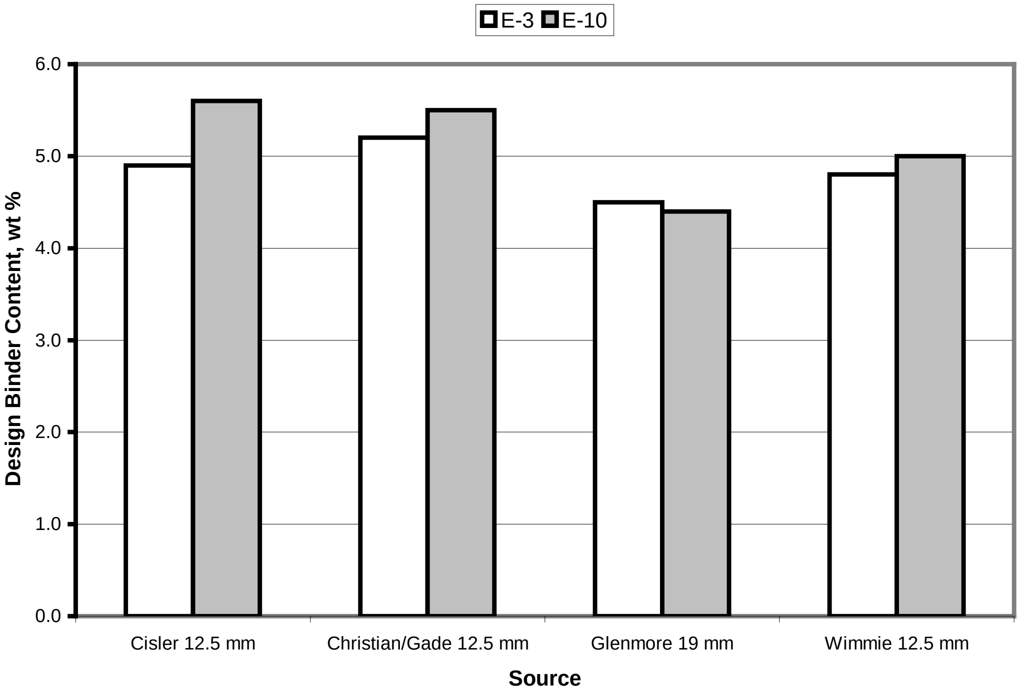

Figure 15. Design Binder Content.

Figures 16 and 17 compare the compactability of the mixtures. Figure 16 compares the density at $N_{initial}$. The E-10 mixtures have lower density at $N_{initial}$ indicating that these mixtures are more difficult to compact. Recently researchers at the National Center for Asphalt Technology (NCAT) have suggested that the number of gyrations to reach 8 percent air voids may be a reasonable indicator of the compactability of mixtures (*9*). The average number of gyrations required to prepare specimens for moisture sensitivity testing is reported in WisDOT mixture designs. The target air voids for moisture sensitivity testing is 7.0 percent. Figure 17 compares the average number of gyrations to reach the target air voids for the mixtures. The E-10 mixtures require greater compactive effort to reach the target air voids, indicating again that these mixtures are more difficult to compact compared to the E-3 mixtures. All of the gyration levels are within the range of typical values reported by NCAT for a variety of mixtures.

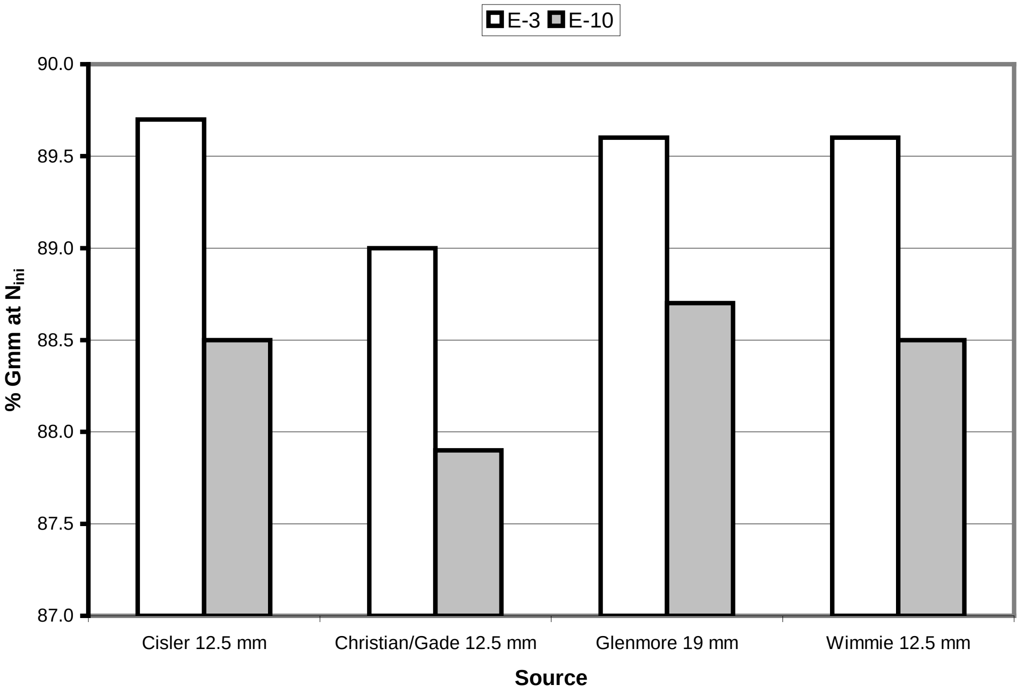

Figure 16. Density at $N_{initial}$.

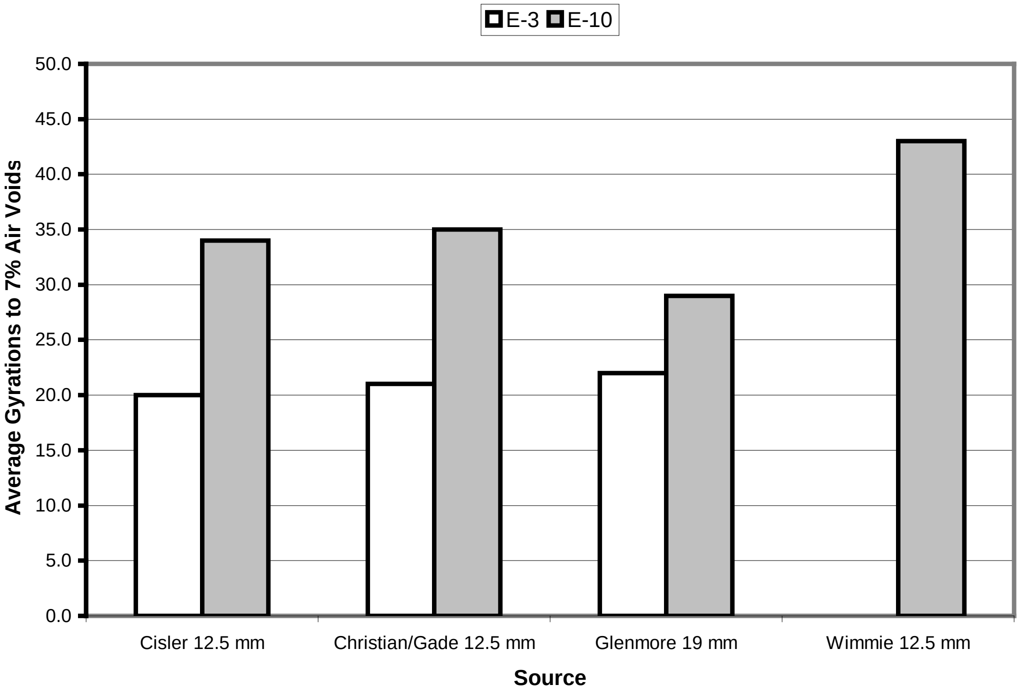

Figure 17. Gyrations to Reach 7 % Air Voids.

2.2 Binders

Two binders, a neat PG 58-28 and a modified PG 70-28, were used in the study. Both binders were provided by Mathy Technology and Engineering Services, Inc. Table 6 presents performance grading properties for the two binders. The continuous grading data show that the PG 70-28 has improved intermediate properties compared to PG 58-28, indicating this binder has lower stiffness at intermediate to low temperatures.

Performance grading provides a snapshot of the rheology the binder at high, intermediate, and low pavement temperatures. To completely characterize the flow characteristics of the binders, master curves were constructed for the Rolling Thin Film Oven Test (RTFOT) conditioned binders. RTFOT binder properties are used in various models for predicting the dynamic modulus and rutting resistance of mixtures. These models are discussed in detail in Chapters 3 and 4.

Table 6. Binder Performance Grading Properties.

Condition	**Test**	**Temp, °C**	**PG 58-28**	**PG 70-28**
Tank	G*/sinδ, kPa AASHTO T 315	58	1.48	
		64	0.73	
		70		1.53
		76		0.97
Rolling Thin Film Residue	G*/sinδ, kPa AASHTO T 315	58	3.92	
		64	1.85	
		70		2.29
		76		1.45
Pressure Aging Vessel Residue	G*sinδ, kPa AASHTO T 315	13		6512
		16		4533
		19	5680	
		22	3802	
	Creep Stiffness (MPa) / m AASHTO T 313	-24	460 / 0.249	491 / 0.245
		-18	212 / 0.343	225 / 0.331
Grade	AASHTO M320	NA	PG 58-28	PG 70-28
Continuous Grade	NA	NA	61.2 (17.0) –30.5	70.5 (15.2) –30.0

Binder master curves require dynamic shear rheometer and bending beam rheometer testing at multiple temperatures. The dynamic shear rheometer testing was conducted in accordance with AASHTO T315, *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer* at the frequencies and temperatures listed in Table 7. The bending beam rheometer testing was conducted in accordance with AASHTO T313, *Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer*. Creep stiffness data was collected with the bending beam rheometer at the loading times and temperatures listed in Table 7. The combined dynamic shear rheometer and bending beam rheometer testing program provided 120 measurements of the stiffness of the binder for construction of master curves. The binder master curve data are presented in Appendix B.

Table 7. Conditions Used in the Master Curve Testing.

Dynamic Shear Rheometer, AASHTO T315	Frequency, rad/sec	0.100, 0.159, 0.251, 0.398, 0.631, 1.000, 1.59, 2.51, 3.98, 6.31, 10.0, 15.9, 25.1, 39.8, 63.1, and 100
	Temperature, °C	10, 22, 34, 46, 58, and 70 (for PG 70 binder only)
Bending Beam Rheometer, AASHTO T313	Time, sec	8, 15, 30, 60, 120, and 240
	Temperature, °C	-12, -18, and –24

Binder master curves were constructed using the Christensen-Anderson model (*10*). Equation 2 presents the Christensen-Andersen model for the frequency dependency of the binder complex shear modulus.

$$G^*(\omega) = G_g \left[1 + \left(\frac{\omega_c}{\omega_r} \right)^{\frac{\log 2}{R}} \right]^{\frac{-R}{\log 2}} \tag{2}$$

where:

G*(ω) = complex shear modulus

G_g = glass modulus assumed equal to 1GPa

ω_r = reduced frequency at the reference temperature, rad/sec

ω_c = cross over frequency at the reference, rad/sec

R = rheological index

The shift factors relative to the defining temperature are given by Equations 3 and 4 for temperatures above and below the defining temperature, respectively.

$$\log a(T) = \frac{-19(T - T_d)}{92 + T - T_d} \tag{3}$$

$$\log a(T) = 13016.07 \left(\frac{1}{\mathrm{T}} - \frac{1}{T_d} \right) \tag{4}$$

where:

$a(T)$ = shift factor
T = temperature, °K
T_d = defining temperature, °K

The three unknown parameters, ω_c, R, and T_d, were obtained through non-linear least squares fitting of Equations 2, 3, and 4 using the data from the testing program summarized in Table 7. The Solver function in Microsoft Excel was used to perform the fitting. The parameter, ω_c, is a function of the reference temperature which was selected to be 20 °C. To construct the complete master curve, the bending beam rheometer creep stiffness data was converted to shear modulus using the following approximate interconversions.

$$G^*(\omega) \approx \frac{S(t)}{3} \tag{5}$$

$$\omega \approx \frac{1}{t} \tag{6}$$

where:

$G^*(\omega)$ = shear complex modulus
$S(t)$ = creep stiffness
ω = frequency in rad/sec
t = time in sec

Figure 18 presents an example fitted master curve and the nomenclature used with the Christensen-Anderson model. The glassy shear modulus for asphalt binders is typically assumed to be equal to 1 GPa. The viscous asymptote is the 45 degree line that the master curve approaches at low frequencies and is an indicator of the steady state viscosity of the binder. The cross-over frequency is the frequency where the phase angle is 45 degrees and is typically close to the point where the viscous asymptote intersects the glassy modulus. The cross-over frequency, ω_c, is an indicator of the hardness of the binder. Finally, the rheological index, R, is the difference between the log of the glassy modulus and the log of the dynamic modulus at the cross-over frequency. It is an indicator of the rheological type.

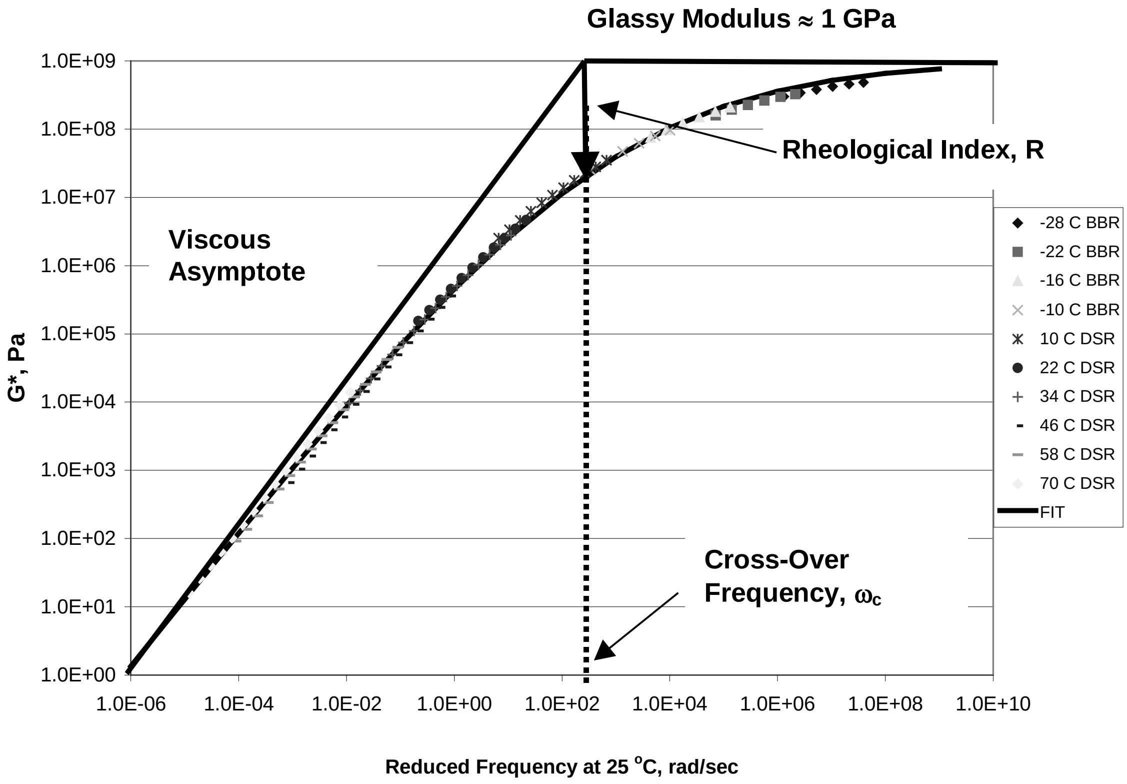

Figure 18. Typical Binder Master Curve With the Christensen Anderson Model Parameters.

In addition to the binder shear modulus, the current version of the Witczak dynamic modulus equation for mixtures requires the binder phase angle (*11*). The binder phase angle can be approximated as being directly proportional to the first derivative of log G* with respect to log ω (*10*). Equation 8 presents the phase angle for the Christensen-Anderson model.

$$\delta = \frac{90}{\left[1 + \left(\frac{\omega_r}{\omega_c}\right)^{\frac{\log 2}{R}}\right]} \qquad (8)$$

where:

ω_r = reduced frequency at the reference temperature, rad/sec

ω_c = cross over frequency at the reference, rad/sec
R = rheological index

The parameters of the master curves for the two binders are summarized in Table 8 for a reference temperature of 20 °C for ω_c. Using these parameters and Equations 2 through 4, and Equation 8 estimates of binder shear modulus and phase angle can be made at any combination of temperature and loading rate. Figure 19 compares the binder shear modulus and phase angle master curves. At temperatures below about 20 °C, corresponding to reduced frequencies around 1.0 rad/sec, the modified PG 70-28 binder has lower stiffness than the neat PG 58-28 binder. At higher temperatures, the PG 70-28 binder has higher stiffness than the neat PG 58-28 binder. The binders have similar shift factors as shown in Figure 20.

Table 8. Christensen-Anderson Master Curve Parameters for RTFOT Conditioned Binders.

Parameter	PG 58-28	PG 70-28
ω_c, at 25 °C, rad/sec	649.8	30.4
R	1.852	2.554
T_d, °C	-13.7	-11.1

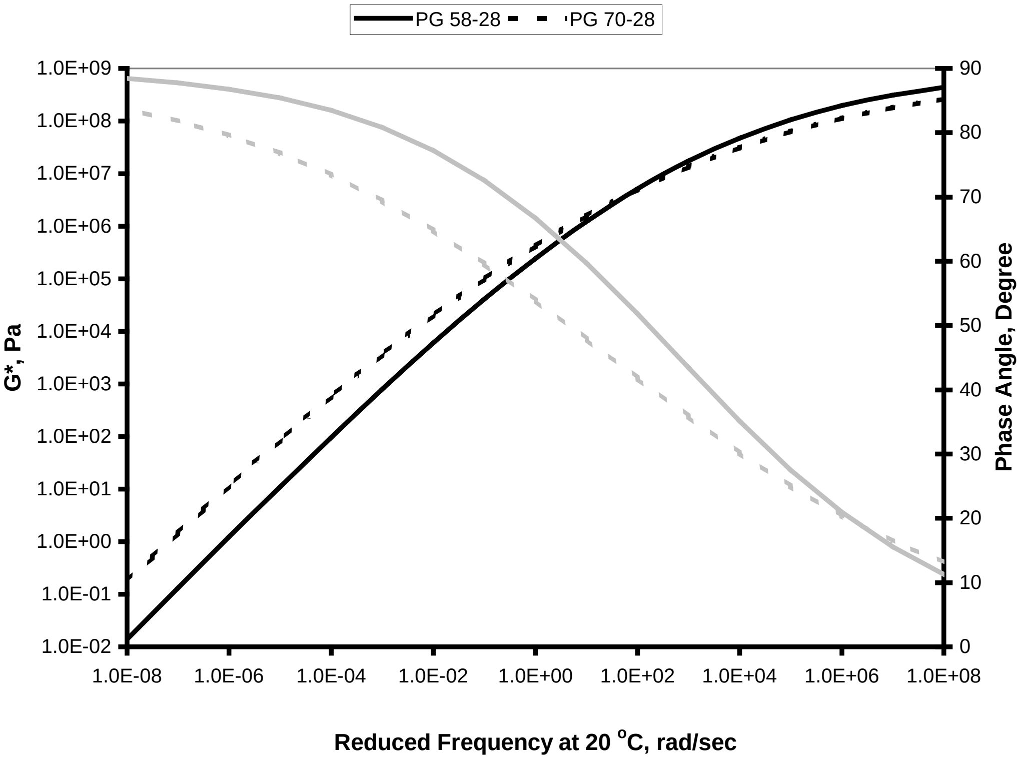

Figure 19. Binder Shear Modulus and Phase Angle Master Curves.

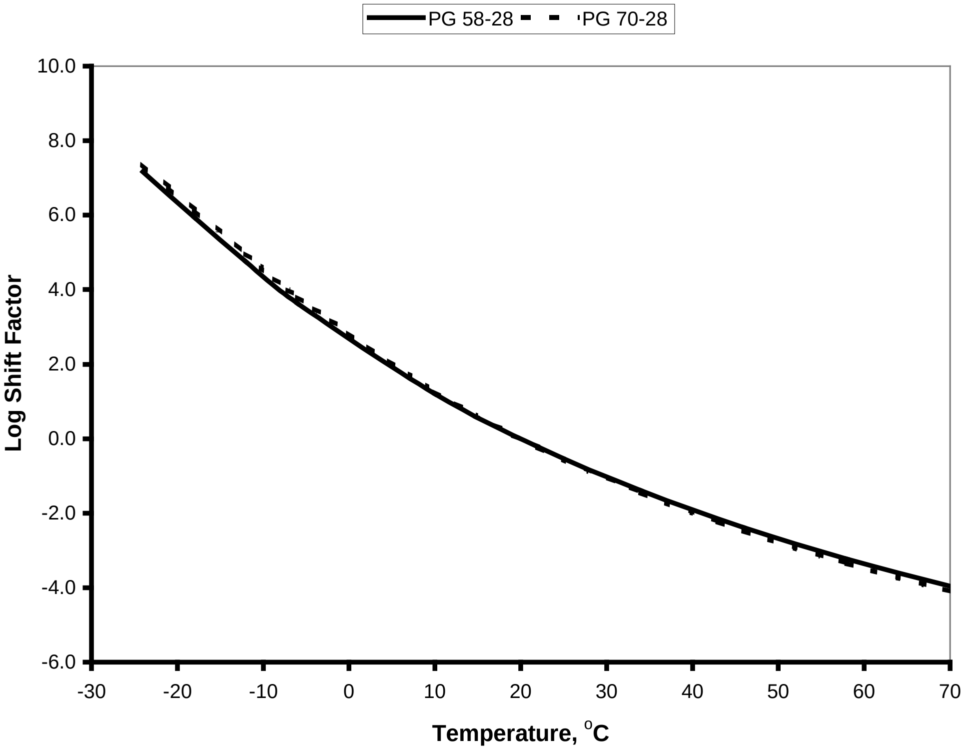

Figure 20. Binder Time-Temperature Shift Factors.

Chapter 3 Dynamic Modulus

3.1 Master Curves

Dynamic modulus master curves were developed for the PG 58-28 binder in both the E-3 and E-10 mixtures and for PG 70-28 binder in the E-10 mixtures. A total of 12 dynamic modulus master curves were developed. The dynamic modulus master curve testing was conducted with an Interlaken AMPT in accordance with AASHTO PP61 *Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Using the Asphalt Mixture Performance Tester (AMPT)* and AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).* For each mixture, tests on duplicate specimens were conducted at the temperatures and frequencies listed in Table 9. A lower high temperature was used for the PG 58-28 binder to minimize creep of the glued gauge points during testing at high temperatures. For each specimen a total of 9 dynamic modulus tests were conducted for the master curve. The test specimens were prepared to a target air void content of 7.0 percent in accordance with AASHTO PP60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC).* All specimens were short term oven conditioned for 4 hours at 135 °C as specified in AASHTO R30, *Mixture Conditioning of Hot-Mix Asphalt (HMA)*. Appendix C contains the measured dynamic modulus data for each specimen of each mixture.

Table 9. Temperatures and Frequencies Using in the Dynamic Modulus Testing.

Mixtures with PG 58-28 Binder		**Mixtures with PG 70-28 Binder**	
Temperature, °C	Loading Frequency, Hz	Temperature, °C	Loading Frequency, Hz
4	10, 1, 0.1	4	10, 1, 0.1
20	10, 1, 0.1	20	10, 1, 0.1
35	10, 1, 0.1, and 0.01	40	10, 1, 0.1, and 0.01

Dynamic modulus master curves were constructed for each mixture following the procedure presented in AASHTO PP61. First the limiting maximum modulus was estimated from the Hirsch model using the average VMA and VFA for the test specimens and a limiting binder shear modulus of 1 GPa (145,000 psi) (*12*). Equation 9 presents the Hirsch model for a limiting binder modulus of 1 GPa.

$$|E^*|_{\max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+435{,}000\left(\frac{VFA\ xVMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\dfrac{\left(1-\dfrac{VMA}{100}\right)}{4{,}200{,}000}+\dfrac{VMA}{435{,}000(VFA)}\right]} \tag{9}$$

where:

$$P_c = \frac{\left(20+\dfrac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\dfrac{435{,}000(VFA)}{VMA}\right)^{0.58}}$$

$|E^*|_{\max}$ = limiting maximum mixture dynamic modulus, psi

VMA = Voids in mineral aggregates, %

VFA = Voids filled with asphalt, %

Then, using the estimated limiting maximum modulus and a reference temperature of 20 °C, the dynamic modulus master curve equation given as Equation 10 was fit to the average measured data at each temperature and frequency combination using numerical optimization. Equation 10 has the same form as the dynamic modulus master curve equation used in the MEPDG (*13*), which is given in Equation 11, but uses shift factors from an Arrhenius equation rather than shift factors based on the binder viscosity-temperature susceptibility parameters. Reduced frequencies computed using Arrhenius time-temperature shift factors are presented in Equation 12. The use of Arrhenius time-temperature shift factors allows the master curve to be constructed without the need for additional binder testing.

$$\log|E^*| = \log(Min)+\frac{[\log(Max)-\log(Min)]}{1+e^{\beta+\gamma\left\{\log\omega+\frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right)-\left(\frac{1}{T_r}\right)\right]\right\}}} \tag{10}$$

where:

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

ω = loading frequency at the test temperature, Hz

Max = limiting maximum modulus, ksi

T_r = reference temperature, °K

T = test temperature, °K

Min = limiting minimum modulus, ksi (treated as a fitting parameter)

ΔE_a = activation energy (treated as a fitting parameter)

β, and γ = fitting parameters

$$\log|E^*| = \log(Min) + \frac{[\log(Max) - \log(Min)]}{1 + e^{\beta + \gamma \log \omega_r}} \tag{11}$$

where:

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

ω_r = reduced frequency, Hz

Max = limiting maximum modulus, ksi

Min = limiting minimum modulus, ksi

β, and γ = fitting parameters

$$\log \omega_r = \log \omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{12}$$

where:

ω_r = reduced frequency at the reference temperature

ω = loading frequency at the test temperature

T_r = reference temperature, °K

T = test temperature, °K

ΔE_a = activation energy

The master curves were constructed using a Microsoft Excel application call MasterSolver that was developed in NCHRP Project 9-29 to fit master curves to data collected with the AMPT in accordance with AASHTO PP61. Table 10 summarizes the parameters and goodness of fit statistics for the fitted master curves. The goodness of fit statistics indicate that the master curves fit the measured data extremely well. The explained variance, R^2, exceeds 99 percent and the standard error is less than 7 percent of the standard deviation of the measured modulus values. Using these parameters in Equation 10, the dynamic modulus for any temperature and loading frequency can be determined.

Table 10. Master Curve Parameters and Goodness of Fit Statistics.

	Cisler			Christian/Gade			Glenmore			Wimmie		
AC	58-28		70-28	58-28		70-28	58-28		70-28	58-28		70-28
Mix	E3	E10	E10	E3	E10	E10	E3	E10	E10	E3	E10	E10
Max, ksi	3174.3	3117.5	3117.5	3163.1	3133.3	3133.3	3204.1	3215.0	3215.0	3163.1	3144.3	3144.3
Min, ksi	6.1	11.3	13.3	20.6	20.1	21.7	23.6	18.6	33.7	10.8	12.2	13.6
β	-0.5299	-0.3944	-0.1543	-0.1467	-0.2012	-0.1640	-0.2769	-0.4045	-0.1596	-0.2979	-0.5169	-0.2503
γ	-0.5090	-0.5468	-0.5435	-0.5649	-0.5524	-0.5153	-0.5511	-0.5264	-0.5938	-0.5620	-0.6156	-0.5440
EA	214463	207535	192885	193607	191063	197309	194227	192567	193360	193162	200376	185084
R^2	0.991	0.997	0.991	0.996	0.997	0.996	0.993	0.997	0.995	0.995	0.999	0.998
Se/Sy	0.068	0.042	0.066	0.045	0.039	0.047	0.061	0.041	0.051	0.051	0.027	0.033

Figures 21 through 24 were constructed to compare the mixture master curves for the four sources over the reduced frequency range covered by the measured data. The data symbols in these figures were selected to be the size of 95 percent confidence intervals. As shown, there is little difference in the measured dynamic modulus data for the three mixtures from each source. The most interesting finding from these figures is that the E-10 mixtures with the PG 70-28 binder tend to have lower modulus values at intermediate and low temperatures, which is consistent with the binder shear modulus master curves shown previously in Figure 19.

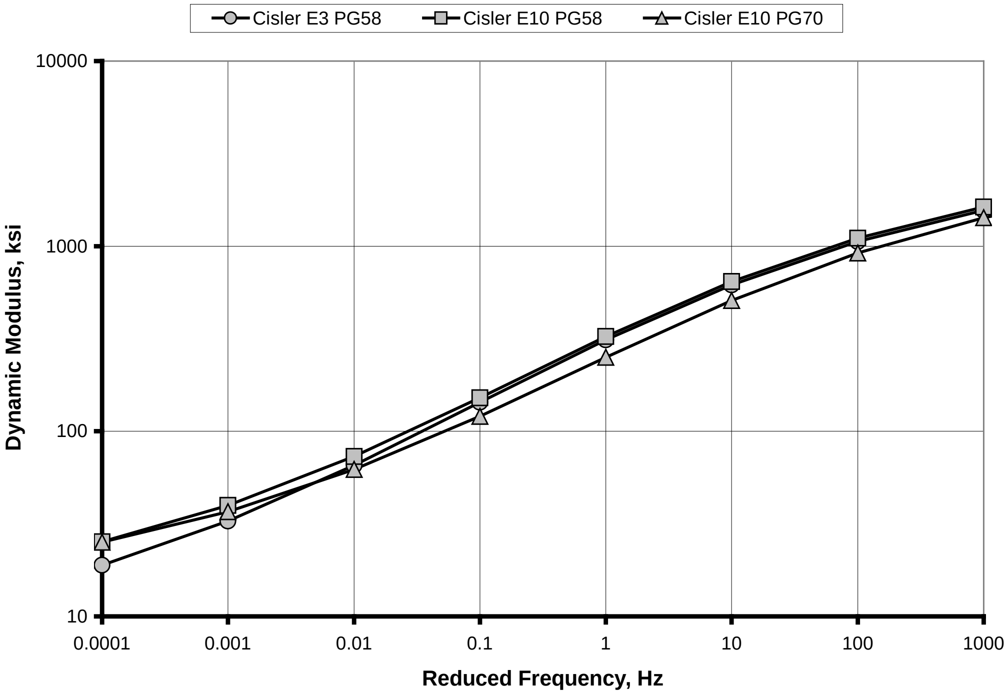

Figure 21. Dynamic Modulus Master Curves for the Cisler Source.

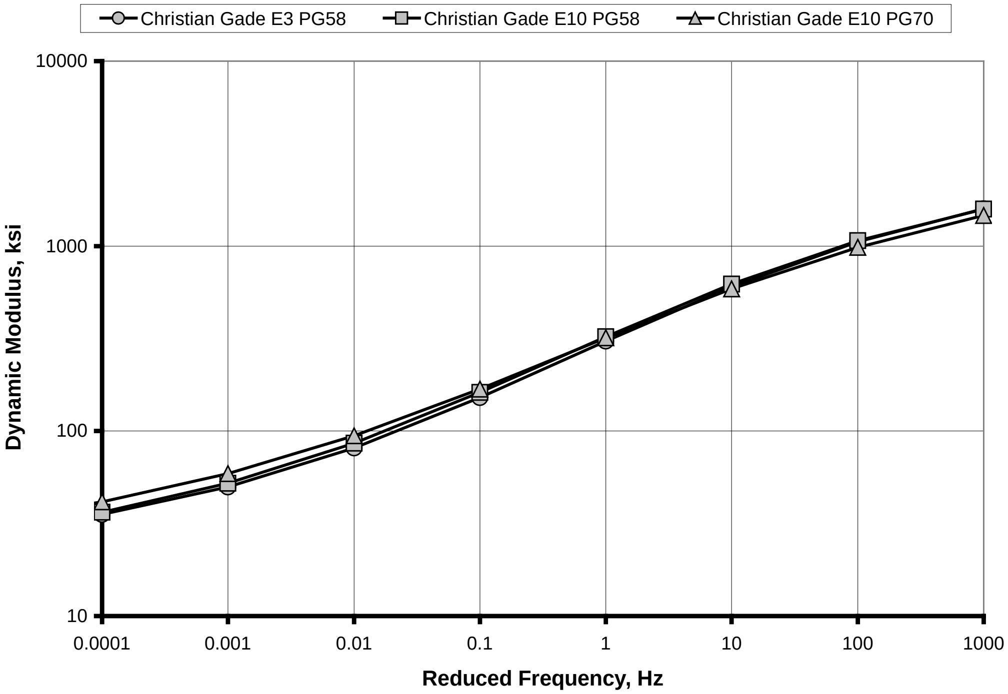

Figure 22. Dynamic Modulus Master Curves for the Christian/Gade Source.

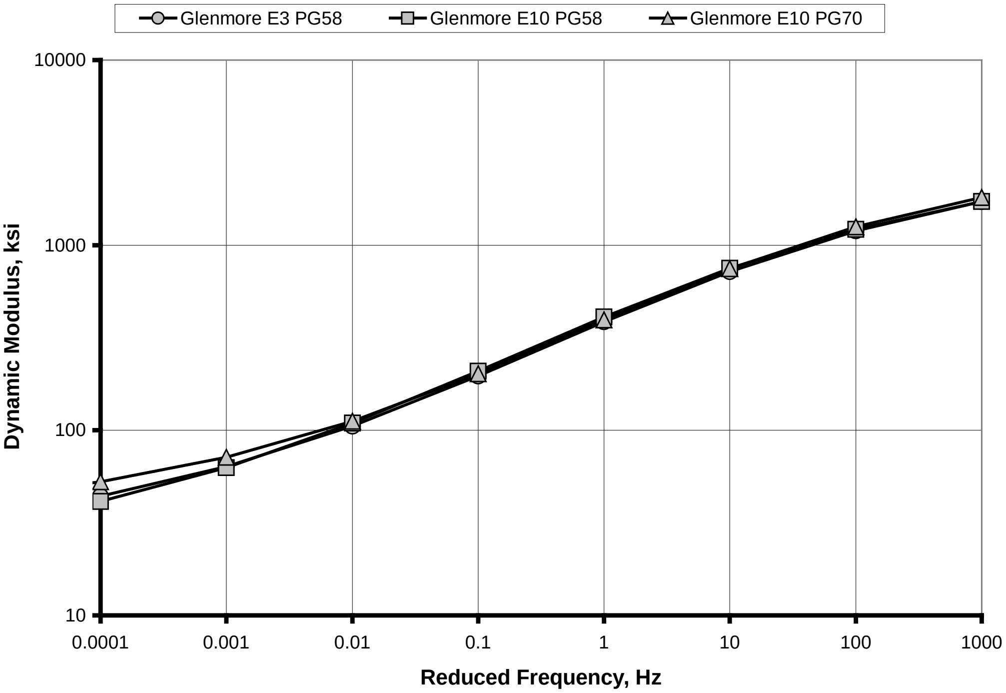

Figure 23. Dynamic Modulus Master Curves for the Glenmore Source.

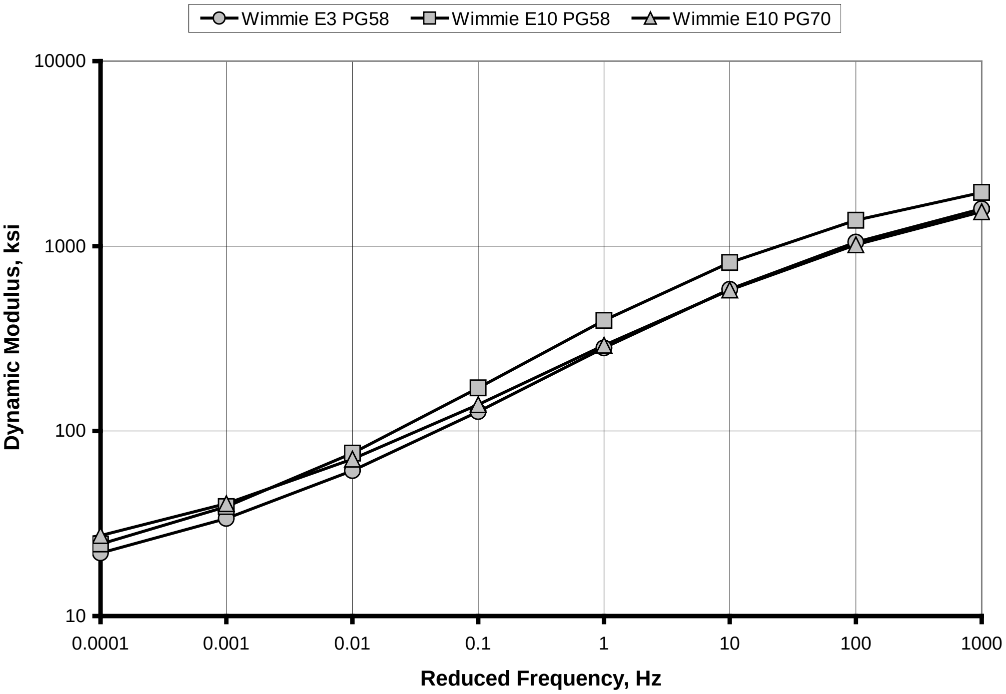

Figure 24. Dynamic Modulus Master Curves for the Wimmie Source.

Figures 25, 26, and 27 compare dynamic modulus master curves from the four sources for the E-3 PG 58 mixtures, E-10 PG 58 mixtures, and E-10 PG 70 mixtures from the four sources. Again the size of the data symbols in these figures were selected to be the size of 95 percent confidence intervals. These figures show the Glenmore and Christian/Gade sources have consistently higher dynamic modulus values for high temperature conditions, suggesting that the aggregate structure in these mixtures provides greater resistance to permanent deformation than the Cisler and Wimmie sources. The limiting minimum modulus represents the stiffness of the aggregate structure. Figure 28 compares limiting minimum modulus values for the four sources. The Glenmore and Christian/Gade sources have significantly higher limiting minimum modulus values compared to the Cisler and Wimmie sources.

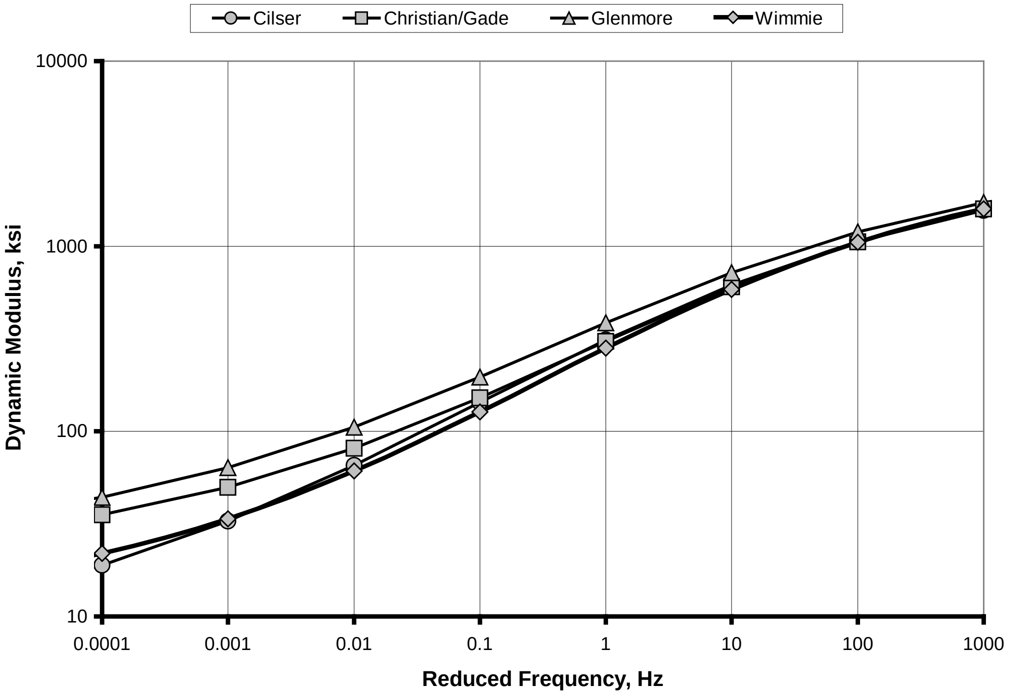

Figure 25. Dynamic Modulus Master Curves for E-3 PG 58 Mixtures.

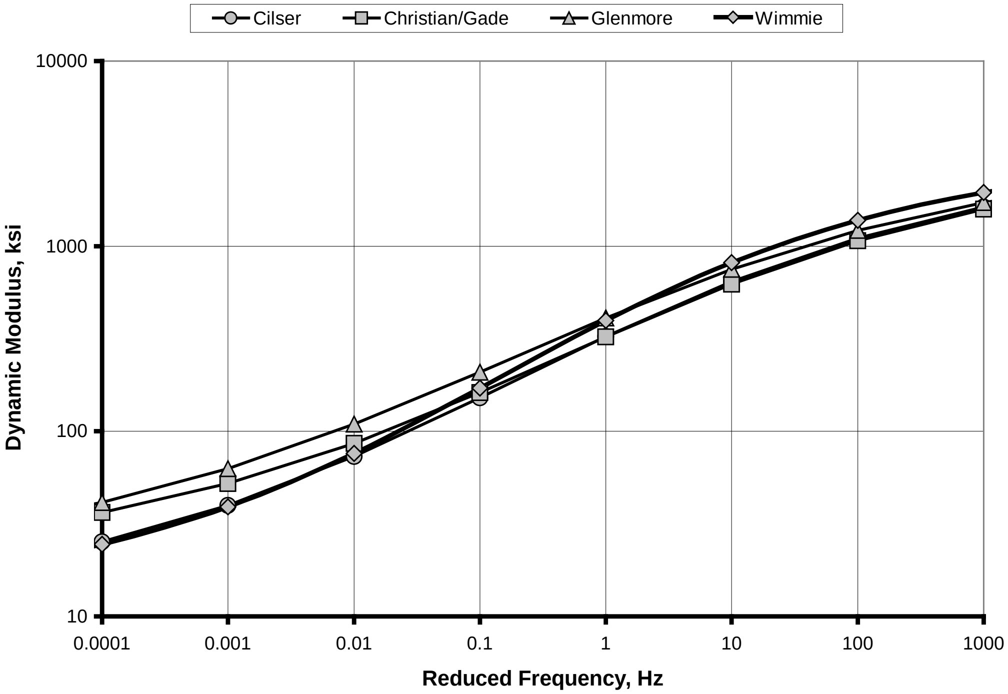

Figure 26. Dynamic Modulus Master Curves for E-10 PG 58 Mixtures.

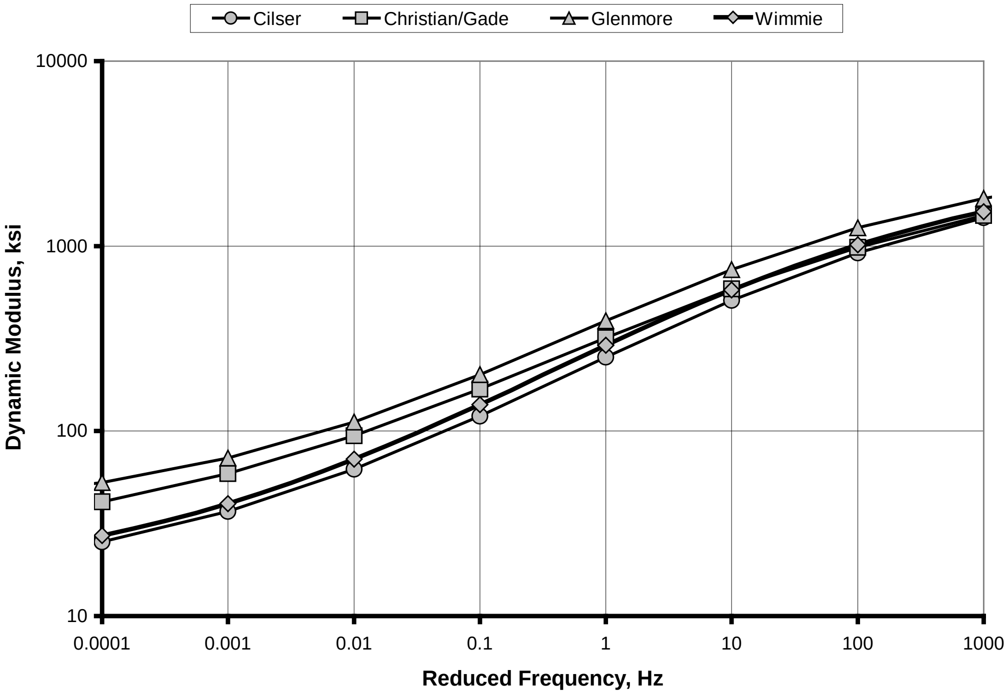

Figure 27. Dynamic Modulus Master Curves for E-10 PG 70 Mixtures.

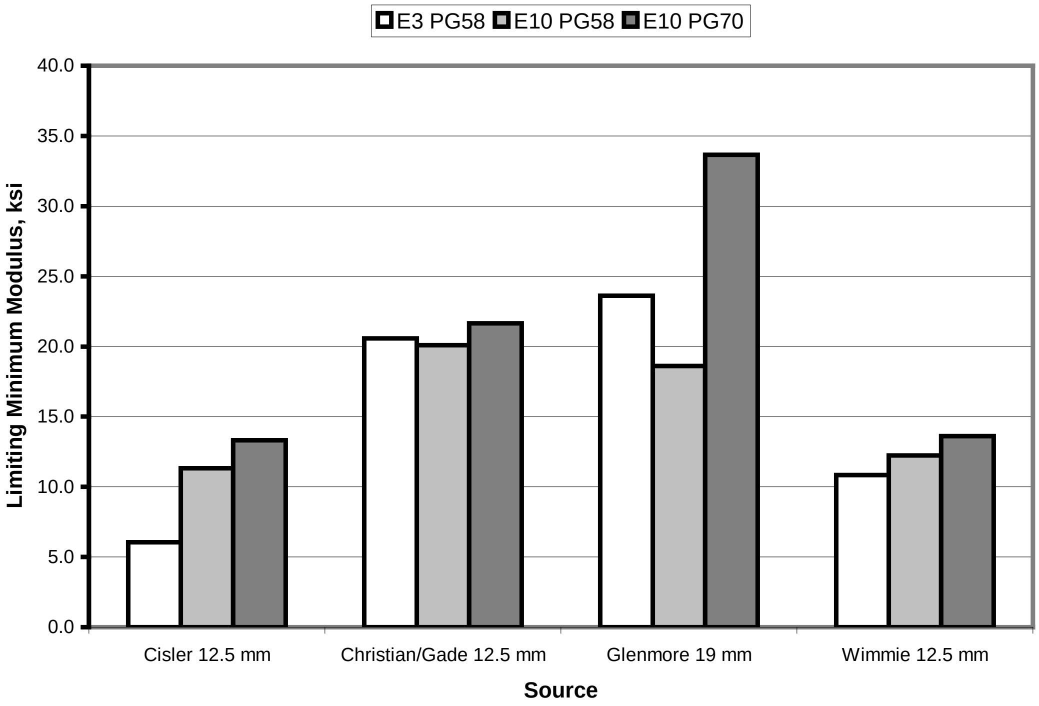

Figure 28. Limiting Minimum Modulus.

3.2 Estimated Rutting

To further investigate the significance of the difference in the mixture moduli shown in Figures 25 through 27, rutting was predicted using the Excel spreadsheet developed by the Arizona State University for the dynamic modulus test *(14)*. This spreadsheet rapidly performs asphalt layer rutting predictions using the calibrated rutting model contained in the MEPDG. The required inputs for this spreadsheet are summarized in Table 11. The climatic data were obtained from the National Oceanic & Atmospheric Administration website for Madison, Wisconsin *(15)*. The dynamic modulus data at the temperatures and frequencies required for this analysis were determined using the MasterSolver application as described in AASHTO PP60, and are summarized in Appendix D.

The results of the analysis are summarized in Table 12 and shown graphically in Figure 29 for the E-3 PG 58 mixtures at 3 million ESAL, Figure 30 for the E-10 PG 58 mixtures at 10 million

ESAL, and Figure 31 for the E-10 PG 70 mixtures at 10 million ESAL. The estimated rutting is very low at the design traffic level for speeds of 40 and 20 mph. The estimated rutting increases significantly for all mixtures for a traffic speed of 1 mph.

Table 11. Input Data for MEPDG Spreadsheet Rutting Predictions.

Input Parameter	Value
Traffic Speed, mph	Varied (40, 20, and 1 mph)
Surface layer thickness, in	2.5
Mean annual air temperature, °F	45.8
Standard deviation of mean annual air temperature, F	19.6
Mean Annual Wind Speed (mph)	10.1
Mean Annual Sunshine (%)	52.9
Annual Cumulative Rainfall Depth (in)	30.5
Traffic Level, ESAL	Varied (0.3, 1.0, 3.0, 10.0, and 30.0 MESAL)
Mixture dynamic modulus	Varied by mix type

Table 12. Summary of Predicted Rutting.

Traffic		Predicted Rut Depth, in											
		Cisler			Christian/Gade			Glenmore			Wimmie		
		58-28		70-28	58-28		70-28	58-28		70-28	58-28		70-28
Speed	Volume	E3	E10	E10	E3	E10	E10	E3	E10	E10	E3	E10	E10
40	0.3	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02
	1.0	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.04
	3.0	0.07	0.06	0.07	0.06	0.06	0.06	0.05	0.04	0.05	0.07	0.05	0.06
	10.0	0.12	0.11	0.13	0.11	0.10	0.10	0.08	0.08	0.08	0.12	0.09	0.11
	30.0	0.21	0.19	0.22	0.18	0.17	0.17	0.14	0.13	0.14	0.20	0.15	0.18
20	0.3	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03
	1.0	0.05	0.05	0.06	0.05	0.04	0.04	0.04	0.03	0.04	0.05	0.04	0.05
	3.0	0.09	0.09	0.10	0.08	0.07	0.07	0.06	0.06	0.06	0.09	0.07	0.08
	10.0	0.15	0.15	0.17	0.14	0.13	0.13	0.11	0.10	0.10	0.16	0.13	0.14
	30.0	0.26	0.26	0.29	0.23	0.21	0.22	0.18	0.17	0.18	0.27	0.21	0.23
1	0.3	0.11	0.09	0.08	0.06	0.06	0.06	0.05	0.05	0.05	0.09	0.08	0.07
	1.0	0.19	0.15	0.15	0.11	0.11	0.10	0.09	0.09	0.08	0.16	0.14	0.13
	3.0	0.32	0.26	0.25	0.19	0.18	0.17	0.15	0.15	0.14	0.27	0.24	0.21
	10.0	0.57	0.45	0.45	0.34	0.32	0.29	0.27	0.26	0.24	0.48	0.43	0.38
	30.0	1.00	0.79	0.79	0.59	0.55	0.51	0.46	0.45	0.42	0.84	0.75	0.66

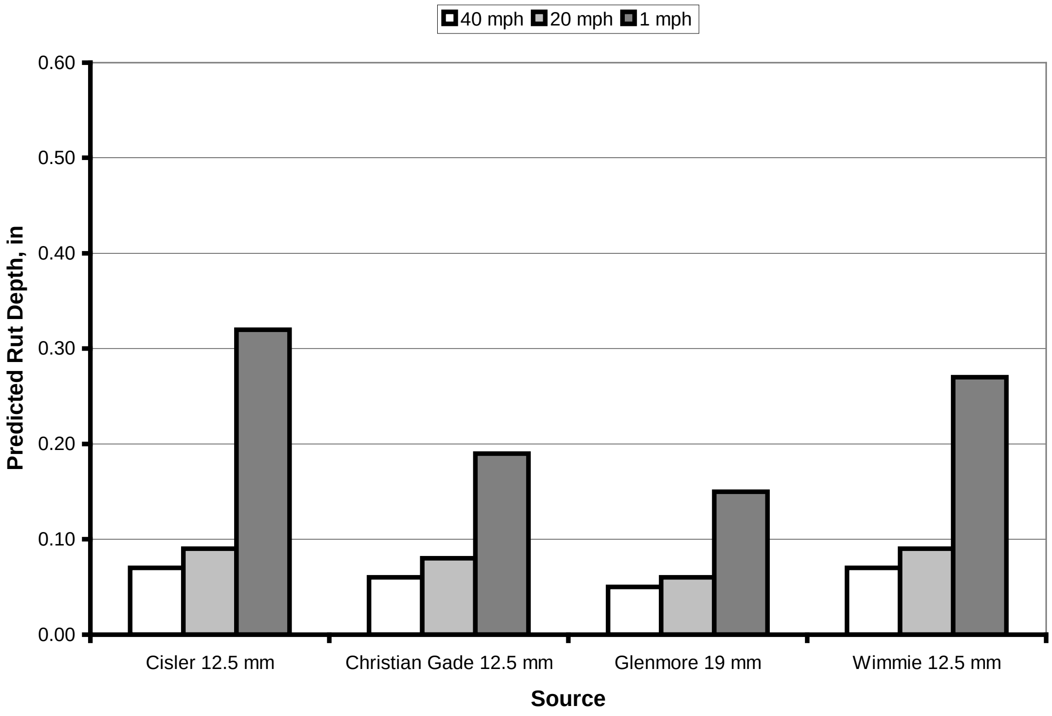

Figure 29. Estimated Rut Depth for Madison, WI at the Design Traffic Level for the E-3 PG 58 Mixtures.

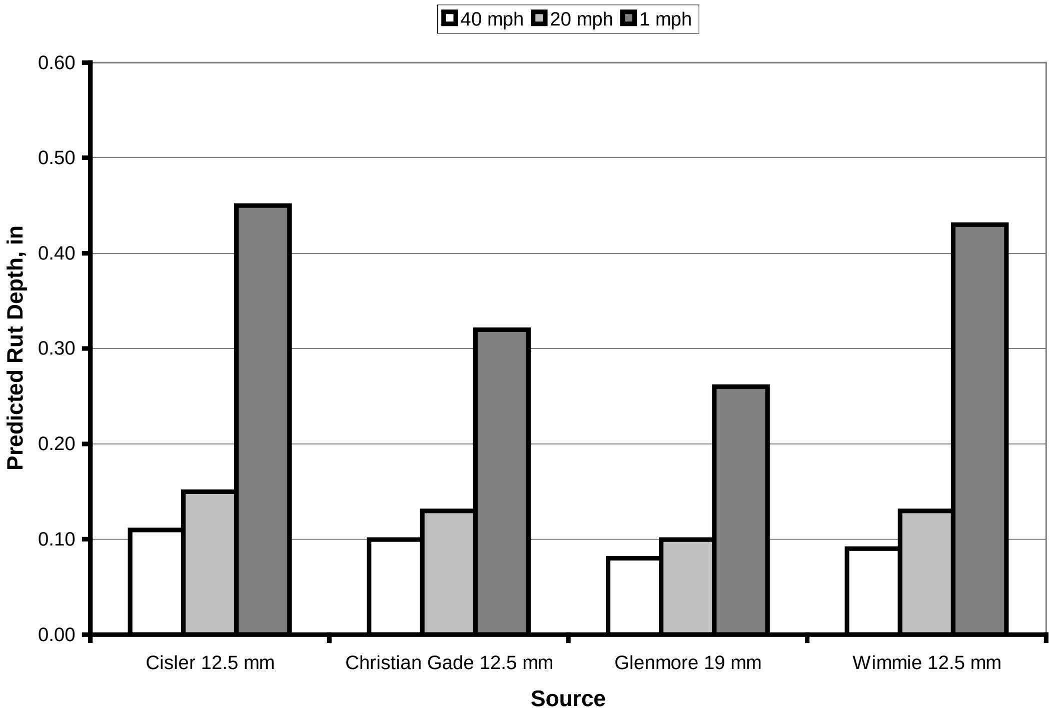

Figure 30. Estimated Rut Depth for Madison, WI at the Design Traffic Level for the E-10 PG 58 Mixtures.

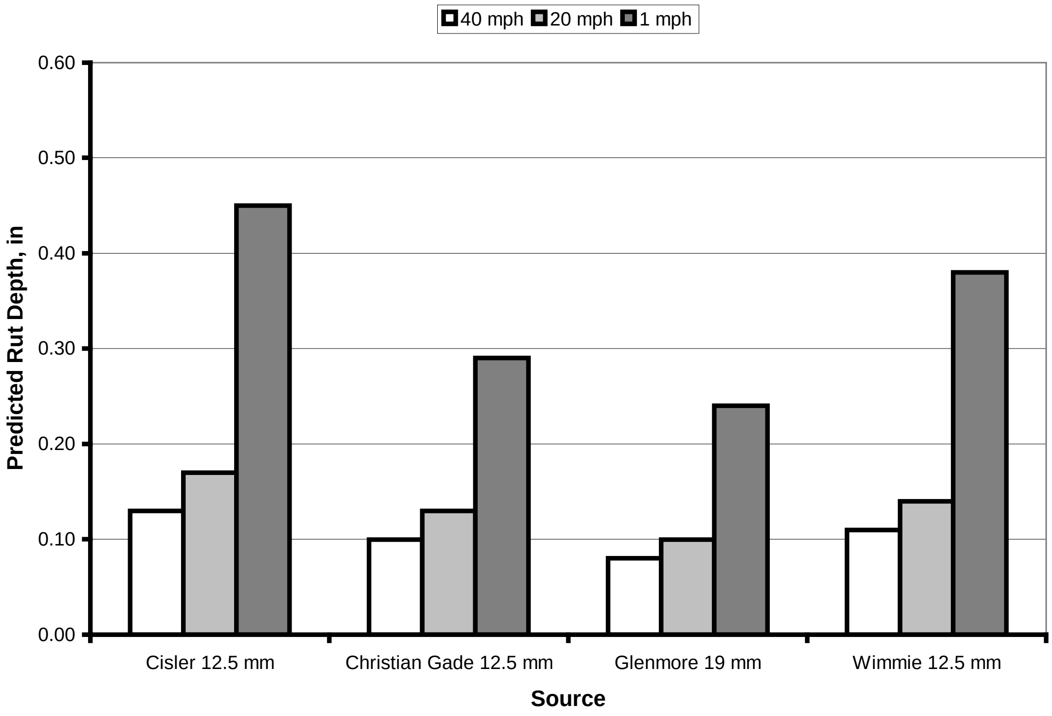

Figure 31. Estimated Rut Depth for Madison, WI at the Design Traffic Level for the E-10 PG 70 Mixtures.

The mixtures are compared at a traffic level of 10 million ESAL in Figures 32, 33, and 34 for traffic speeds of 40, 20, and 1 mph, respectively. These figures show that there is little improvement in the estimated rutting for the E-10 mixtures compared to the E-3 mixtures for traffic speeds of 40 and 20 mph. Additionally for these traffic speeds, the E-10 PG 70 mixtures do not show any improvement in rutting resistance compared to the E-10 PG 58 mixtures. In fact, the Cisler and Wimmie E-10 PG 70 mixtures have slightly higher predicted rutting than the corresponding PG 58 mixture. The reason that this occurs is the PG 70 binder and mixtures are somewhat softer at intermediate temperatures compared to the PG 58 binder and mixtures. For uniform traffic, more loads are applied at intermediate temperature conditions compared to the high temperature conditions where the PG 70 binder and mixtures have greater stiffness.

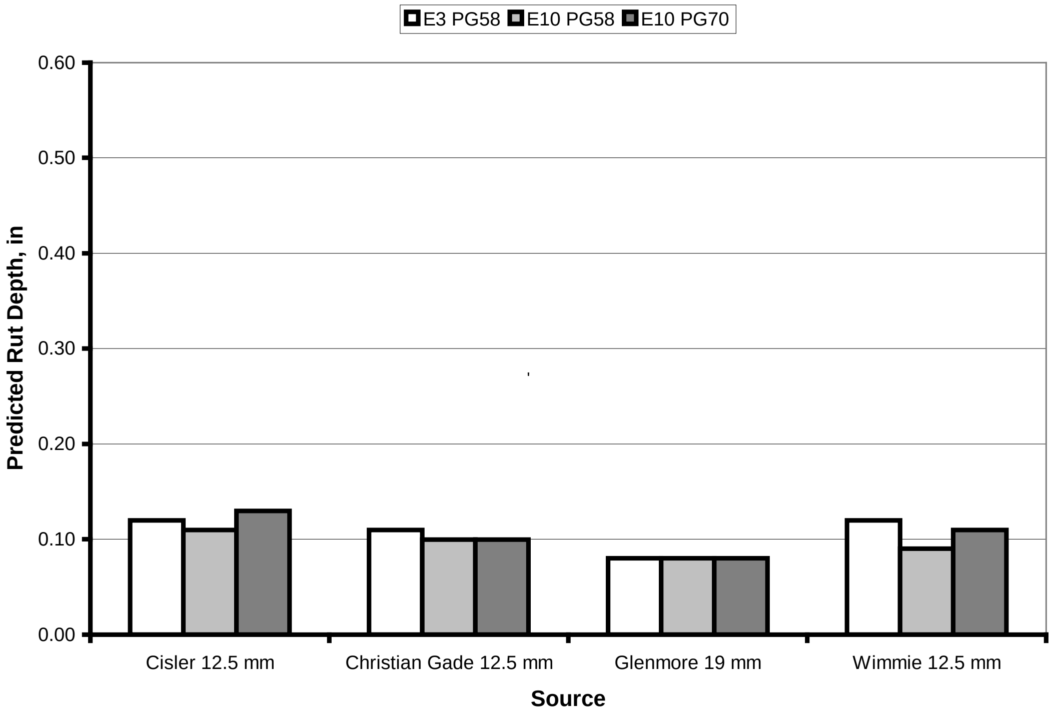

Figure 32. Comparison of Predicted Rutting at 10 Million ESAL for Design Traffic Speed of 40 mph.

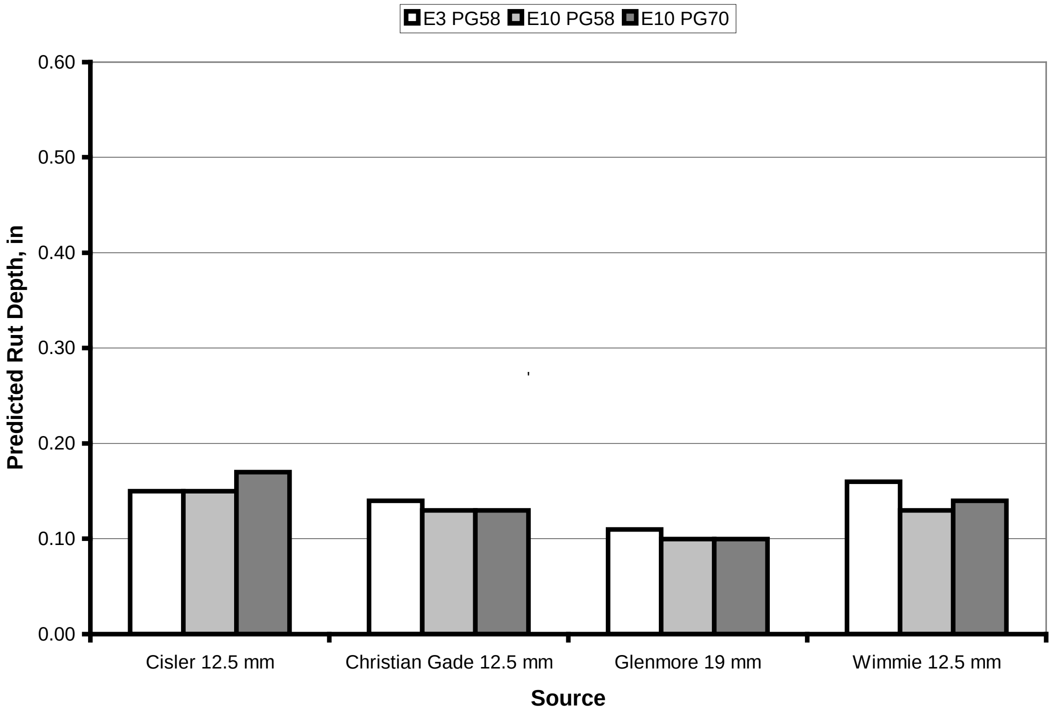

Figure 33. Comparison of Predicted Rutting at 10 Million ESAL for Design Traffic Speed of 20 mph.

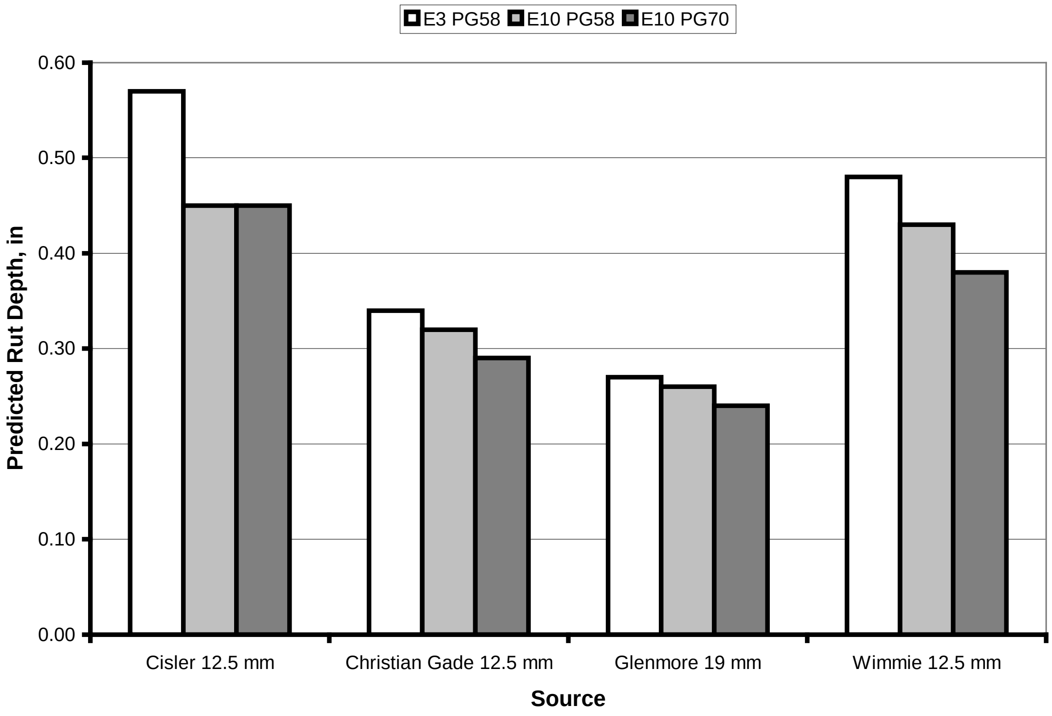

Figure 34. Comparison of Predicted Rutting at 10 Million ESAL for Design Traffic Speed of 1 mph.

For the traffic speed of 1 mph, the E-10 PG 70 mixtures do show minor improvement in predicted rutting. This slow speed corresponds to dynamic modulus values for lower reduced frequencies where the PG 70 binder and mixtures begin to have higher stiffness. For the 1 mph traffic speed, the Christian/Gade and Glenmore E-10 mixtures have significantly lower predicted rutting compared to the Cisler and Wimmie E-10 mixtures. This is the result of the higher limiting minimum modulus values and higher stiffness at low reduced frequencies for these two mixtures.

3.3 Dynamic Modulus Predictive Models

For Level 2 and 3 analyses, the MEPDG uses the Witczak dynamic modulus equation to predict the dynamic modulus of asphalt concrete from binder properties and mixture composition. Equation 13 presents the latest version of the Witczak dynamic modulus equation (*11*).

$$\log|E^*| = -0.349 + 0.754(A)|G_b^*|^{-0.0052} + \frac{B}{C} \tag{13}$$

where:

$$A = 6.65 - 0.032\rho_{200} + 0.0027\rho_{200}{}^2 + 0.011\rho_4 - 0.0001\rho_4{}^2 + 0.006\rho_{38} - 0.00014\rho_{38}{}^2 - 0.08V_a - 1.06\left(\frac{V_{beff}}{V_a + V_{beff}}\right)$$

$$B = 2.56 + 0.03V_a + 0.71\left(\frac{V_{beff}}{V_a + V_{beff}}\right) + 0.012\rho_{38} - 0.0001\rho_{38}{}^2 - 0.01\rho_{34}$$

$$C = 1 + e^{\left(-0.7814 - 0.5785\log|G_b^*| + 0.8834\log\delta_b\right)}$$

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

ρ_{200} = percent passing 200 sieve, %

ρ_4 = percent retained on #4 sieve, %

ρ_{38} = percent retained on 3/8 in sieve, %

ρ_{34} = percent retained on 3/4 in sieve, %

V_a = mix air void content, vol. %

V_{beff} = effective binder content of the mix, vol. %

$|G_b^*|$ = binder dynamic shear modulus, psi

δ_b = binder phase angle, degree

Using this model, the dynamic modulus of the mixture can be estimated from mixture volumetric properties (air voids and effective binder content), gradation, and the shear modulus and phase angle of the binder at the temperature and loading frequency of interest. For this model, the frequency of loading for the binder is related to the frequency of loading for the mixture by Equation 14.

$$f_b = \frac{f_m}{2\pi} \tag{14}$$

where:

f_b = loading frequency for the binder

f_m = loading frequency for the mixture

Another popular model for predicting the dynamic modulus of asphalt concrete from binder properties and mixture composition is the Hirsch model (*12*). The Hirsch model is based on the law of mixtures and is given in Equation 15.

$$|E^*| = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+G_b\left(\frac{VFA\ x VMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{G_b(VFA)}\right]} \tag{15}$$

where:

$$P_c = \frac{\left(20+\frac{G_b(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{G_b(VFA)}{VMA}\right)^{0.58}}$$

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

VMA = Voids in mineral aggregates, %

VFA = Voids filled with asphalt, %

G_b = binder shear modulus, psi

The Hirsch model has fewer parameters compared to the Witczak model. Additionally, for the Hirsch model, the loading frequency of the binder is the same as that for the mixture.

Dynamic modulus values were predicted using the Witczak and Hirsch models for the conditions used in the dynamic modulus testing program. The average gradation and volumetric properties of the specimens included in the dynamic modulus testing program were used in the predictions. Binder shear modulus and phase angle data for the predictions were obtained from the master curves discussed in Chapter 2 for the temperature and loading rate used in the testing and as required by the predictive model. A total of 120 dynamic modulus predictions were made; 10 temperature/frequency combinations for 12 mixtures. The predicted modulus values for both models are summarized in Appendix E. Figures 35 and 36 present comparisons of measured and predicted dynamic modulus values for the Witczak and Hirsch models, respectively.

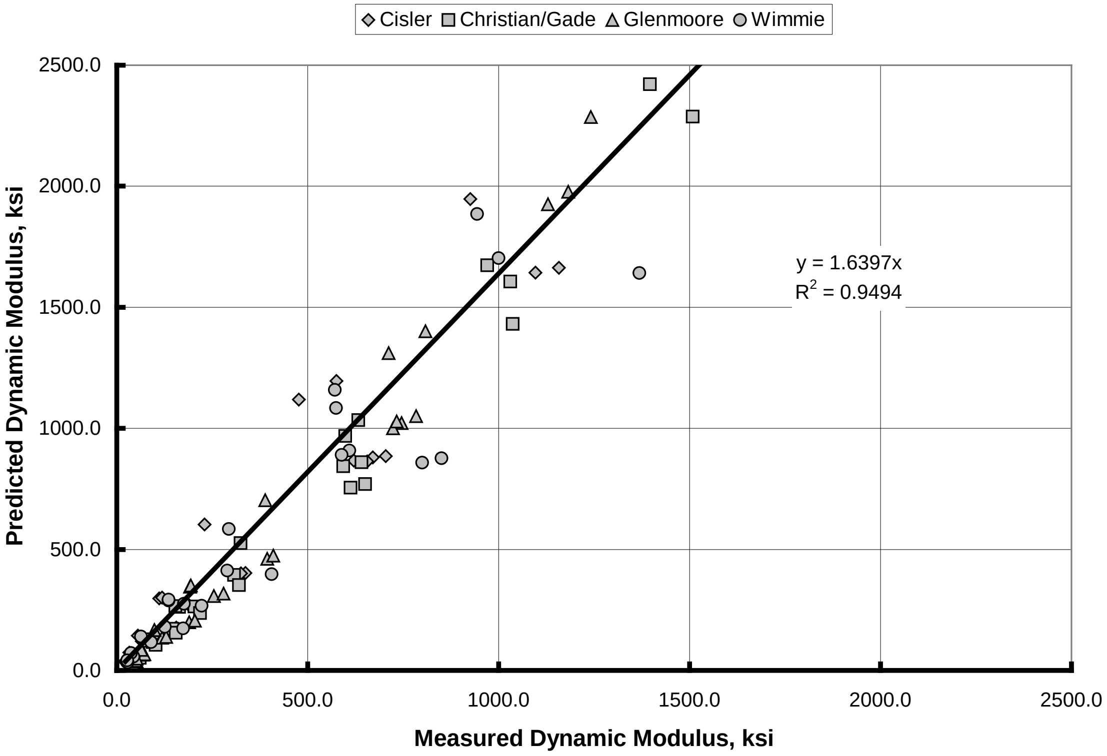

Figure 35. Comparison of Measured and Latest Witczak Equation Predicted Dynamic Modulus Values.

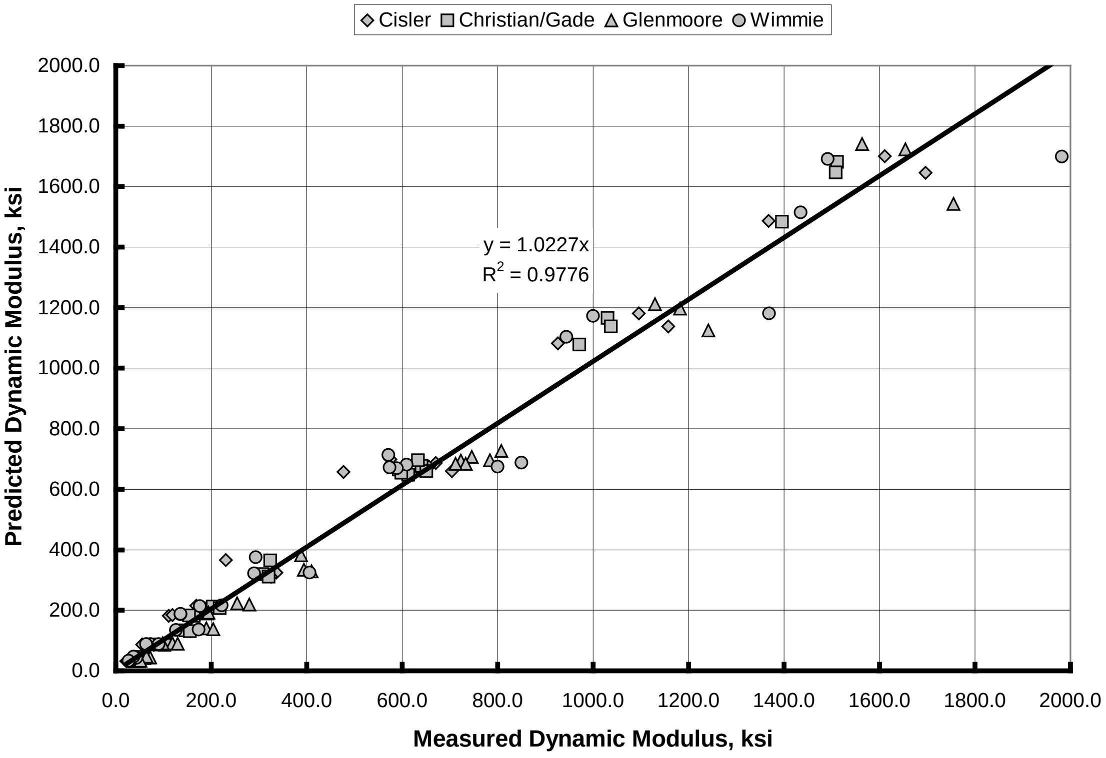

Figure 36. Comparison of Measured and Hirsch Model Predicted Dynamic Modulus Values.

The comparisons show the Hirsch model reasonably predicts the measured dynamic modulus values over the wide range of dynamic modulus values included in the testing program. Figure 37 shows a plot of the difference between the Hirsch model predictions and the measured data. On average the Hirsch model overpredicts the measured data by about 2 percent. The errors are reasonably distributed about zero, with maximum errors of approximately ± 50 percent of the measured value. The comparison is not as good for the Witczak dynamic modulus equation. This equation consistently over estimates the measured dynamic modulus by 64 percent. Figure 38 shows a plot of the difference between the Witczak equation and the measured data. Except at low stiffnesses, the errors are consistently positive and reach as high as 150 percent of the measured value.

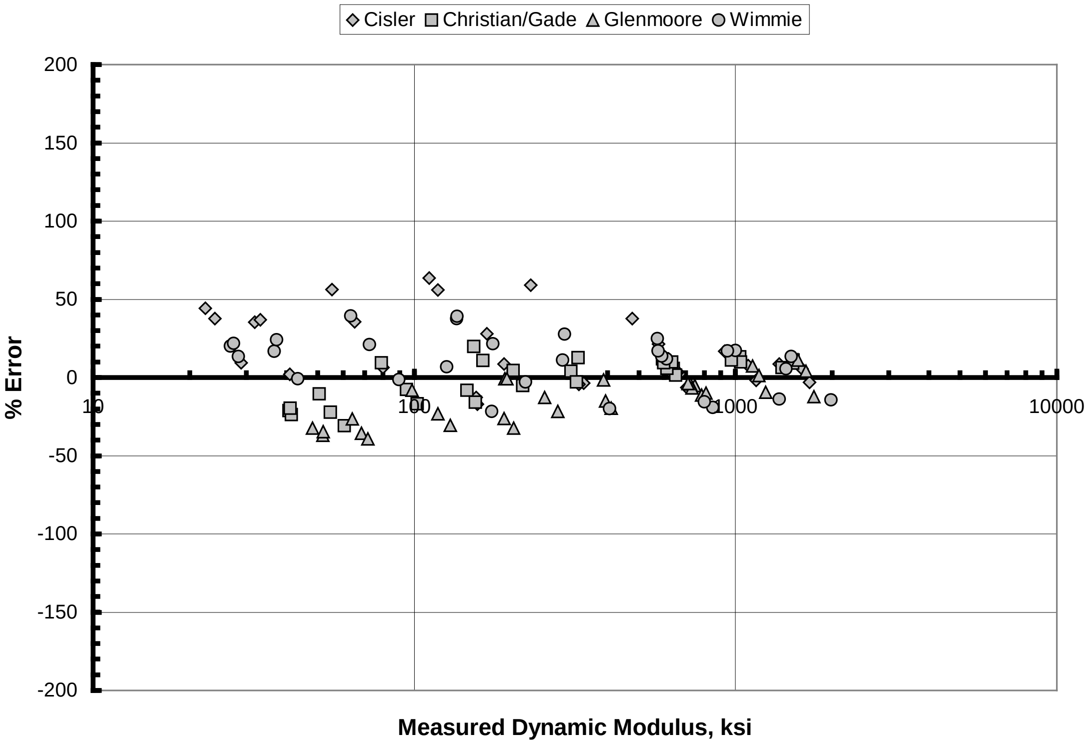

Figure 37. Hirsch Model Errors.

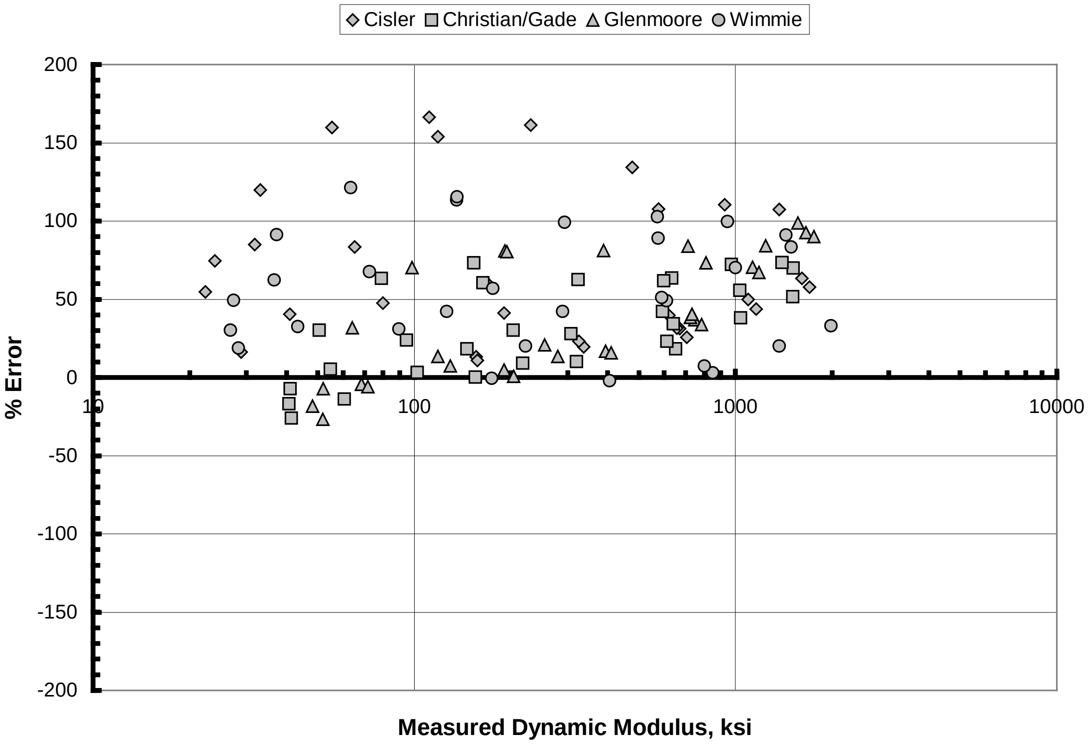

Figure 38. Latest Witczak Equation Errors.

The likely cause of the poor predictions for the latest version of the Witczak dynamic modulus equation is the relationship that Witczak and his colleagues developed to convert between historical binder viscosity measurements and current binder shear modulus and phase angle measurements. The Witczak dynamic modulus equation was originally formulated using viscosity-temperature susceptibility parameters to characterize binder stiffness effects (*13*). For the latest version, empirical relationships were developed to estimate binder shear modulus and phase angle from the viscosity-temperature susceptibility parameters. The estimated binder properties were used to calibrate the latest version of the Witczak dynamic modulus equation (*11*). For a given binder, the binder shear modulus predictions can be in error by almost a factor of 5, and the phase angle predictions can be in error by almost 15 degrees.

Figures 39 and 40 present a comparison of the earlier viscosity based Witczak dynamic modulus predictive equation using the typical viscosity temperature susceptibility parameters for PG 58-28 and PG 70-28 binders recommended in the MEPDG documentation (*13*). This earlier version of the Witczak dynamic modulus equation shows improved accuracy compared to current version even though it uses typical binder properties rather than measured binder properties. Although the model still overpredicts the measured modulus values, the overprediction is significantly lower, averaging 19 percent compared to 64 percent for the current version of the Witczak Dynamic modulus equation.

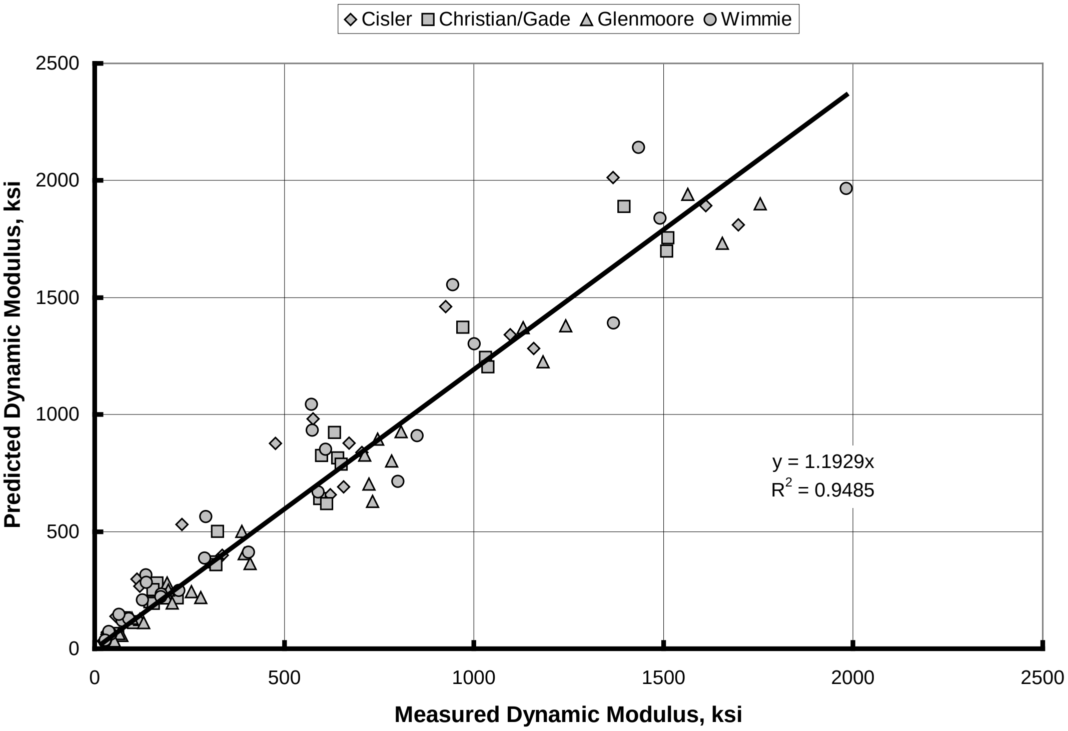

Figure 39. Comparison of Measured and Viscosity Based Witczak Equation Predicted Dynamic Modulus Values.

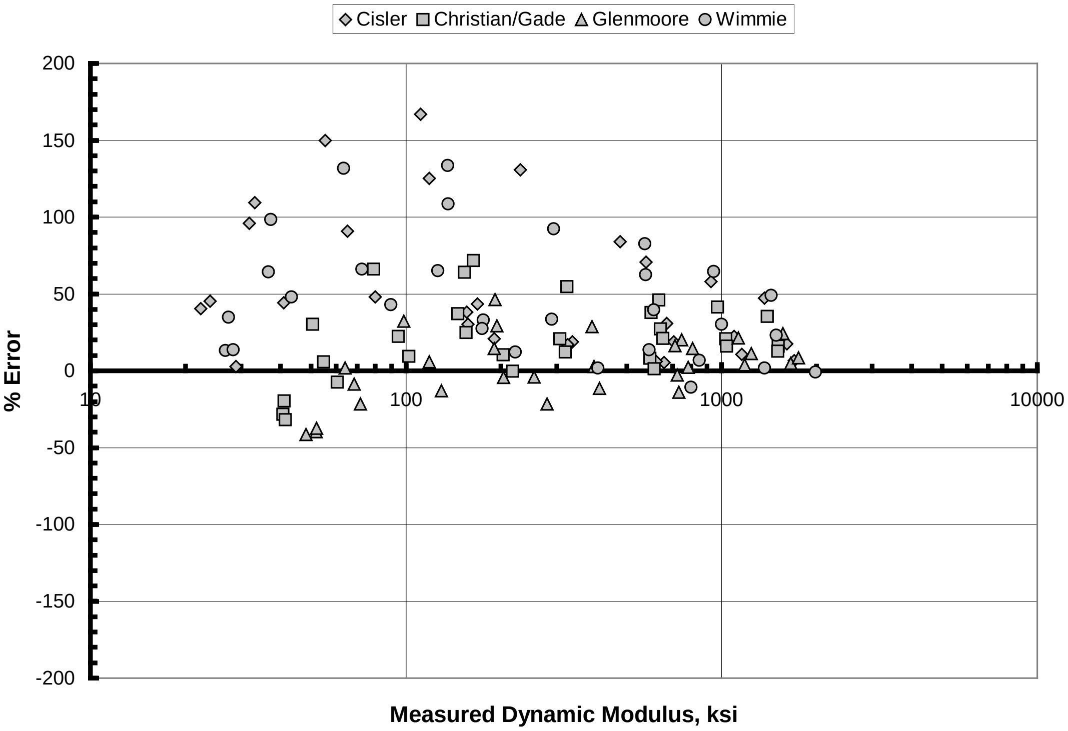

Figure 40. Viscosity Based Witczak Equation Errors.

Chapter 4 Flow Number

4.1 Testing Conditions

Testing conditions for the flow number test have not been standardized. Two approaches for this testing have emerged from recent research. NCHRP Project 9-33 has recommended using an unconfined test with the following conditions:

- Repeated axial stress: 600 kPa,
- Temperature: 50 % reliability high performance grade temperature, without traffic or speed adjustments, from LTPPBind3.1 at a depth of 20 mm for surface courses and the top of the layer for intermediate and base courses .
- Air Void Content: 7.0 ± 0.5 percent.

For tests conducted using these conditions, criteria have been developed for various traffic levels and were previously presented in Chapter 1.

The second approach is the confined test that is currently being used in NCHRP Project 9-30A in the development of an improved rutting model for asphalt concrete. This test uses a confining pressure of 69 kPa and a repeated deviatoric stress of 483 kPa. The Project 9-30A researchers believe that confining pressure is needed to differentiate the difference in rutting resistance for various mixture types.

In this project, flow number tests were conducted for both unconfined and confined testing conditions using the stress states recommended in NCHRP Projects 9-33 and 9-30A, respectively. All testing was performed on specimens compacted to a target air void content of 7.0 ± 0.5 percent in accordance with AASHTO PP60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)*. The testing was conducted in accordance with AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).* The tests were conducted at a temperature of 49.6 °C, which is the 50 % reliability high performance grade temperature from LTPPBind3.1 at a depth of 20 mm for Madison, Wisconsin. Duplicate specimens were used in the unconfined testing. Triplicate specimens were used in the confined testing.

4.2 Unconfined Flow Number Results

Table 13 presents the results of the unconfined flow number tests. The flow numbers were computed using the Francken model algorithm that has been recently introduced into the AMPT software (*17*). Equation 16 presents the Francken model which in the AMPT flow number testing is fit to the entire permanent deformation curve using nonlinear least squares optimization. The flow number is then determined from the second derivative of the fitted curve. The flow number is the number of cycles were the second derivative, Equation 17, changes from negative to positive. In the ruggedness testing performed in NCHRP Project 9-29, the Francken model has been found to be a very repeatable method for determining the flow number (*4*). As shown in Table 13, the coefficient of variation of the flow numbers for the unconfined test varied from 0 to 26.5 percent.

$$\varepsilon_p = A\left(n^B\right) + C\left[e^{D*n} - 1\right] \tag{16}$$

where:

ε_p = permanent strain, %

n = number of cycles

A, B, C, and D = fitting parameters

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD^2e^{Dn} \tag{17}$$

where:

$\frac{d^2\varepsilon_p}{dn^2}$ = second derivative

n = number of cycles

A, B, C, and D = fitting parameters from Equation 17

Table 13. Summary of Unconfined Flow Number Test Results.

Source	Mixture	Binder	Air Voids, %			Flow Number, Cycles				
			Specimen 1	Specimen 2	Average	Specimen 1	Specimen 2	Average	Standard Deviation	Coefficient of Variation, %
Cisler	E3	PG 58-28	6.8	7.0	6.9	24	18	21	4.24	20.2
	E10	PG 58-28	6.8	7.1	7.0	39	38	38	0.71	1.8
	E10	PG 70-28	6.7	7.1	6.9	291	232	262	41.72	16.0
Christian/ Gade	E3	PG 58-28	7.3	6.8	7.0	25	34	30	6.36	21.6
	E10	PG 58-28	7.1	7.2	7.2	45	45	45	0	0.0
	E10	PG 70-28	7.2	7.0	7.1	687	1004	846	224.15	26.5
Glenmore	E3	PG 58-28	6.7	6.7	6.7	94	98	96	2.82	2.9
	E10	PG 58-28	6.8	7.2	7.0	89	83	86	4.24	4.9
	E10	PG 70-28	7.1	7.1	7.1	1130	1131	1130	0.71	0.1
Wimmie	E3	PG 58-28	6.8	7.0	6.9	33	30	32	2.12	16.0
	E10	PG 58-28	6.8	6.5	6.6	55	52	54	2.12	6.7
	E10	PG 70-28	6.7	6.8	6.8	353	295	324	41.01	4.0

The unconfined flow number results are presented graphically in Figure 41 and 42. Figure 41 shows the data for all three mixtures. Figure 42 shows only the data for the mixtures with PG 58 binder to expand the scale and better show the difference between the E-3 and E-10 mixtures. In both figures, the error bars represent 95 percent confidence intervals based on the pooled standard deviation from the four sources for the mixtures tested. The rutting resistance of asphalt mixtures improves with increasing flow number. Figure 41 shows the rutting resistance of the E-10 PG 70 mixtures is substantially better than that for the E-3 PG 58 mixtures and the E-10 PG 58 mixtures. Figure 42 shows the rutting resistance for the E-10 PG 58 mixtures is generally better than that for the E-3 PG 58 mixtures except for the Glenmore 19 mm mixture where the E-10 PG 58 mixture has poorer rutting resistance than the E-3 PG 58 mixture. For the PG 58 mixtures, the three 12.5 mm mixtures have similar rutting resistance, while the rutting resistance of the 19 mm mixture is somewhat higher. For the PG 70 mixtures, the Cisler and Wimmie sources have similar rutting resistance; the rutting resistance of the Christian/Gade and Glenmore sources are significantly higher compared to the Cisler and Wimmie sources.

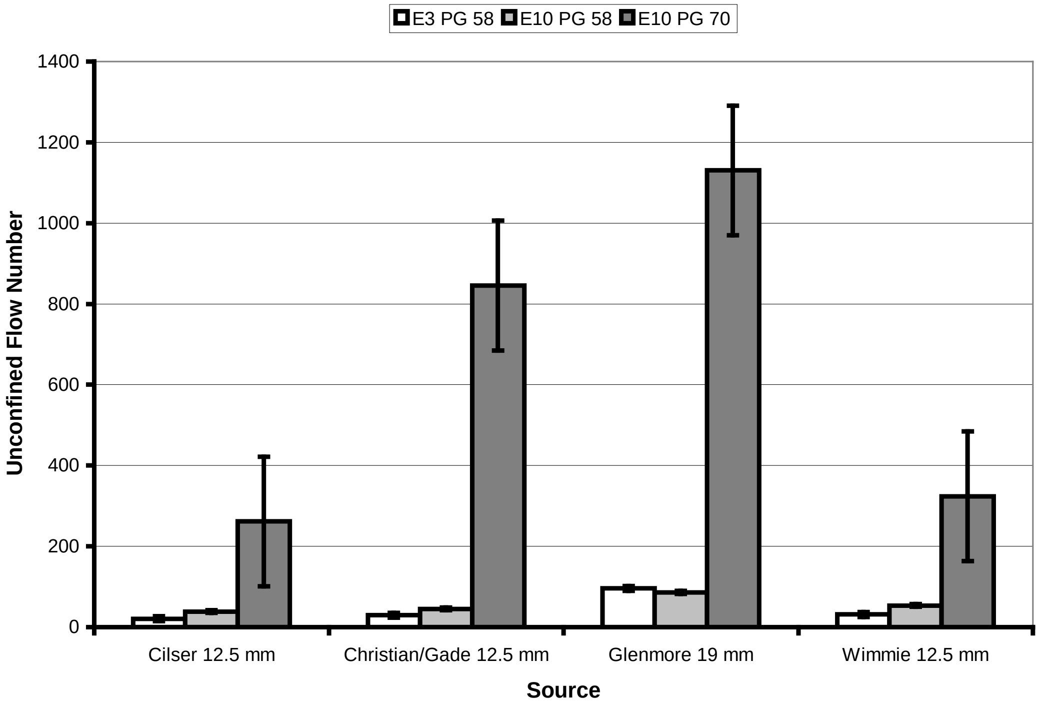

Figure 41. Unconfined Flow Numbers, All Mixtures.

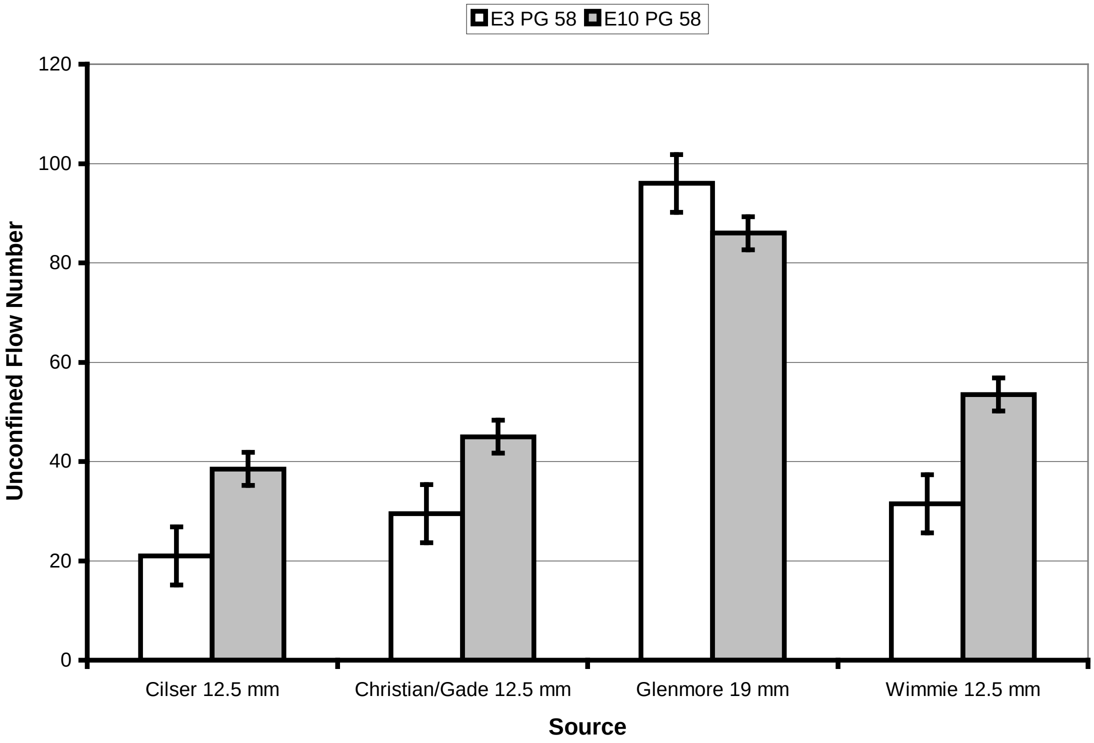

Figure 42. Unconfined Flow Numbers, PG 58-28 Mixtures.

As discussed in Chapter 2, the primary difference between the E-3 and E-10 mixtures is the fine aggregate angularity is higher for the E-10 mixtures. Additionally, the 19 mm Glenmore mixture has lower design VMA compared to the 12.5 mm mixtures from the other sources. To determine if the unconfined flow number test is sensitive to these changes in mixture properties, a multiple regression analysis was performed on the data from the E-3 and E-10 mixtures incorporating PG 58-28 binder. The analysis is summarized in Table 14. The resulting model provides a good fit to the measured with the coefficients for both VMA and FAA being statistically significant at the 98 percent level. A plot of the resulting model and data are presented in Figure 43. The data labels in Figure 43 show the design VMA for the 8 mixtures included in the analysis. The solid lines are trend lines from the model for VMA values of 13.5, 14.5, and 15.5 percent.

Table 14. Summary of Multiple Regression Analysis of Unconfined Flow Number Data for E-3 and E-10 Mixtures with PG 58-28.

Regression Statistics						
Multiple R	0.954469					
R Square	0.911012					
Adjusted R Square	0.875416					
Standard Error	9.606181					
Observations	8					
Analysis of Variance						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	4723.481	2361.741	25.59356	0.002362	
Residual	5	461.3936	92.27871			
Total	7	5184.875				
Model						
	Coefficients	*Standard Error*	*t Statistic*	*p-value*	*Lower 95% CI*	*Upper 95% CI*
Intercept	-517.374	170.2199	-3.03945	0.028769	-954.938	-79.8107
Design VMA	-16.2856	4.109258	-3.96314	0.010709	-26.8487	-5.72241
FAA	17.97616	3.373258	5.329021	0.003117	9.304939	26.64738

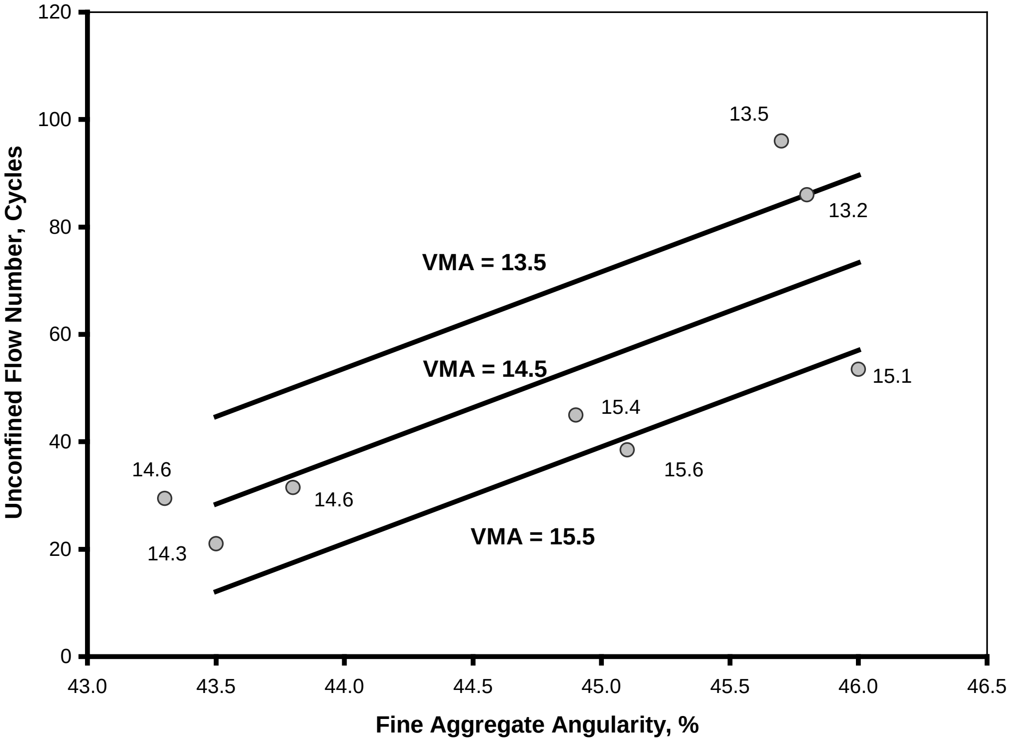

Figure 43. Plot of Multiple Regression Model for Unconfined Flow Number for Mixtures with PG 58-28 Binder.

Table 15 ranks the rutting resistance of the mixtures based on the tentative criteria developed in NCHRP 9-33 and the average flow number. The NCHRP 9-33 criteria were previously presented in Table 1 of Chapter 1. The NCHRP 9-33 criteria include only mixtures with design traffic greater than 3 million ESAL; therefore, all of the E-3 mixtures are acceptable for 3 million ESAL. The Glenmore E-3 mixture has acceptable rutting resistance for up to 10 million ESAL. Of the E-10 PG 58 mixtures included in the study, only the Glenmore and Wimmie mixtures classify as acceptable for 10 million ESAL loading based on the NCHRP 9-33 criteria. Based on the NCHRP 9-33 criteria, the E-10 PG 70 mixtures from the Cisler and Wimmie sources have rutting resistance ratings of <30 million ESAL while the E-10 PG 70 mixtures from Christian/Gade and Glenmore have the highest rutting resistance of > 30 million ESAL.

Table 15. Rutting Resistance Based on NCHRP Project 9-33 Tentative Flow Number Criteria

Source	Mixture	Binder	Average Flow Number	NCHRP 9-33 Rating, MESAL
Cisler	E3	PG 58-28	21	3
	E10	PG 58-28	38.5	3
	E10	PG 70-28	261.5	30
Christian/Gade	E3	PG 58-28	29.5	3
	E10	PG 58-28	45	3
	E10	PG 70-28	845.5	> 30
Glenmore	E3	PG 58-28	96	10
	E10	PG 58-28	86	10
	E10	PG 70-28	1130.5	> 30
Wimmie	E3	PG 58-28	31.5	3
	E10	PG 58-28	53.5	10
	E10	PG 70-28	324	30

4.3 Confined Flow Number Results

Flow numbers from the confined testing are summarized in Table 16. The flow numbers from the confined tests are highly variable with most of the coefficients of variation exceeding 50 percent. The cause of the increased variability is not clear. One reasonable hypothesis is that the confining pressure reduces the importance of the asphalt binder on the failure properties of the mixture making the flow number more dependent on the aggregate portion of the mixture. The properties of the aggregate portion of an asphalt mixture are significantly more variable within a specimen and from specimen to specimen than the asphalt binder; therefore, the variability of the flow number increases.

The permanent strain in the confined tests prior to flow was somewhat less variable. Table 17 summarizes the number of cycles to 1 percent permanent strain. The coefficients of variations for these data, while still high, were significantly lower than those for the flow numbers. Because the cycles to 1 percent permanent strain data were significantly less variable, this data was used to analyze the sensitivity of the confined flow number test to mixture variations.

Table 16. Summary of Flow Numbers from the Confined Flow Number Testing.

Source	Mixture	Binder	Flow Number					
			Specimen 1	Specimen 2	Specimen 3	Average	Standard Deviation	Coefficient of Variation, %
Cisler	E3	PG 58-28	238	1038	315	530.3	441.3	83.2
	E10	PG 58-28	403	253	2349	1001.7	1169.2	116.7
	E10	PG 70-28	377	2053	951	1127.0	851.7	75.6
Christian/ Gade	E3	PG 58-28	3436	1360	1135	1977.0	1268.5	64.2
	E10	PG 58-28	231	944	6840	2671.7	3627.4	135.8
	E10	PG 70-28	3274	1204	969	1815.7	1268.4	69.9
Glenmore	E3	PG 58-28	404	1061	859	774.7	336.5	43.4
	E10	PG 58-28	1344	778	1163	1095.0	289.1	26.4
	E10	PG 70-28	1183	9997	9997	7059.0	5088.8	72.1
Wimmie	E3	PG 58-28	1486	1169	427	1027.3	543.5	52.9
	E10	PG 58-28	5349	1786	9997	5710.7	4117.4	72.1
	E10	PG 70-28	773	1685	1954	1470.7	619.0	42.1

Table 17. Summary of the Number of Cycles to 1 Percent Permanent Strain from the Confined Flow Number Testing.

Source	Mixture	Binder	Cycles to 1 Percent Permanent Strain					
			Specimen 1	Specimen 2	Specimen 3	Average	Standard Deviation	Coefficient of Variation, %
Cisler	E3	PG 58-28	65	55	56	58.7	5.5	9.4
	E10	PG 58-28	125	73	112	103.3	27.1	26.2
	E10	PG 70-28	85	472	220	259.0	196.4	75.8
Christian/ Gade	E3	PG 58-28	85	80	26	63.7	32.7	51.4
	E10	PG 58-28	76	138	145	119.7	38.0	31.7
	E10	PG 70-28	1765	849	1307	1307.0	458.0	35.0
Glenmore	E3	PG 58-28	639	443	582	554.7	100.8	18.2
	E10	PG 58-28	357	290	384	343.7	48.4	14.1
	E10	PG 70-28	2072	5879	10000	5983.7	3965.0	66.3
Wimmie	E3	PG 58-28	58	52	53	54.3	3.2	5.9
	E10	PG 58-28	88	124	90	100.7	20.2	20.1
	E10	PG 70-28	430	474	477	460.3	26.3	5.7

The cycles to 1 percent permanent strain are presented graphically in Figure 44. The error bars represent 95 percent confidence intervals based on the measured data. The rutting resistance of asphalt mixtures improves as the number of cycles increases. Figure 44 shows the rutting resistance of the E-10 PG 70 mixtures is better than that for the E-3 PG 58 mixtures and the E-10 PG 58 mixtures. The rutting resistance of the E-10 PG 58 mixtures is generally better than that for the E-3 PG 58 mixtures except for the Glenmore 19 mm mixture where the E-10 PG 58 mixture has slightly poorer rutting resistance than the E-3 PG 58 mixture. For the PG 58 mixtures, the three 12.5 mm mixtures have similar rutting resistance, while the rutting resistance of the 19 mm mixture is somewhat higher. For the PG 70 mixtures, the Cisler and Wimmie sources have similar rutting resistance; the rutting resistance of the Christian/Gade and Glenmore sources are higher compared to the Cisler and Wimmie sources. These findings are similar to those for the flow numbers from the unconfined tests.

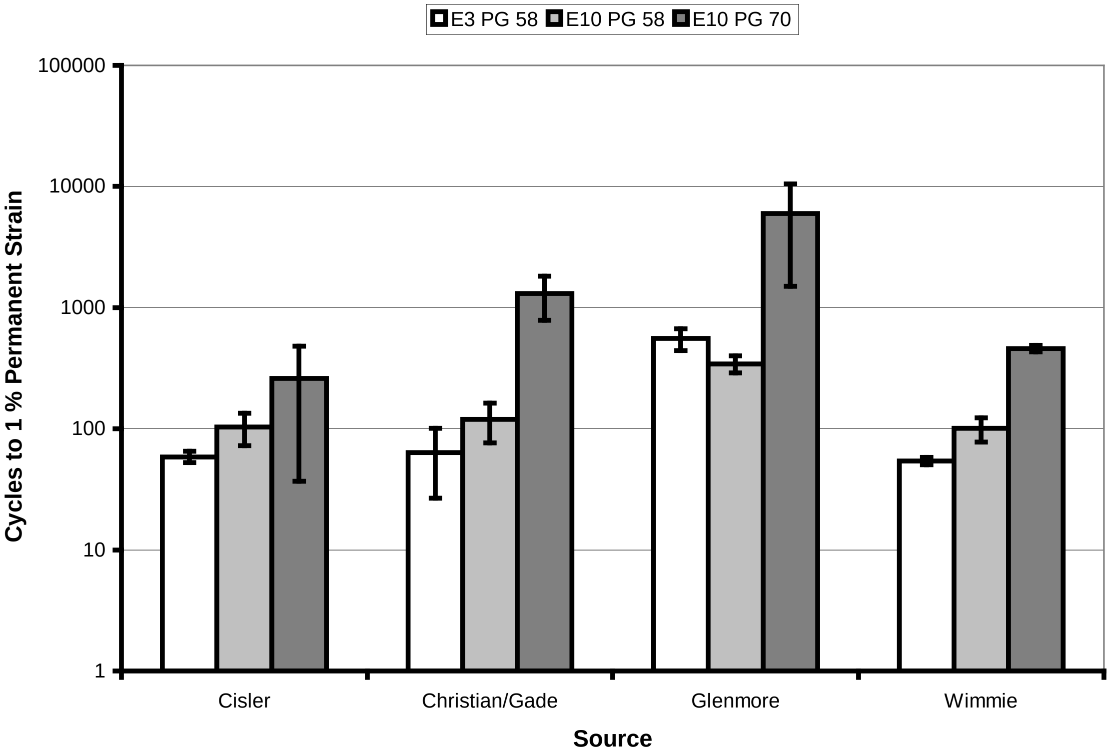

Figure 44. Cycles to 1 Percent Permanent Strain in the Confined Flow Number Tests.

To determine if cycles to 1 percent permanent strain in the confined flow number test is sensitive to changes in VMA and fine aggregate angularity, a multiple regression analysis was performed on the data from the E-3 and E-10 mixtures incorporating PG 58-28 binder. The analysis is summarized in Table 18. The resulting model is similar, but not as strong as the one formulated from the unconfined flow number data. The explained variance is somewhat lower and the statistical significance of the coefficients for VMA and FAA are not as strong. This is probably the result of the greater variability in the confined flow number test.

Table 18. Summary of Multiple Regression Analysis of Cycles to 1 Percent Strain in Confined Flow Number Tests for E3 and E10 Mixtures with PG 58-28.

Regression Statistics						
Multiple R	0.86725					
R Square	0.752122					
Adjusted R Square	0.652971					
Standard Error	106.0383					
Observations	8					
Analysis of Variance						
	Df	*SS*	*MS*	*F*	*Significance F*	
Regression	2	170586.8	85293.38	7.585602	0.030591	
Residual	5	56220.57	11244.11			
Total	7	226807.3				
Model						
	Coefficients	*Standard Error*	*t Statistic*	*p-value*	*Lower 95% CI*	*Upper 95% CI*
Intercept	-1832.26	1878.98	-0.97513	0.374279	-6662.32	2997.806
Design VMA	-126.011	45.36024	-2.77801	0.038994	-242.613	-9.40903
FAA	85.83362	37.23586	2.305133	0.069327	-9.88405	181.5513

The Spearman rank correlation coefficient can be used to assess whether the unconfined and confined flow number tests provide different rankings of the rutting resistance of the 12 mixtures tested. The Spearman rank correlation coefficient is similar to the well know Pearson product-moment correlation coefficient except the analysis is performed on rank data (*18*). Table 19 summarizes this analysis for the data from the unconfined and confined flow number tests. In Table 19, the rutting resistance of the mixtures are ranked with the mixture with the poorest rutting resistance having a rank of 1. The E-3, 12.5 mm mixtures generally have the poorest rutting resistance, followed by the PG 58 E-10, 12.5 mm mixtures, then the 19 mm PG 58 mixtures and finally the E-10 PG 70 mixtures. The resulting Spearman rank correlation coefficient of 0.937 is statistically significant at the 99 percent level confirming that the rankings from the two types of flow number tests are very similar.

Table 19. Summary of Spearman Rank Correlation Analysis for Unconfined and Confined Flow Number Test Data.

Mixture			Ranking			
Source	Design Traffic	PG Grade	Unconfined Flow Number	Confined Cycles to 1 % Permanent Strain	Ranking Difference	Ranking Difference^2
Cisler	3	58-28	1	2	-1	1
	10	58-28	4	5	-1	1
	10	70-28	9	7	2	4
Christian/Gade	3	58-28	2	3	-1	1
	10	58-28	5	6	-1	1
	10	70-28	11	11	0	0
Glenmore	3	58-28	8	9	-1	1
	10	58-28	7	8	-1	1
	10	70-28	12	12	0	0
Wimmie	3	58-28	3	1	2	4
	10	58-28	6	4	2	4
	10	70-28	10	10	0	0
					Sum	18
					Spearman Rank Correlation Coefficient	0.937

4.4 Rutting Resistance Predictive Model

In NCHRP Projects 9-25 and 9-31 a model was developed to estimate rutting resistance from mixture volumetric composition (*8*). This model was subsequently improved through additional research in NCHRP Project 9-33 and Airfield Asphalt Pavement Technology Program Project 04-02 (*19*). Equation 18 presents the latest version of this model, which can be used to estimate the rutting resistance of a mixture from volumetric composition, in-place compaction and binder properties (*19*).

$$TR = 9.85 \times 10^{-5} \left(\mathrm{P} N_{eq} K_s \right)^{1.373} V_d^{1.5185} V_{IP}^{-1.4727} M \tag{18}$$

where:

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

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

P = resistivity, s/nm

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

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

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

$\cong$ the sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0

G_a = the bulk specific gravity of the aggregate blend

VMA = design voids in the mineral aggregate for the mixture, volume

N_{et} = design gyrations

K_s = speed correction

= $(v/70)^{0.8}$, where v is the average traffic speed in km/hr

V_d = design air void content, volume %

V_{IP} = air void content, volume %, in-place

M = 7.13 for mixtures containing typical polymer-modified binders, 1.00 otherwise

Table 20 summarizes the allowable traffic from this model for an in-place air void content of 7 percent and traffic speeds of 40, 20, and 1 mph.

Table 20. Summary of Estimated Rutting Resistance.

Mixture			Gradation				Aged Binder G*/sinδ Pa	Design Volumetrics				M	In-Place V_{ip} %	40 mph		20 mph		1 mph	
Source	Design Traffic Level	Binder Grade	0.3 mm	0.15 mm	0.075 mm	Sa m/kg^2		Gsb	VMA %	N	V_d %			K	TR MESAL	K	TR MESAL	K	TR MESAL
Cisler	E3	PG 58-28	13.3	5.9	4.1	4.66	99900	2.650	14.3	75	4	1	7	0.935	10	0.537	4	0.049	0.2
Cisler	E10	PG 58-28	11.2	5.6	3.7	4.1	99900	2.665	15.8	100	4	1	7	0.935	7	0.537	3	0.049	0.1
Cisler	E10	PG 70-28	11.2	5.6	3.7	4.1	153504	2.665	15.8	100	4	7.13	7	0.935	86	0.537	40	0.049	1.5
Christian/ Gade	E3	PG 58-28	11.9	6.4	3.8	4.42	99900	2.733	14.6	75	4	1	7	0.935	8	0.537	4	0.049	0.1
Christian/ Gade	E10	PG 58-28	12.8	7.1	4.1	4.8	99900	2.736	15.4	100	4	1	7	0.935	12	0.537	6	0.049	0.2
Christian/ Gade	E10	PG 70-28	12.8	7.1	4.1	4.8	153504	2.736	15.8	100	4	7.13	7	0.935	143	0.537	67	0.049	2.5
Glenmore	E3	PG 58-28	11.7	5.4	3.5	4.12	99900	2.747	13.5	75	4	1	7	0.935	10	0.537	4	0.049	0.2
Glenmore	E10	PG 58-28	11.5	5.5	3.3	4.06	99900	2.747	13.2	100	4	1	7	0.935	15	0.537	7	0.049	0.3
Glenmore	E10	PG 70-28	11.5	5.5	3.3	4.06	153504	2.747	13.2	100	4	7.13	7	0.935	192	0.537	90	0.049	3.3
Wimmie	E3	PG 58-28	13.5	5.6	3.3	4.48	99900	2.713	14.6	75	4	1	7	0.935	8	0.537	4	0.049	0.1
Wimmie	E10	PG 58-28	11.7	4.6	2.6	3.78	99900	2.721	15.1	100	4	1	7	0.935	7	0.537	3	0.049	0.1
Wimmie	E10	PG 70-28	11.7	4.6	2.6	3.78	153504	2.721	15.1	100	4	7.13	7	0.935	88	0.537	41	0.049	1.5

Figure 45 compares the estimated allowable traffic for the 12 mixtures for the 40 mph traffic speed. This comparison agrees reasonably well with the WisDOT designs. Based on the model, all E-3 mixtures have adequate rutting resistance. The Christian/Gade and Glenmore E-10 mixtures with PG 58-28 binder also have adequate rutting resistance. The rutting resistance for the Cisler and Wimmie E-10 mixtures with PG 58-28 binder are not sufficient for design traffic of 10 million ESAL. These mixtures have estimated allowable traffic levels of approximately 7 million ESAL. All of the E-10 PG 70 mixtures have adequate rutting resistance for 30 million ESAL traffic. The Christian/Gade and Glenmore E-10 mixtures with PG 70-28 binder are predicted to have adequate rutting resistance for 100 million ESAL traffic.

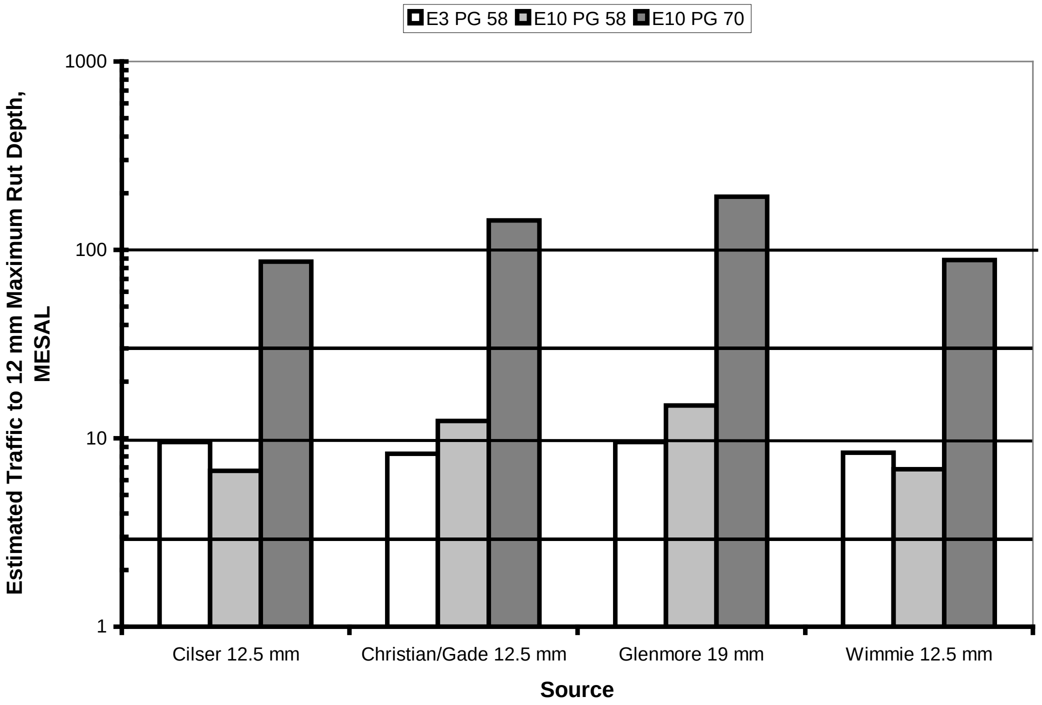

Figure 45. Comparison of Estimated Allowable Traffic for Traffic Speed of 40 mph.

4.5 Adjusted Flow Number Criteria

The NCHRP Project 9-33 flow number criteria appear to be conservative for the mixtures tested in this study. The allowable traffic from the predictive model is more in line with the reported field performance of the mixtures. One potential reason that the NCHRP Project 9-33 criteria are not in good agreement is the algorithm for computing the flow number has been changed since the NCHRP 9-33 were developed. The NCHRP Project 9-33 criteria were developed from flow number data collected using a forward finite difference algorithm (*2*). The flow number computed from this algorithm was found to be sensitive to the cycle interval used in the computations. During ruggedness testing of the AMPT, the finite difference algorithm was replaced with the Francken model used in this study (*4*).

Revised flow number criteria can be developed by relating the allowable traffic from the predictive model to the measured flow number. This is the same methodology that was originally used to develop the NCHRP 9-33 criteria. The results are summarized in Table 21 and shown graphically in Figure 46. For estimating the rutting resistance with the predictive model, the average volumetric properties of the specimens tested were used and the traffic speed was assumed to be 40 mph. Figure 46 shows that there is a good relationship between predicted rutting resistance and the flow number. The revised flow number criteria were obtained by solving the relationship in Figure 46 for flow number at various design traffic levels. The results are presented in Table 22 rounded to the nearest 5 cycles.

Table 21. Estimated Allowable Traffic at 40 mph and Measured Flow Numbers.

Mixture			Estimated Allowable Traffic, MESAL	Flow Number, Cycles
Source	Design Traffic Level	Binder Grade		
Cisler	E3	PG 58-28	6.5	21
Cisler	E10	PG 58-28	6.3	39
Cisler	E10	PG 70-28	80.8	262
Christian/Gade	E3	PG 58-28	6.7	30
Christian/Gade	E10	PG 58-28	7.2	45
Christian/Gade	E10	PG 70-28	85.0	846
Glenmore	E3	PG 58-28	16.2	96
Glenmore	E10	PG 58-28	18.4	86
Glenmore	E10	PG 70-28	231.3	1131
Wimmie	E3	PG 58-28	9.7	32
Wimmie	E10	PG 58-28	13.9	54
Wimmie	E10	PG 70-28	175.4	324

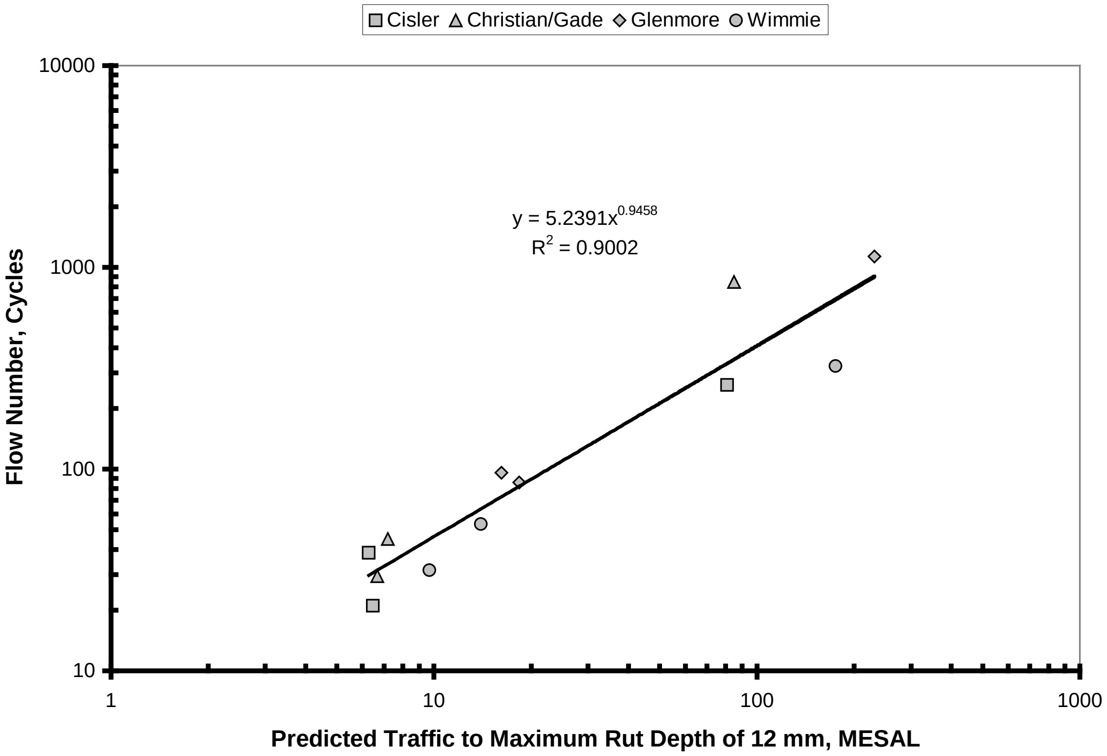

Figure 46. Relationship Between Flow Number and Estimated Allowable Traffic at 40 mph.

Table 22. Minimum Flow Number for Various Traffic Levels.

Design Traffic Level, MESAL	Minimum Flow Number, Cycles
3	15
10	50
30	135
100	415

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

5.1.2 Dynamic Modulus

Dynamic modulus master curves were developed with the AMPT and its associated testing and analysis procedures for mixtures from four aggregate sources: Cisler, Christian/Gade, Glenmore, and Wimmie. For each aggregate source, master curves were developed for E-3 and E-10 mixtures containing a neat PG 58-28 binder, and an E-10 mixture containing a modified PG 70-28. A total of 12 master curves were developed. Comparison of the master curves revealed the following:

1. For a given aggregate source, the E-3 PG 58, E-10 PG 58, and E-10 PG 70 mixtures all had similar dynamic modulus values when the variability of the testing was considered.
2. For the three mixture types, the Christian/Gade and Glenmore sources had consistently higher dynamic modulus values for high temperature conditions and higher limiting minimum modulus values. The limiting minimum modulus represents the stiffness of the aggregate, suggesting that the aggregate structure in these mixtures provides greater resistance to permanent deformation than the Cisler and Wimmie sources.

The dynamic modulus master curves were used with the Excel spreadsheet developed in NCHRP Project 9-19 to predict rutting in a 2.5 in surface course for the climate of Madison, Wisconsin. This analysis provided the following conclusions:

1. For traffic speeds of 40 and 20 mph, less than 0.15 in of rutting is expected to accumulate in mixtures from the four sources for their design traffic level.
2. For a traffic speed of 1 mph, the predicted rutting was significantly higher ranging from 0.15 to 0.45 in at the design traffic level. The predicted rutting was consistently lower for the Christian/Gade and Glenmore sources.

3. The PG 70 binder had only a minor impact on the predicted rutting because for uniform seasonal loading, many more load application occur at intermediate and low temperatures were the stiffness of the E-10 PG 70 mixtures is the same or lower than that for the E-10 PG 58 mixtures.

The measured dynamic modulus values were compared to dynamic modulus values predicted using the Hirsch model and two forms of the Witczak dynamic modulus equation. All three models provide the capability to estimate mixture dynamic modulus from mixture composition and binder properties. These comparisons showed the following:

1. The Hirsch model provides a reasonable prediction of the dynamic modulus for the 12 mixtures that were tested. On average the Hirsch model overestimates the measured dynamic modulus by only 2 percent, and has errors that are reasonably distributed about zero with maximum errors of approximately ± 50 percent of the measured value. The Hirsch model requires a binder modulus master curve for the binder in the mixture and mixture volumetric properties that are available from mixture design data.
2. The latest version of the Witczak dynamic modulus equation, using measured binder modulus and phase angle data, provided the poorest fit to the measured data. On average, this model overestimated the measured dynamic modulus by 64 percent with errors ranging from –25 to + 150 percent of the measured value. The bias in this model appears to have been introduced by the relationships used in the calibration of this model to predict binder moduli and phase angles from historical viscosity temperature susceptibility data.
3. The viscosity based Witczak dynamic modulus equation with typical viscosity temperature susceptibility parameters for PG 58-28 and PG 70-28 binders provided a better fit to the measured data than the latest Witczak dynamic modulus equation. On average this model overestimated the dynamic modulus by 19 percent with errors ranging from –50 to +150 percent of the measured value.

5.1.2 Flow Number

Unconfined and confined flow numbers were measured with the AMPT for mixtures from four aggregate sources: Cisler, Christian/Gade, Glenmore, and Wimmie. Flow numbers were measured using a temperature of 49.6 °C, which is 50 percent reliability high performance grade temperature from LTPPBind 3.1 for surface courses in Madison, Wisconsin. For each source, flow numbers were measured for E-3 and E-10 mixtures containing a neat PG 58-28 binder, and an E-10 mixture containing a modified PG 70-28.

Data from the unconfined and confined flow number tests were found to be correlated and sensitive to the same mixture properties. The data from unconfined flow number tests were found to be significantly less variable.

The flow number was affected by the grade of the binder, the fine aggregate angularity, and design VMA of the mixture. The binder grade had the greatest effect, with the flow number increasing by a factor of 6 to 20 when the binder grade was increased from PG 58-28 to PG 70-28. The effects of fine aggregate angularity and design VMA were much less. Increasing the fine aggregate angularity from 43 to 45 or decreasing the design VMA by 1 percent increased the flow number by a factor of 2.

The flow number criteria developed in NCHRP Project 9-33 appear to be conservative for the mixtures tested. Based on the NCHRP Project 9-33 criteria, only two of the E-10 PG 58 mixtures had flow numbers exceeding the NCHRP 9-33 criteria for 3 million ESAL.

Rutting resistance for the 12 mixtures was predicted using a model developed in NCHRP Projects 9-25 and 9-31 and further refined in NCHRP Project 9-33 and Airfield Asphalt Pavement Technology Project 04-02. With this model the allowable traffic to a maximum rut depth of 12 mm can be estimated from volumetric composition, binder properties, and in-place compaction. The allowable traffic predicted with this model more closely approximated the field performance of the mixtures tested. A good relationship was found between the measured flow numbers and the allowable traffic predicted with the model. This relationship was used to developed revised flow number criteria.

5.2 Recommendations

5.2.1 Uses of AMPT Equipment

The AMPT equipment and associated testing and analysis procedures provide the capability to rapidly evaluate properties of asphalt mixtures associated with pavement structural design and rutting performance. WisDOT should continue with the planned purchase of this equipment and the collection of dynamic modulus and flow number data for additional Wisconsin mixtures. This will allow WisDOT to begin transitioning to mechanistic based asphalt mixture and pavement structural design. For pavement structural design, the AMPT can be used to construct the dynamic modulus master curves needed in the AASHTO MEPDG. For mixture design, unconfined flow number tests conducted in the AMPT provide a rapid means of evaluating the rutting resistance of asphalt mixtures. Before widespread implementation of the AMPT equipment is planned by WisDOT, additional evaluation of the MEPDG and the flow number criteria are needed as discussed below.

5.2.2 MEPDG

The dynamic modulus master curves developed in this study for E-3, E-10 PG 58, and E-10 PG 70 mixtures can be used to by the WisDOT to evaluate the AASHTO MEPDG for WisDOT conditions. The master curves developed in this study can be used as input in the MEPDG to predict the performance of various pavement sections. These predictions can then be compared to performance data contained in the WisDOT pavement management database. Dynamic modulus values for other mixtures can be estimated from mixture composition using the Hirsch model, provided a representative binder master curve is available. If a binder master curve is not available, the Witczak dynamic modulus equation with typical viscosity-temperature susceptibility parameters may be used to estimate dynamic modulus values. Use of the Witczak dynamic modulus equation with measured binder modulus and phase angles is not recommended due to the apparent bias in this model.

5.2.3 Mixture Design

Future evaluation of mixture rutting resistance should be conducted using unconfined flow number tests. Data from unconfined and confined flow number tests were found to be correlated and sensitive to the same mixture properties. However, unconfined flow number tests were much more repeatable than confined flow number tests.

The NCHRP 9-33 criteria for rutting resistance using the flow number test appear to be conservative based on the reported field performance of the mixtures tested. Revised criteria were developed in this project that better represent the field performance of the mixtures tested. Flow number tests should be conducted on additional mixtures with known performance to validate the revised criteria.

Mixture flow numbers can be estimated from mixture composition using the model developed in NCHRP Projects 9-25 and 9-31 (Equation 18) and the relationship between flow number and allowable traffic shown in Figure 46. When using Equation 18 to predict allowable traffic, it is assumed that the aggregates in the mixture meet the angularity requirements given in AASHTO M323.

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Appendix A. WisDOT Approved Mixture Designs

Contents

MATHY CONSTRUCTION CO.
GENERAL CONTRACTORS
920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650
PHONE 608-781-4683 FAX 608-781-4694

AASHTO R18

Report of Bituminous Mix Design

Project Name	Marshfield - Spencer STH 13 (E-3)
Date	October 18, 2005
Project #	1620-00-70
Test #	22-5-12-E3-12.5
County	Marathon
Specifications	12.5mm E3 Mix
Course/Layer	
Design ESALs	2,000,000

Mix Properties

Trial #	1	2	3	4	5	6
AC Content (% by Wt)	4.0	4.5	5.0	5.5		4.9
Compaction Level	**Design**	**Design**	**Design**	**Design**		**Max**
Air Voids V_a (%)	6.6	5.1	3.6	2.5		4.0
$\%G_{mm}$ @ N_i	87.3	88.8	90.0	90.9		90.5
$\%G_{mm}$ @ N_{final}	93.4	94.9	96.4	97.5		**96.9**
VMA (%)	14.7	14.4	14.2	14.3		13.5
VFA (%)	55.2	64.9	74.9	82.5		70.2
Density (kg/m^3)	2355	2375	2395	2403		2409
G_{mb}	2.355	2.375	2.395	2.403		2.409
G_{mm}	2.521	2.502	2.483	2.465		**2.487**

Gyrations	
N_i	7
N_d	75
N_m	115

Antistrip
None

Mix Design

Property	Value	Specification
Design P_b	4.9	
Added P_b	4.9	
V_a	4.0	4.0
VMA	14.3	14.0 Min
VFA	72.0	65 - 75
G_{mm}	2.487	
G_{mb}	2.387	
P_{be}	4.4	
P_{ba}	0.5	
Dust/Binder Ratio	0.9	0.6 - 1.2
$\%G_{mm}$ @ N_i	89.7	< 89.0 Rec
$\%G_{mm}$ @ N_d	96.0	~ 96.0
$\%G_{mm}$ @ N_m	96.9	98.0 Max
TSR Ratio	80.3	70 Min
Rec. Mix Temp.	275-300	

Primary AC Source	*AC Type*	*Gb*
MIF - LaCrosse	PG 58-28	1.03
Alternate Sources		
MIF - LaCrosse	PG 64-28	1.031
MIF - LaCrosse	PG 64-22	1.036

Average # of Gyrations	20

Since this design is material specific, the conclusions and recommendations contained within are obtained from material submitted to and subjected to observations under laboratory conditions. Adjustments may become necessary when field laboratory data is obtained from plant produced mix. No guarantee or warranty is implied or offered.

WisDOT Mix Design ID: 250-0058-2005 - Reviewed by: Judie Ryan; WisDOT Mix Design Specialist

Signature ______ Cert. No. 361 Date: 6/4/2008

MATHY CONSTRUCTION CO.
GENERAL CONTRACTORS
920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650
PHONE 608-781-4683 FAX 608-781-4694

43 Min
40 Min

AASHTO R18

Report of Bituminous Mix Design

Project Name	Marshfield - Spencer STH 13 (E-3)
Date	October 18, 2005
Project #	1620-00-70
Test#	22-5-12-E3-12.5
County	Marathon
Specifications	12.5mm E3 Mix
Course/Layer	

Aggregate Sources

	Percent	Material	Location / Source	G_{sb}
1	20	1/2" Bit. Rock (124)	Cisler 5,26,7E Marathon	2.660
2	20	3/8 Bit Rock(129)	Cisler 5,26,7E Marathon	2.642
3	30	3/16 Screenings (130)	Cisler 5,26,7E Marathon	2.665
4	30	5/8 Screened Sand (231)	River Pit PL 22 9,27,7E Marathon	2.635
5				
6				
7				

Total	1	2	3	4	5	6	7	Combined G_{sb}	2.650
Virgin Agg Blend								Combined G_{se}	2.682

Aggregate Gradations

Sieve		Material							Job Mix	Spec	
(Std)	(mm)	1	2	3	4	5	6	7		High	Low
2"	50	100.0	100.0	100.0	100.0				100.0		
1.5"	37.5	100.0	100.0	100.0	100.0				100.0		
1"	25	100.0	100.0	100.0	100.0				100.0		
3/4"	19	100.0	100.0	100.0	100.0				100.0		
1/2"	12.5	79.0	100.0	100.0	99.0				95.5		
3/8"	9.5	31.0	97.0	100.0	97.0				84.7		
#4	4.75	4.2	33.0	98.0	88.0				63.2		
#8	2.36	2.8	14.0	67.0	78.0				46.9		
#16	1.18	2.4	9.0	44.0	68.0				35.9		
#30	0.6	2.1	6.5	30.0	51.0				26.0		
#50	0.3	1.9	4.5	21.0	19.0				13.3		
#100	0.15	1.6	4.0	14.0	2.0				5.9		
#200	0.075	1.3	3.0	10.0	0.8				4.1		
Soundness		162-12	162-12	162-12						12 Max	
LAR 100/500 Rev		2004	2004	2004						13 & 45 Max	
Crush 1 Face (%)		100.0	100.0	100.0	27.0				92.9	75 Min	
Crush 2 Face (%)		100.0	100.0	100.0	24.0				92.6	60 Min	
Sand Equiv.									83.0	40 Min	
Flat & Elong (%)		2.0	2.9	2.2	1.1				2.2	5 Max	
Fine Agg Ang									43.5	43 Min	
Water Abs.		0.4	0.3	0.6	0.6				0.4		

Test Methods: D312, T176/D2419, T11/C117, T27/C136, D4791, D5821, T304/C1252, T96/C131, T209/D2041, T166/D2726

Test Number: 0 - 250 - 0053 - 2002

Labsite:

Page 1 of 2

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 4060-00-72
HORICON ST, CITY MAYVILLE, CTH TW - CLARK ST
CONST OPS - GRADE, BASE & SURFACE
STH 28

Date Sampled: 03/11/02
By: PAULA ABREGO

Date Received: 05/08/02

Date Tested:
By: JAMES BONGARD

Source: CHRISTIAN

Legal Description: W, SW, Section: 33, T: 12 N, R: 15, E

County: DODGE

Design Lab: NORTHEAST ASPHA;LT, INC.
Design ID: 800202

Mix Type: E3-12.5
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	5/8" X 1/2" CHIP	CHRISTIAN	Pit	W, SW, Section: 33, T: 12 N, R: 15, E	217-32-2001
2	1/2" X 1/4" CHIP	CHRISTIAN	Pit	W, SW, Section: 33, T: 12 N, R: 15, E	217-32-2001
3	WASHED MFG'D SAND	CHRISTIAN	Pit	W, SW, Section: 33, T: 12 N, R: 15, E	217-32-2001
4	SCREENED NATURAL SAND	CHRISTIAN	Pit	W, SW, Section: 33, T: 12 N, R: 15, E	217-32-2001
5	WASHED NATURAL SAND	CHRISTIAN	Pit	W, SW, Section: 33, T: 12 N, R: 15, E	217-32-2001
6	SCREENED NATURAL SAND	MICHELS BECKER	Pit	SW, SW, Section: 27, T: 11 N, R: 18, E	217-114-1997

Sieve Sizes	1	2	3	4	5	6	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	71.4	100.0	100.0	100.0	100.0	100.0	95.7
9.5 (3/8")	13.3	93.6	100.0	100.0	99.9	100.0	86.0
4.75 (#4)	2.7	5.5	87.6	87.3	85.7	94.5	63.8
2.36 (#8)	2.3	3.0	58.0	68.7	65.4	80.4	48.4
1.18 (#16)	2.1	2.7	37.3	51.2	45.2	67.4	36.0
0.600 (#30)	2.0	2.6	23.0	36.5	26.8	50.2	24.7
0.300 (#50)	2.0	2.6	13.7	23.1	10.8	18.5	11.7
0.150 (#100)	1.9	2.5	7.6	15.2	4.5	4.4	5.4
75 µm (#200)	1.8	2.4	4.4	10.4	2.6	2.4	3.5
Agg Blend %:	15.0	15.0	25.0	8.0	14.0	23.0	100.0
Gsb:	2.785	2.787	2.741	2.741	2.745	2.645	2.733

% AC (Total): 5.2 Added
Grade: PG 58-28
Source: AMOCO-MILW
AC Sp. Gr: 1.029 @ 25/25°C
RAP % AC:
Mixing Temp (°C): 135-149
Compaction Temp (°C):
Design Comp. Effort: 75 Ndes

% Air Voids: 4.02%
Gmm: 2.565
Gmb: 2.462
Gse: 2.794
%VMA 14.6
% VFB: 72.5
Sand Equiv. (%): 0.0
Stability (N):

Agg. Angularity (Fines): 43.3
Gmm Dryback Correction:
Unit Wt (PCF): 153.23
Fracture: 95.2 1F 92.4 2F
Thin/Elong: 0.5
TSR: 87.8
TSR Comp. Effort: 21.0 N
Anitstrip: NONE

Verified Date: 10/10/2002

Verified By: JUDIE RYAN

Test Number: 0 - 250 - 0053 - 2002

Labsite:

Page 2 of 2

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 4060-00-72

HORICON ST, CITY MAYVILLE, CTH TW - CLARK ST
CONST OPS - GRADE, BASE & SURFACE
STH 28

Date Sampled:	**Date Received:**	**Date Tested:**
03/11/02	05/08/02	
By: PAULA ABREGO		By: JAMES BONGARD

Source: CHRISTIAN **Legal Description:** W, SW, Section: 33, T: 12 N, R: 15, E **County:** DODGE

Remarks: Satisfactory

Nini = 7	%Gmm = 89.0
Nmax = 115	%Gmm = 96.5
DP = 0.9	
MA = 0.9	

Test Number: 0 - 250 - 0096 - 2003

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Labsite:
Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Page 1 of 2

Main Project ID: 4517-00-71
LIBAL STREET, VILLAGE OF ALLOUEZ
LE BRUN ROAD-VANDE HEI ROAD & KALB STREET-N. VILLAGE LIMITS
LOCAL STREET

Quantity:

Date Sampled: 03/14/03
By: KARL RUNSTROM

Date Received: 06/30/03

Date Tested:
By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Design Lab: NORTHEAST ASPHALT, INC.
Design ID: 805002

Mix Type: E-3 - 19.0 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	7/8" X 5/8" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
2	5/8" X 1/2" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
3	1/2" X 1/4" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
4	1/4" SCREENINGS	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
5	WASHED MANUFACTURED SAN	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
6	WASHED NATURAL SAND	VAN HANDEL	Pit	33, T: 21 N, R: 20, E	

Sieve Sizes	1	2	3	4	5	6	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	99.7	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	53.2	76.5	100.0	100.0	100.0	100.0	89.9
9.5 (3/8")	12.5	20.6	92.2	100.0	100.0	100.0	76.9
4.75 (#4)	1.9	4.8	9.9	88.8	88.6	93.2	62.9
2.36 (#8)	1.9	3.7	5.0	59.5	53.0	80.3	45.0
1.18 (#16)	1.8	3.1	4.3	42.9	29.3	69.2	32.6
0.600 (#30)	1.8	2.8	4.0	33.1	15.9	56.3	23.8
0.300 (#50)	1.8	2.7	3.9	27.7	9.4	28.8	13.5
0.150 (#100)	1.8	2.6	3.8	23.3	5.8	5.9	5.6
75 µm (#200)	1.6	2.4	3.4	17.2	3.0	2.6	3.3
Agg Blend %	16.0	11.0	5.0	5.0	35.0	28.0	100.0
Gsb:	2.740	2.743	2.708	2.798	2.790	2.697	2.747

% AC (Total): 4.5 Added
Grade: PG 58-28
Source: KOCH-GREEN BAY
AC Sp. Gr: 1.031 @ 25/25°C
RAP % AC:
%VMA: 13.5
% VFB: 70.3
Sand Equiv. (%): 80.0

% Air Voids: 4.01%
Gmm: 2.592
Gmb: 2.488
Gse: 2.791
Nini: 7
Ndes: 75
Nmax: 115

FAA: 45.7
Gmm Corr:
Unit Wt (PCF): 154.85
% Gmm: 89.6
% Gmm: 96.7

Mixing Temp (°C): 135-149
Compaction Temp (°C):
Moisture Absorption: 1.00
Dust Proportion: 1.00
Fracture: 100.0 1F 100.0 2F
Thin/Elong: 0.8
TSR: 73.9 **Comp. Effort:** 22.0 N
Anitstrip: NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.1		2.608	2.465	5.5	13.9	60.4
B	4.6		2.588	2.488	3.9	13.6	71.3
C	5.1	.00	2.567	2.512	2.1	13.2	84.1
D	5.6		2.547	2.524	.9	13.3	93.2

Verified Date: 07/01/2003 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0096 - 2003

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Labsite:

Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Page 2 of 2

Main Project ID: 4517-00-71

LIBAL STREET, VILLAGE OF ALLOUEZ
LE BRUN ROAD-VANDE HEI ROAD & KALB STREET-N. VILLAGE LIMITS
LOCAL STREET

Quantity:

Date Sampled:	**Date Received:**	**Date Tested:**
03/14/03	06/30/03	
By: KARL RUNSTROM		By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Remarks:

Note: The above mix design was submitted as non-compliant with WisDOT S.S. 407.2.2.1 General and WisDOT Test Method 1559-01 regarding the requirement for design submittal a minimum of 2 working days prior to paving. Per District approval, this design was considered "satisfactory for use" prior to the submittal and review process. Continued non-compliance with the specified procedures for mix design submittal may result in a change of submittal status for the designer and/or affiliated design laboratory.

Test Number: 0 - 250 - 0048 - 2005

Labsite:
Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Page 1 of 2

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Main Project ID: 6390-00-71
LETENDRE AVE. & WISC. RIVER DRIVE
SWANSON ROAD - SENECA RD
WOOD COUNTY

Quantity:

Date Sampled:
05/11/05
By: JOHN JORGENSON

Date Received:

Date Tested:

Source: WMMIE

Legal Description: , NW, Section: 28, T: 23 N, R: 9, E

County: PORTAGE

Design Lab: MATHY
Design ID: 83-5-10-E3-12.5

Mix Type: E-3 - 12.5 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	1/2" BIT GRAVEL	WMMIE	Pit		0 - 225 - 82 - 2006
2	1/4" SCREENINGS (249)	WMMIE	Pit		0 - 225 - 82 - 2006
3	MAN SAND (342)				
4	5/8" SCREENED SAND (231)				

Sieve Sizes	1	2	3	4	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	75.0	100.0	100.0	98.0	94.5
9.5 (3/8")	30.0	98.0	100.0	91.0	83.0
4.75 (#4)	2.9	71.0	100.0	77.0	63.2
2.36 (#8)	1.2	50.0	70.0	65.0	47.0
1.18 (#16)	1.1	35.0	48.0	56.0	35.4
0.600 (#30)	1.0	22.0	30.0	39.0	23.3
0.300 (#50)	0.9	16.0	17.0	11.0	11.9
0.150 (#100)	0.9	11.0	7.4	2.7	6.4
75 µm (#200)	0.7	7.0	3.2	1.5	3.8
Agg Blend %	20.0	40.0	15.0	25.0	100.0
Gsb:	2.734	2.734	2.715	2.662	2.713

% AC (Total): 4.8 Added
Grade: PG 58-28
Source: MIF, LACROSSE
AC Sp. Gr: 1.030 @ 25/25°C
RAP % AC:
%VMA: 14.6
% VFB: 72.6
Sand Equiv. (%): 84.0

% Air Voids: 3.98%
Gmm: 2.536
Gmb: 2.435
Gse: 2.738
Nini: 7
Ndes: 75
Nmax: 115

FAA: 43.8
Gmm Corr:
Unit Wt (PCF): 151.55
% Gmm: 89.6
% Gmm: 96.8

Mixing Temp (°C): 275-300 F
Compaction Temp (°C):
Moisture Absorption: 0.60
Dust Proportion: 1.00
Fracture: 94.2 1F 92.7 2F
Thin/Elong: 3.0
TSR: 91.5 **Comp. Effort:** N
Anitstrip: NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.0	4.00	2.568	2.410	6.1	14.7	58.4
B	4.5	4.50	2.548	2.427	4.7	14.6	67.5
C	5.0	5.00	2.528	2.443	3.4	14.4	76.8
D	5.5	5.50	2.509	2.455	2.2	14.5	85.1

Verified Date: 06/04/2008 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0048 - 2005

Labsite:

Page 2 of 2

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 6390-00-71

LETENDRE AVE. & WISC. RIVER DRIVE
SWANSON ROAD - SENECA RD
WOOD COUNTY

Quantity:

Date Sampled:
05/11/05
By: JOHN JORGENSON

Date Received:

Date Tested:

Source: WMMIE

Legal Description: , NW, Section: 28, T: 23 N, R: 9, E

County: PORTAGE

Remarks: Satisfactory

Original aggregate data referenced in mix design was 0-162-0035-2001.
~~Alternate AC Grade PG 64-28, AC Source MIF-LaCrosse, AC Sp. Gr. 1.031.~~
Alternate AC Grade PG 64-22, AC Source MIF-LaCrosse, AC Sp. Gr. 1.036..

Test Number: 0 - 250 - 0186 - 2004

Labsite:
Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Page 1 of 2

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Main Project ID: 1610-04-73
ABBOTSFORD - MEDFORD ROAD
CTH O INTERSECTION
STH 13

Quantity:

Date Sampled:
08/21/04
By: JOHN JORGENSON

Date Received:
08/21/04

Date Tested:
By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Design Lab: MATHY CONSTRUCTION CO.
Design ID: 22-4-07-E10-12.5

Mix Type: E-10 - 12.5 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	1/2" CRUSHED ROCK	CISLER	QRY	NW, NW, Section: 5, T: 26 N, R: 7, E	0 - 217 - 0014 - 2004
2	3/8" CRUSHED ROCK	CISLER	QRY	NW, NW, Section: 5, T: 26 N, R: 7, E	0 - 217 - 0014 - 2004
3	3/16" CRUSHED ROCK	CISLER	QRY	NW, NW, Section: 5, T: 26 N, R: 7, E	0 - 217 - 0014 - 2004
4	MAN SAND	CISLER	QRY	NW, NW, Section: 5, T: 26 N, R: 7, E	0 - 217 - 0014 - 2004
5	BLEND SAND	RIVER	Pit	NW, SE, Section: 9, T: 27 N, R: 7, E	0 - 217 - 0064 - 2004

Sieve Sizes	1	2	3	4	5	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	81.0	100.0	100.0	100.0	99.0	95.1
9.5 (3/8")	36.0	97.0	100.0	100.0	98.0	83.3
4.75 (#4)	6.0	33.0	98.0	98.0	94.0	64.7
2.36 (#8)	4.0	10.0	68.0	69.0	86.0	46.3
1.18 (#16)	3.3	6.3	42.0	41.0	80.0	32.4
0.600 (#30)	3.1	5.0	27.0	28.0	58.0	22.7
0.300 (#50)	2.8	4.2	18.0	17.0	14.0	11.2
0.150 (#100)	2.4	3.6	12.0	8.0	1.4	5.6
75 µm (#200)	1.9	2.9	9.3	4.5	0.6	3.7
Agg Blend %	25.0	15.0	15.0	30.0	15.0	100.0
Gsb:	2.672	2.642	2.665	2.684	2.635	2.665

% AC (Total): 5.6 Added	**% Air Voids:** 4.00%	**FAA:** 45.1	**Mixing Temp (°C):** 135-149
Grade: PG 58-28	**Gmm:** 2.476	**Gmm Corr:**	**Compaction Temp (°C):**
Source: MIF-LACROSSE	**Gmb:** 2.377	**Unit Wt (PCF):** 147.94	**Moisture Absorption:** 0.50
AC Sp. Gr: 1.030 @ 25/25°C	**Gse:** 2.701		**Dust Proportion:** 0.70
RAP % AC:	**Nini:** 8	**% Gmm:** 88.5	**Fracture:** 98.1 1F 98.0 2F
%VMA: 15.8	**Ndes:** 100		**Thin/Elong:** 2.1
% VFB: 74.7	**Nmax:** 160	**% Gmm:** 96.9	**TSR:** 84.5 **Comp. Effort:** 34.0 N
Sand Equiv. (%): 85.0			**Anitstrip:** NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	5.0	.00	2.499	2.360	5.6	15.9	65.0
B	5.5		2.480	2.375	4.2	15.8	73.2
C	6.0		2.462	2.384	3.1	15.9	80.2
D	6.5		2.444	2.394	2.0	16.0	87.3

Verified Date: 01/11/2005 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0186 - 2004

Labsite:
Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Page 2 of 2

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Main Project ID: 1610-04-73
ABBOTSFORD - MEDFORD ROAD
CTH O INTERSECTION
STH 13

Quantity:

Date Sampled:	**Date Received:**	**Date Tested:**
08/21/04	08/21/04	
By: JOHN JORGENSON		By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Remarks: Satisfactory

Note: This design review has been updated to reflect the additional satisfactory use of MIF-LaCrosse PG 64-28 (having a specific gravity of 1.031) and MIF-LaCrosse PG 64-22 (having a specific gravity of 1.036) in meeting the mixture volumetric properties. Use on projects must still meet the contract requirements.

Test Number: 0 - 250 - 0061 - 2002

Labsite:

Page 1 of 1

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 1420-08-70
MADISON TO FOND DU LAC ROAD
USH 151 BUSINESS INTERCHANGE
USH 151

Date Sampled:	**Date Received:**	**Date Tested:**
05/09/02	05/09/02	
By: PAULA ABREGO		By: S. ROGERS

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Design Lab: NORTHEAST ASPHALT, INC.
Design ID: 801102

Mix Type: E10-12.5
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	5/8" X 1/2" CHIP	GADE	Pit	SE, Section: 33, T: 12 N, R: 10, E	
2	1/2" X 1/4" CHIP	GADE	Pit	SE, Section: 33, T: 12 N, R: 10, E	
3	WASHED MFG'D SAND	GADE	Pit	SE, Section: 33, T: 12 N, R: 10, E	
4	WASHED NATURAL SAND	GADE	Pit	SE, Section: 33, T: 12 N, R: 10, E	
5	SCREENED NATURAL SAND				

Sieve Sizes	1	2	3	4	5	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	71.4	100.0	100.0	100.0	100.0	96.6
9.5 (3/8")	13.3	93.6	100.0	99.9	100.0	88.8
4.75 (#4)	2.7	5.5	87.6	85.7	94.5	68.6
2.36 (#8)	2.3	3.0	58.0	65.4	80.4	49.2
1.18 (#16)	2.1	2.7	37.3	45.2	67.4	34.8
0.600 (#30)	2.0	2.6	23.0	26.8	50.2	23.0
0.300 (#50)	2.0	2.6	13.7	10.8	18.5	11.5
0.150 (#100)	1.9	2.5	7.6	4.5	4.4	5.5
75 µm (#200)	1.8	2.4	4.4	2.6	2.4	3.3
Agg Blend %:	12.0	12.0	50.0	9.0	17.0	100.0
Gsb:	2.785	2.787	2.741	2.745	2.645	2.736

% AC (Total):	5.5 Added	**% Air Voids:**	4.04%	**Agg. Angularity (Fines):**	44.9
Grade:	PG 58-28	**Gmm:**	2.552	**Gmm Dryback Correction:**	
Source:	MILWAUKEE AMO(	**Gmb:**	2.449	**Unit Wt (PCF):**	152.43
AC Sp. Gr:	1.029 @ 25/25°C	**Gse:**	2.793	**Fracture:**	97.0 1F 94.7 2F
RAP % AC:		**%VMA**	15.4	**Thin/Elong:**	0.2
Mixing Temp (°C):	135-149	**% VFB:**	73.8	**TSR:**	78.8
Compaction Temp (°C):		**Sand Equiv. (%):**	79.0	**TSR Comp. Effort:**	35.0 N
Design Comp. Effort:	100 Ndes	**Stability (N):**		**Anitstrip:**	NONE

Remarks: Satisfactory

Nini = 8 %Gmm = 87.9
Nmax = 160 %Gmm = 96.8
DP = 0.7
MA = 1.0
Aggregates 1, 2, 3, 4 Christian/Gade Pit, S33, T12N, R15E, Dodge County, Agg Test # 217-32-2001
Aggregate 5 Becker Pit, S27, T11N, R18W, Washington County
Note: This design has been updated to reflect the additional satisfactory use of Milwaukee Amoco PG 64-28.

Verified Date: 10/28/2002 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0055 - 2004

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Labsite:
Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Page 1 of 2

Main Project ID: 1130-18-71
DE PERE - GREEN BAY

USH 41

Quantity:

Date Sampled:	**Date Received:**	**Date Tested:**
05/17/04	05/17/04	
By: M. NOEL FORTIER		By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Design Lab: NORTHEAST ASPHALT, INC
Design ID: 805602

Mix Type: E-30 - 19.0 mm
Last Field Change Test Number:
Date:

	Material Description	**Aggregate Source**	**Pit/Quarry**	**Location**	**Test Number**
1	7/8" X 5/8" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
2	5/8" X 1/2" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
3	1/2" X 1/4" CHIP	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
4	WASHED MANUFACTURED SAN	GLENMORE	QRY	NE, Section: 6, T: 22 N, R: 21, E	0 - 217 - 0024 - 2002
5	WASHED NATURAL SAND	VAN HANDEL	Pit	SW, Section: 33, T: 21 N, R: 20, E	

Sieve Sizes	**1**	**2**	**3**	**4**	**5**	**JMF Blend**
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	99.7	100.0	100.0	100.0	100.0	99.9
12.5 (1/2")	53.2	76.5	100.0	100.0	100.0	89.2
9.5 (3/8")	12.5	20.6	92.2	100.0	100.0	76.9
4.75 (#4)	1.9	4.8	9.9	88.6	93.2	58.7
2.36 (#8)	1.9	3.7	5.0	53.0	80.3	41.4
1.18 (#16)	1.8	3.1	4.3	29.3	69.2	29.5
0.600 (#30)	1.8	2.8	4.0	15.9	56.3	21.1
0.300 (#50)	1.8	2.7	3.9	9.4	28.8	11.7
0.150 (#100)	1.8	2.6	3.8	5.8	5.9	4.6
75 μm (#200)	1.6	2.4	3.4	3.0	2.6	2.6
Agg Blend %	20.0	6.0	11.0	38.0	25.0	100.0
Gsb:	2.740	2.743	2.708	2.790	2.697	2.745

% AC (Total): 4.4 Added	**% Air Voids:** 4.01%	**FAA:** 45.8	**Mixing Temp (°C):** 135-149
Grade: PG 58-28	**Gmm:** 2.595	**Gmm Corr:**	**Compaction Temp (°C):**
Source: KOCH-GREEN BAY	**Gmb:** 2.491	**Unit Wt (PCF):** 155.04	**Moisture Absorption:** 1.00
AC Sp. Gr: 1.031 @ 25/25°C	**Gse:** 2.790		**Dust Proportion:** 0.80
RAP % AC:	**Nini:** 8	**% Gmm:** 88.7	**Fracture:** 99.9 1F 99.9 2F
%VMA: 13.2	**Ndes:** 100		**Thin/Elong:** 0.8
% VFB: 69.7	**Nmax:** 160	**% Gmm:** 96.5	**TSR:** 80.7 **Comp. Effort:** 29.0 N
Sand Equiv. (%): 81.0			**Anitstrip:** NONE

Volumetric Data

Point	**% AC Total**	**% AC Added**	**Gmm**	**Gmb**	**Va**	**VMA**	**VFB**
A	4.0		2.612	2.478	5.1	13.3	61.7
B	4.5		2.591	2.495	3.7	13.2	72.0
C	5.0		2.571	2.510	2.4	13.1	81.7
D	5.5		2.551	2.530	.8	12.9	93.8

Verified Date: 12/27/2004 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0055 - 2004

Labsite:

Page 2 of 2

Materials Laboratory Testing System Tests On:

Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Highway Construction Lab
Truax Center,3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 1130-18-71
DE PERE - GREEN BAY

Quantity:

USH 41

Date Sampled:	**Date Received:**	**Date Tested:**
05/17/04	05/17/04	
By: M. NOEL FORTIER		By: JAMES BONGARD

Source: *SOURCE NOT AVAILABLE **Legal Description:** , , Section: , T: N, R: , **County:**

Remarks: Satisfactory

Test Number: 0 - 250 - 0047 - 2005

Labsite:
Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Page 1 of 2

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Main Project ID: 1525-05-70
WEST GRAND AVENUE, CITY OF WISCONSIN RAPIDS
RIVERVIEW EXPRESSWAY - 25TH AVENUE (ROADWAY)
STH 13, 73

Quantity:

Date Sampled:
05/11/05
By: JOHN JORGENSON

Date Received:

Date Tested:

Source: WIMMIE

Legal Description: , NW, Section: 28, T: 23 N, R: 9, E

County: PORTAGE

Design Lab: MATHY
Design ID: 83-5-09-E10-12.5

Mix Type: E-10 - 12.5 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	1/2" BIT GRAVEL	WIMMIE	Pit		0 - 225 - 82 - 2006
2	1/4" SCREENINGS (249)	WIMMIE	Pit		0 - 225 - 82 - 2006
3	MAN SAND (342)				
4	5/8" SCREENED SAND (231)				

Sieve Sizes	1	2	3	4	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	75.0	100.0	100.0	98.0	94.8
9.5 (3/8")	30.0	98.0	100.0	91.0	84.3
4.75 (#4)	2.9	71.0	100.0	77.0	66.7
2.36 (#8)	1.2	50.0	70.0	65.0	47.7
1.18 (#16)	1.1	35.0	48.0	56.0	34.2
0.600 (#30)	1.0	22.0	30.0	39.0	21.9
0.300 (#50)	0.9	16.0	17.0	11.0	12.8
0.150 (#100)	0.9	11.0	7.4	2.7	7.1
75 µm (#200)	0.7	7.0	3.2	1.5	4.1
Agg Blend %	20.0	40.0	30.0	10.0	100.0
Gsb:	2.734	2.734	2.715	2.662	2.721

% AC (Total): 5.0 Added	**% Air Voids:** 3.99%	**FAA:** 46.0	**Mixing Temp (°C):** 275-300 F
Grade: PG 58-28	**Gmm:** 2.534	**Gmm Corr:**	**Compaction Temp (°C):**
Source: MIF, LACROSSE	**Gmb:** 2.433	**Unit Wt (PCF):** 151.43	**Moisture Absorption:** 0.60
AC Sp. Gr: 1.030 @ 25/25°C	**Gse:** 2.745		**Dust Proportion:** 0.90
RAP % AC:	**Nini:** 8	**% Gmm:** 88.5	**Fracture:** 93.9 1F 92.4 2F
%VMA: 15.1	**Ndes:** 100		**Thin/Elong:** 3.2
% VFB: 73.5	**Nmax:** 160	**% Gmm:** 97.2	**TSR:** 91.8 **Comp. Effort:** 43.0 N
Sand Equiv. (%): 84.0			**Anitstrip:** NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.0	4.00	2.574	2.395	6.9	15.5	55.3
B	4.5	4.50	2.554	2.416	5.4	15.2	64.6
C	5.0	5.00	2.534	2.436	3.9	14.9	74.1
D	5.5	5.50	2.515	2.454	2.4	14.8	83.6

Verified Date: 06/04/2008 **Verified By:** JUDIE RYAN

Test Number: 0 - 250 - 0047 - 2005	**Labsite:**	Page 2 of 2

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 1525-05-70
WEST GRAND AVENUE, CITY OF WISCONSIN RAPIDS
RIVERVIEW EXPRESSWAY - 25TH AVENUE (ROADWAY)
STH 13, 73

Quantity:

Date Sampled:	**Date Received:**	**Date Tested:**
05/11/05 By: JOHN JORGENSON		

Source: WMMIE
Legal Description: , NW, Section: 28, T: 23 N, R: 9, E
County: PORTAGE

Remarks: Satisfactory
Original aggregate test data referenced in mix design submittal is 0-162-0035-2001.
Alternate AC Grade PG 64-28, AC Source MIF-LaCrosse, and AC Sp. Gr. 1.031.
Alternate AC Grade PG 64-22, AC Source MIF-LaCrosse, and AC Sp. Gr. 1.036.

Appendix B. Binder Master Curve Data.

Table B1. Binder Master Curve Data.

Temperature, °C	Frequency, rad/sec	PG 58-28		PG 70-28		Comment
		G*, Pa	Phase Angle, degree	G*, Pa	Phase Angle, degree	
-24	0.13	1.930E+08	NA	2.000E+08	NA	Frequency and G* estimated from BBR
-24	0.07	1.693E+08	NA	1.720E+08	NA	Frequency and G* estimated from BBR
-24	0.03	1.437E+08	NA	1.430E+08	NA	Frequency and G* estimated from BBR
-24	0.02	1.183E+08	NA	1.163E+08	NA	Frequency and G* estimated from BBR
-24	0.01	9.500E+07	NA	9.167E+07	NA	Frequency and G* estimated from BBR
-24	0.00	7.467E+07	NA	7.133E+07	NA	Frequency and G* estimated from BBR
-24	0.13	2.313E+08	NA	1.937E+08	NA	Frequency and G* estimated from BBR
-24	0.07	1.987E+08	NA	1.673E+08	NA	Frequency and G* estimated from BBR
-24	0.03	1.647E+08	NA	1.397E+08	NA	Frequency and G* estimated from BBR
-24	0.02	1.340E+08	NA	1.137E+08	NA	Frequency and G* estimated from BBR
-24	0.01	1.060E+08	NA	9.067E+07	NA	Frequency and G* estimated from BBR
-24	0.00	8.200E+07	NA	7.033E+07	NA	Frequency and G* estimated from BBR
-18	0.13	1.037E+08	NA	1.050E+08	NA	Frequency and G* estimated from BBR
-18	0.07	8.433E+07	NA	8.500E+07	NA	Frequency and G* estimated from BBR
-18	0.03	6.433E+07	NA	6.567E+07	NA	Frequency and G* estimated from BBR
-18	0.02	4.900E+07	NA	5.000E+07	NA	Frequency and G* estimated from BBR
-18	0.01	3.667E+07	NA	3.700E+07	NA	Frequency and G* estimated from BBR
-18	0.00	2.667E+07	NA	2.700E+07	NA	Frequency and G* estimated from BBR
-18	0.13	9.967E+07	NA	1.047E+08	NA	Frequency and G* estimated from BBR
-18	0.07	8.133E+07	NA	8.500E+07	NA	Frequency and G* estimated from BBR
-18	0.03	6.367E+07	NA	6.600E+07	NA	Frequency and G* estimated from BBR
-18	0.02	4.867E+07	NA	5.033E+07	NA	Frequency and G* estimated from BBR
-18	0.01	3.633E+07	NA	3.733E+07	NA	Frequency and G* estimated from BBR
-18	0.00	2.633E+07	NA	2.700E+07	NA	Frequency and G* estimated from BBR
-12	0.13	4.333E+07	NA	3.967E+07	NA	Frequency and G* estimated from BBR
-12	0.07	3.333E+07	NA	3.033E+07	NA	Frequency and G* estimated from BBR
-12	0.03	2.433E+07	NA	2.233E+07	NA	Frequency and G* estimated from BBR
-12	0.02	1.733E+07	NA	1.600E+07	NA	Frequency and G* estimated from BBR
-12	0.01	1.200E+07	NA	1.133E+07	NA	Frequency and G* estimated from BBR
-12	0.00	8.000E+06	NA	7.667E+06	NA	Frequency and G* estimated from BBR
-12	0.13	4.533E+07	NA	3.867E+07	NA	Frequency and G* estimated from BBR
-12	0.07	3.467E+07	NA	3.000E+07	NA	Frequency and G* estimated from BBR
-12	0.03	2.533E+07	NA	2.200E+07	NA	Frequency and G* estimated from BBR
-12	0.02	1.800E+07	NA	1.567E+07	NA	Frequency and G* estimated from BBR
-12	0.01	1.267E+07	NA	1.133E+07	NA	Frequency and G* estimated from BBR
-12	0.00	8.667E+06	NA	7.667E+06	NA	Frequency and G* estimated from BBR
10	0.10	3.740E+05	64.34	4.356E+05	56.08	
10	0.16	5.198E+05	63.46	5.866E+05	55.95	
10	0.25	7.178E+05	62.30	7.837E+05	55.90	
10	0.40	9.859E+05	60.54	1.041E+06	54.74	
10	0.63	1.334E+06	59.35	1.374E+06	54.20	
10	1.00	1.811E+06	57.84	1.812E+06	53.26	
10	1.59	2.420E+06	56.42	2.382E+06	52.51	
10	2.51	3.218E+06	54.86	3.107E+06	51.61	
10	3.98	4.240E+06	53.31	4.030E+06	50.73	
10	6.31	5.550E+06	51.82	5.215E+06	49.71	
10	10.00	7.189E+06	50.26	6.707E+06	48.70	
10	15.85	9.254E+06	48.63	8.569E+06	47.65	
10	25.12	1.180E+07	47.07	1.090E+07	46.55	
10	39.81	1.493E+07	45.50	1.376E+07	45.34	
10	63.10	1.871E+07	43.83	1.730E+07	44.12	
10	100.00	2.319E+07	42.10	2.152E+07	42.72	
22	0.10	3.08E+04	72.63	5.91E+04	56.51	
22	0.16	4.45E+04	71.69	7.86E+04	56.95	
22	0.25	6.39E+04	70.65	1.06E+05	57.52	
22	0.40	9.13E+04	69.40	1.42E+05	57.33	
22	0.63	1.30E+05	68.46	1.89E+05	57.58	
22	1.00	1.83E+05	67.48	2.54E+05	57.69	
22	1.59	2.57E+05	66.58	3.41E+05	57.46	
22	2.51	3.58E+05	65.68	4.57E+05	57.43	

Temperature, °C	Frequency, rad/sec	PG 58-28		PG 70-28		Comment
		G*, Pa	Phase Angle, degree	G*, Pa	Phase Angle, degree	
22	3.98	4.95E+05	64.83	6.11E+05	57.32	
22	6.31	6.79E+05	63.96	8.15E+05	57.10	
22	10.00	9.20E+05	63.17	1.08E+06	56.83	
22	15.85	1.24E+06	62.38	1.43E+06	56.52	
22	25.12	1.64E+06	61.68	1.88E+06	56.16	
22	39.81	2.15E+06	60.98	2.46E+06	55.74	
22	63.10	2.77E+06	60.32	3.20E+06	55.25	
22	100.00	3.43E+06	59.82	4.09E+06	54.78	
34	0.10	2.576E+03	81.30	9.886E+03	55.11	
34	0.16	3.901E+03	80.58	1.321E+04	55.60	
34	0.25	5.871E+03	79.58	1.756E+04	56.40	
34	0.40	8.807E+03	78.34	2.353E+04	56.48	
34	0.63	1.312E+04	76.88	3.118E+04	57.32	
34	1.00	1.930E+04	75.85	4.202E+04	57.38	
34	1.59	2.832E+04	74.64	5.655E+04	57.98	
34	2.51	4.114E+04	73.52	7.596E+04	58.50	
34	3.98	5.970E+04	72.54	1.028E+05	58.86	
34	6.31	8.598E+04	71.61	1.391E+05	59.18	
34	10.00	1.230E+05	70.71	1.885E+05	59.47	
34	15.85	1.748E+05	69.93	2.556E+05	59.65	
34	25.12	2.464E+05	69.19	3.467E+05	59.80	
34	39.81	3.441E+05	68.48	4.708E+05	59.84	
34	63.10	4.765E+05	67.81	6.373E+05	59.77	
34	100.00	6.440E+05	67.19	8.595E+05	59.57	
46	0.10	3.062E+02	88.30	1.689E+03	59.02	
46	0.16	4.775E+02	87.35	2.286E+03	59.04	
46	0.25	7.434E+02	85.44	3.080E+03	58.95	
46	0.40	1.154E+03	84.78	4.149E+03	58.25	
46	0.63	1.786E+03	83.90	5.545E+03	58.70	
46	1.00	2.737E+03	82.85	7.490E+03	58.70	
46	1.59	4.178E+03	81.77	1.010E+04	59.08	
46	2.51	6.320E+03	80.62	1.365E+04	59.50	
46	3.98	9.484E+03	79.45	1.849E+04	59.95	
46	6.31	1.420E+04	78.35	2.513E+04	60.43	
46	10.00	2.109E+04	77.27	3.420E+04	61.00	
46	15.85	3.115E+04	76.24	4.673E+04	61.51	
46	25.12	4.574E+04	75.33	6.404E+04	62.03	
46	39.81	6.694E+04	74.47	8.802E+04	62.47	
46	63.10	9.742E+04	73.70	1.212E+05	62.88	
46	100.00	1.414E+05	72.82	1.670E+05	63.09	
58	0.10	4.646E+01	89.62	4.67E+02	63.28	
58	0.16	7.382E+01	89.42	6.52E+02	62.80	
58	0.25	1.155E+02	88.98	8.71E+02	60.05	
58	0.40	1.815E+02	88.61	1.21E+03	60.39	
58	0.63	2.844E+02	88.07	1.62E+03	60.03	
58	1.00	4.490E+02	87.27	2.18E+03	59.75	
58	1.59	7.017E+02	86.42	2.95E+03	59.48	
58	2.51	1.089E+03	85.51	3.99E+03	59.53	
58	3.98	1.685E+03	84.60	5.38E+03	59.71	
58	6.31	2.592E+03	83.63	7.26E+03	60.18	
58	10.00	3.966E+03	82.67	9.87E+03	60.46	
58	15.85	6.023E+03	81.67	1.34E+04	61.02	
58	25.12	9.108E+03	80.67	1.83E+04	61.57	
58	39.81	1.370E+04	79.70	2.51E+04	62.21	
58	63.10	2.045E+04	78.76	3.45E+04	62.88	
58	100.00	3.027E+04	77.85	4.74E+04	63.44	
70	0.10	NT	NT	1.31E+02	71.95	
70	0.16	NT	NT	1.85E+02	70.21	
70	0.25	NT	NT	2.63E+02	67.29	
70	0.40	NT	NT	3.72E+02	65.70	
70	0.63	NT	NT	5.23E+02	64.88	
70	1.00	NT	NT	7.16E+02	63.46	

Temperature, °C	Frequency, rad/sec	PG 58-28		PG 70-28		Comment
		G*, Pa	Phase Angle, degree	G*, Pa	Phase Angle, degree	
70	1.59	NT	NT	9.86E+02	62.47	
70	2.51	NT	NT	1.35E+03	61.72	
70	3.98	NT	NT	1.84E+03	61.35	
70	6.31	NT	NT	2.50E+03	60.97	
70	10.00	NT	NT	3.40E+03	60.92	
70	15.85	NT	NT	4.63E+03	61.08	
70	25.12	NT	NT	6.30E+03	61.34	
70	39.81	NT	NT	8.61E+03	61.81	
70	63.10	NT	NT	1.18E+04	62.37	
70	100.00	NT	NT	1.61E+04	62.95	

Appendix C. Measured Dynamic Modulus Data

Table C1. Dynamic Modulus Data for Cisler E-3 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.8		7.0		6.9	17.2	60.0	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1641.3	13.7	1581.0	13.6	1611.2	2.6	13.7	0.1
4	1	1109.2	19.0	1082.9	19.1	1096.1	1.7	19.1	0.1
4	0.1	674.4	24.8	667.1	25.3	670.7	0.8	25.1	0.3
20	10	654.6	26.1	657.5	26.5	656.1	0.3	26.3	0.3
20	1	339.0	29.5	334.2	29.9	336.6	1.0	29.7	0.3
20	0.1	159.2	29.4	152.5	30.1	155.8	3.1	29.8	0.5
35	10	170.9	36.3	166.0	37.0	168.5	2.0	36.7	0.5
35	1	64.9	31.0	65.6	31.7	65.3	0.7	31.3	0.5
35	0.1	32.5	23.4	31.1	23.6	31.8	3.1	23.5	0.1
35	0.01	22.5	14.3	22.3	14.0	22.4	0.6	14.1	0.2

Table C2. Dynamic Modulus Data for Cisler E-10 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.8		7.1		7.0	18.8	62.8	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1703.5	13.4	1690.1	13.7	1696.8	0.6	13.5	0.3
4	1	1170.9	18.6	1144.7	18.8	1157.8	1.6	18.7	0.2
4	0.1	717.4	24.3	691.3	24.4	704.4	2.6	24.4	0.1
20	10	618.0	25.9	624.1	26.4	621.1	0.7	26.2	0.4
20	1	325.6	28.8	325.2	29.6	325.4	0.1	29.2	0.6
20	0.1	157.7	28.4	156.4	30.1	157.1	0.6	29.3	1.1
35	10	191.1	34.3	189.0	35.2	190.1	0.8	34.8	0.7
35	1	82.1	29.1	77.6	30.9	79.9	4.0	30.0	1.3
35	0.1	43.3	20.7	38.6	22.9	40.9	8.1	21.8	1.6
35	0.01	31.2	11.9	26.7	14.2	28.9	11.0	13.1	1.6

Table C3. Dynamic Modulus Data for Cisler E-10 PG 70-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.7		7.1		6.9	18.7	63.1	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1378.5	14.5	1356.3	13.9	1367.4	1.2	14.2	0.4
4	1	924.6	19.2	927.2	18.3	925.9	0.2	18.7	0.6
4	0.1	567.9	23.4	582.9	22.5	575.4	1.8	22.9	0.6
20	10	492.8	27.3	461.4	28.2	477.1	4.7	27.7	0.7
20	1	241.8	30.6	219.0	31.9	230.4	7.0	31.2	1.0
20	0.1	117.3	30.0	105.4	31.6	111.4	7.6	30.8	1.1
40	10	111.5	32.8	125.1	34.0	118.3	8.1	33.4	0.8
40	1	52.4	27.7	58.5	29.1	55.5	7.7	28.4	1.0
40	0.1	31.1	21.9	35.3	22.7	33.2	8.9	22.3	0.5
40	0.01	21.8	16.7	26.0	17.5	23.9	12.4	17.1	0.6

Table C4. Dynamic Modulus Data for Christian/Gade E-3 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		7.3		6.8		7.0	17.6	60.2	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1397.6	14.4	1625.2	13.9	1511.4	10.6	14.1	0.4
4	1	942.1	19.7	1118.9	18.7	1030.5	12.1	19.2	0.7
4	0.1	576.8	25.1	704.2	23.4	640.5	14.1	24.3	1.2
20	10	570.4	26.8	616.0	26.8	593.2	5.4	26.8	0.0
20	1	291.9	30.4	322.7	30.8	307.3	7.1	30.6	0.2
20	0.1	137.7	31.1	153.8	32.0	145.8	7.8	31.5	0.6
35	10	194.2	33.7	211.8	32.6	203.0	6.1	33.1	0.8
35	1	87.9	29.7	101.2	28.1	94.5	9.9	28.9	1.1
35	0.1	49.1	22.6	60.4	20.8	54.8	14.6	21.7	1.3
35	0.01	36.2	15.5	45.3	13.6	40.8	15.9	14.6	1.3

Table C5. Dynamic Modulus Data for Christian/Gade E-10 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		7.1		7.2		7.2	18.6	61.8	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1523.1	13.9	1493.9	14.0	1508.5	1.4	13.9	0.1
4	1	1052.2	18.7	1022.1	18.8	1037.1	2.1	18.7	0.1
4	0.1	665.5	23.8	635.4	23.9	650.5	3.3	23.8	0.1
20	10	641.9	26.1	582.7	27.1	612.3	6.8	26.6	0.7
20	1	339.4	30.2	300.9	31.4	320.2	8.5	30.8	0.8
20	0.1	166.8	31.4	142.7	32.8	154.8	11.0	32.1	1.0
35	10	227.5	32.3	208.1	32.4	217.8	6.3	32.4	0.0
35	1	107.2	28.7	97.1	28.6	102.2	7.0	28.7	0.1
35	0.1	63.7	21.5	57.3	22.0	60.5	7.5	21.7	0.3
35	0.01	45.5	15.5	37.4	18.9	41.5	13.8	17.2	2.4

Table C6. Dynamic Modulus Data for Christian/Gade E-10 PG 70-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		7.2		7.0		7.1	18.5	61.6	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1275.1	14.4	1516.5	13.4	1395.8	12.2	13.9	0.7
4	1	878.6	18.6	1063.0	17.3	970.8	13.4	17.9	0.9
4	0.1	565.4	22.5	699.9	21.0	632.6	15.0	21.7	1.0
20	10	560.9	25.3	635.9	25.1	598.4	8.9	25.2	0.2
20	1	302.8	28.9	344.8	28.9	323.8	9.2	28.9	0.0
20	0.1	151.0	30.6	176.1	30.7	163.6	10.8	30.7	0.1
40	10	144.2	33.3	162.4	32.6	153.3	8.4	33.0	0.5
40	1	72.9	30.4	84.9	29.5	78.9	10.7	29.9	0.6
40	0.1	45.2	28.9	56.1	23.8	50.6	15.3	26.3	3.6
40	0.01	35.9	19.6	46.3	18.7	41.1	17.8	19.2	0.7

Table C7. Dynamic Modulus Data for Glenmore E-3 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.7		6.7		6.7	16.2	58.6	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1536.6	12.0	1590.9	12.4	1563.8	2.5	12.2	0.3
4	1	1118.6	16.4	1140.3	16.8	1129.4	1.4	16.6	0.3
4	0.1	746.8	21.3	744.6	22.3	745.7	0.2	21.8	0.7
20	10	718.5	24.1	727.7	24.2	723.1	0.9	24.2	0.1
20	1	390.1	28.4	398.1	28.8	394.1	1.4	28.6	0.2
20	0.1	189.9	30.3	190.4	31.3	190.1	0.2	30.8	0.7
35	10	257.5	30.6	251.8	32.5	254.7	1.6	31.6	1.4
35	1	120.3	27.4	116.7	29.2	118.5	2.2	28.3	1.3
35	0.1	69.3	21.6	67.5	23.4	68.4	1.9	22.5	1.3
35	0.01	52.7	16.0	51.2	17.0	52.0	2.1	16.5	0.7

Table C8. Dynamic Modulus Data for Glenmore E-10 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.8		7.2		7.0	16.2	56.8	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1624.1	12.2	1685.1	12.6	1654.6	2.6	12.4	0.3
4	1	1170.6	16.5	1193.5	17.1	1182.0	1.4	16.8	0.4
4	0.1	782.9	21.5	784.1	21.9	783.5	0.1	21.7	0.3
20	10	732.7	23.9	732.6	24.6	732.7	0.0	24.3	0.6
20	1	413.2	27.9	406.5	29.1	409.8	1.2	28.5	0.9
20	0.1	210.7	30.0	197.2	31.8	204.0	4.7	30.9	1.3
35	10	282.5	30.3	276.2	32.0	279.3	1.6	31.2	1.2
35	1	132.2	28.3	126.5	29.7	129.3	3.1	29.0	1.0
35	0.1	74.8	23.6	68.5	24.3	71.7	6.2	24.0	0.5
35	0.01	50.7	18.0	45.8	18.1	48.3	7.3	18.1	0.0

Table C9. Dynamic Modulus Data for Glenmore E-10 PG 70-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		7.1		7.1		7.1	16.3	56.4	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1757.5	12.5	1752.6	13.2	1755.0	0.2	12.8	0.5
4	1	1253.0	16.8	1230.8	17.6	1241.9	1.3	17.2	0.6
4	0.1	827.3	21.3	788.8	22.1	808.0	3.4	21.7	0.6
20	10	744.9	25.2	678.6	25.1	711.7	6.6	25.1	0.1
20	1	400.3	28.8	376.5	29.0	388.4	4.3	28.9	0.1
20	0.1	191.7	30.8	190.9	30.5	191.3	0.3	30.7	0.2
40	10	209.1	31.7	179.0	32.0	194.1	11.0	31.8	0.2
40	1	103.0	28.6	93.6	28.5	98.3	6.8	28.5	0.1
40	0.1	65.4	23.1	62.8	23.0	64.1	2.8	23.1	0.1
40	0.01	53.5	17.1	50.7	18.6	52.1	3.8	17.9	1.1

Table C10. Dynamic Modulus Data for Wimmie E-3 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.8		7.0		6.9	17.5	60.6	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1427.4	14.3	1555.3	14.8	1491.4	6.1	14.5	0.4
4	1	961.6	19.4	1039.1	20.1	1000.3	5.5	19.7	0.5
4	0.1	594.6	24.6	623.6	25.4	609.1	3.4	25.0	0.6
20	10	595.6	27.5	581.8	28.1	588.7	1.7	27.8	0.4
20	1	288.0	31.4	291.4	32.1	289.7	0.8	31.7	0.5
20	0.1	121.9	31.8	130.4	33.0	126.2	4.8	32.4	0.8
35	10	175.2	35.2	176.5	35.1	175.9	0.5	35.2	0.1
35	1	71.1	30.5	73.9	30.0	72.5	2.8	30.3	0.3
35	0.1	35.8	28.5	37.5	21.9	36.6	3.3	25.2	4.7
35	0.01	25.3	14.9	28.2	13.5	26.8	7.6	14.2	1.0

Table C11. Dynamic Modulus Data for Wimmie E-10 PG 58-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.8		6.5		6.6	17.7	62.7	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	2063.7	14.2	1900.8	13.4	1982.3	5.8	13.8	0.5
4	1	1413.0	19.5	1323.5	18.7	1368.2	4.6	19.1	0.6
4	0.1	872.7	24.8	827.7	24.0	850.2	3.7	24.4	0.5
20	10	805.4	26.9	794.4	26.1	799.9	1.0	26.5	0.6
20	1	400.1	31.4	411.1	30.9	405.6	1.9	31.2	0.4
20	0.1	164.9	32.9	183.4	33.1	174.1	7.5	33.0	0.1
35	10	218.5	35.7	225.8	35.7	222.1	2.3	35.7	0.0
35	1	87.1	31.3	92.2	32.6	89.6	4.0	31.9	0.9
35	0.1	43.0	23.8	43.7	26.1	43.3	1.2	24.9	1.6
35	0.01	27.6	17.4	29.1	16.6	28.3	3.7	17.0	0.6

Table C12. Dynamic Modulus Data for Wimmie E-10 PG 70-28 Mixture.

		Specimen 1		Specimen 2		Average Air Voids, %	Average VMA, %	Average VFA, %	
Air Voids		6.7		6.8		6.8	17.9	62.0	
Temp, C	Freq, Hz	Modulus, ksi	Phase Angle, degree	Modulus, ksi	Phase Angle, degree	Modulus Average, ksi	Modulus CV, %	Phase Angle Average, degree	Phase Angle Std. Dev., degree
4	10	1320.8	15.5	1548.3	15.4	1434.5	11.2	15.4	0.1
4	1	866.0	20.4	1021.9	20.5	943.9	11.7	20.5	0.1
4	0.1	521.2	24.5	621.4	25.1	571.3	12.4	24.8	0.4
20	10	511.7	27.2	636.3	26.8	574.0	15.4	27.0	0.3
20	1	260.1	30.8	326.9	29.8	293.5	16.1	30.3	0.7
20	0.1	119.6	31.1	151.1	30.9	135.4	16.5	31.0	0.2
40	10	130.4	32.5	141.1	31.7	135.7	5.6	32.1	0.6
40	1	61.0	27.9	65.9	26.8	63.5	5.5	27.3	0.8
40	0.1	34.0	22.9	40.4	20.9	37.2	12.2	21.9	1.4
40	0.01	25.1	16.7	29.7	14.7	27.4	11.7	15.7	1.4

Appendix D. Fitted Master Curves Used in ASU Spreadsheet Solution.

Table D1. Fitted Master Curves for E-3 PG 58-28 Mixtures.

Temp., F	Frequency, Hz	Dynamic Modulus, ksi			
		Cisler	Christian /Gade	Glenmore	Wimmie
14	25	2634.7	2575.7	2641.3	2582.3
14	10	2528.9	2452.2	2523.5	2458.6
14	5	2438.0	2345.7	2422.3	2352.0
14	1	2189.5	2054.8	2146.5	2059.9
14	0.5	2066.3	1912.1	2011.1	1916.2
14	0.1	1747.4	1551.1	1665.9	1550.9
40	25	1835.6	1761.5	1862.8	1766.3
40	10	1642.8	1551.8	1661.6	1554.0
40	5	1491.5	1389.6	1504.5	1389.1
40	1	1136.6	1020.4	1140.4	1011.9
40	0.5	988.9	872.9	991.3	860.6
40	0.1	677.8	577.6	683.1	557.1
70	25	724.7	710.1	818.9	695.3
70	10	569.0	555.0	654.9	535.6
70	5	466.6	455.1	546.5	433.0
70	1	281.7	279.8	348.7	254.4
70	0.5	223.4	225.9	285.3	200.4
70	0.1	128.3	139.1	179.4	115.3
100	25	170.8	204.3	257.8	179.5
100	10	124.3	154.9	197.9	130.9
100	5	97.9	126.6	162.7	103.6
100	1	57.3	82.4	106.3	62.4
100	0.5	46.2	69.9	89.9	51.2
100	0.1	29.3	50.4	63.9	34.2
130	25	42.2	71.6	91.7	52.8
130	10	32.5	58.7	74.8	41.4
130	5	27.1	51.3	65.0	35.1
130	1	18.8	39.6	49.2	25.4
130	0.5	16.4	36.2	44.6	22.6
130	0.1	12.6	30.5	36.9	18.2

Table D2. Fitted Master Curves for E-10 PG 58-28 Mixtures.

Temp., F	Frequency, Hz	Dynamic Modulus, ksi			
		Cisler	Christian /Gade	Glenmore	Wimmie
14	25	2628.3	2524.5	2626.9	2828.9
14	10	2525.4	2402.0	2511.8	2743.2
14	5	2436.1	2297.0	2413.2	2666.2
14	1	2187.6	2011.9	2145.5	2440.5
14	0.5	2062.8	1872.8	2014.2	2321.3
14	0.1	1736.5	1522.4	1679.4	1992.2
40	25	1861.0	1739.6	1880.2	2155.8
40	10	1664.8	1536.9	1685.4	1955.9
40	5	1509.8	1379.9	1532.8	1791.4
40	1	1144.1	1021.9	1175.7	1381.6
40	0.5	991.9	878.2	1027.8	1202.4
40	0.1	673.1	588.2	717.3	812.8
70	25	752.4	730.2	864.3	952.6
70	10	590.0	575.5	696.9	745.1
70	5	483.5	474.9	584.6	606.3
70	1	292.6	295.7	375.7	354.7
70	0.5	233.0	239.7	307.4	276.5
70	0.1	136.4	148.4	191.6	152.7
100	25	188.7	220.8	281.1	232.0
100	10	139.2	167.8	214.7	165.4
100	5	111.0	137.2	175.3	128.3
100	1	67.7	88.9	111.8	73.6
100	0.5	55.8	75.1	93.3	59.3
100	0.1	37.4	53.4	64.0	38.2
130	25	53.3	77.9	96.3	58.7
130	10	42.2	63.3	76.9	45.3
130	5	36.0	55.0	65.7	37.9
130	1	26.4	41.8	47.8	27.0
130	0.5	23.6	37.9	42.6	24.0
130	0.1	19.1	31.5	34.0	19.3

Table D3. Fitted Master Curves for E-10 PG 70-28 Mixtures.

Temp., F	Frequency, Hz	Dynamic Modulus, ksi			
		Cisler	Christian /Gade	Glenmore	Wimmie
14	25	2435.1	2442.9	2738.4	2467.7
14	10	2300.7	2317.2	2630.1	2332.8
14	5	2186.7	2211.3	2534.8	2218.4
14	1	1883.1	1930.5	2266.2	1913.3
14	0.5	1737.9	1796.5	2130.0	1767.1
14	0.1	1380.4	1465.1	1772.9	1406.6
40	25	1590.7	1639.0	1984.6	1660.0
40	10	1384.9	1447.3	1775.2	1453.2
40	5	1228.5	1301.0	1608.9	1295.0
40	1	882.2	972.3	1216.1	940.5
40	0.5	747.5	841.5	1053.4	800.7
40	0.1	483.9	577.6	716.8	523.8
70	25	603.9	682.0	871.1	683.8
70	10	466.4	544.6	691.6	533.4
70	5	379.1	455.0	573.6	436.2
70	1	228.3	293.5	361.4	265.1
70	0.5	182.7	242.0	294.8	212.3
70	0.1	110.0	155.7	185.9	127.3
100	25	165.2	216.1	268.3	202.8
100	10	123.7	168.1	206.2	151.3
100	5	100.1	139.8	170.3	121.8
100	1	63.5	93.9	113.7	75.8
100	0.5	53.2	80.4	97.6	62.9
100	0.1	37.3	58.6	72.2	42.9
130	25	54.8	81.0	99.9	67.6
130	10	44.2	67.0	83.1	53.5
130	5	38.2	58.9	73.5	45.6
130	1	28.7	45.5	58.2	33.1
130	0.5	25.9	41.5	53.7	29.5
130	0.1	21.4	34.7	46.4	23.7

Appendix E. Estimated Dynamic Modulus Data

Table E1. Hirsch Model Estimated Dynamic Moduli.

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	VMA, %	VFA, %	Binder G*, psi	Estimated E*, ksi
Cisler	E3	PG 58-28	4	10	1611.2	17.2	60.0	5875.8	1700.8
			4	1	1096.1	17.2	60.0	2074.4	1180.4
			4	0.1	670.7	17.2	60.0	591.1	686.8
			20	10	656.1	17.2	60.0	568.5	674.3
			20	1	336.6	17.2	60.0	130.9	324.4
			20	0.1	155.8	17.2	60.0	25.0	136.0
			35	10	168.5	17.2	60.0	60.2	215.6
			35	1	65.3	17.2	60.0	10.6	88.5
			35	0.1	31.8	17.2	60.0	1.6	43.1
			35	0.01	22.4	17.2	60.0	0.2	32.3
	E10	PG 58-28	4	10	1696.8	18.8	62.8	5875.8	1646.3
			4	1	1157.8	18.8	62.8	2074.4	1138.4
			4	0.1	704.4	18.8	62.8	591.1	660.0
			20	10	621.1	18.8	62.8	568.5	648.0
			20	1	325.4	18.8	62.8	130.9	311.0
			20	0.1	157.1	18.8	62.8	25.0	130.4
			35	10	190.1	18.8	62.8	60.2	206.7
			35	1	79.9	18.8	62.8	10.6	85.0
			35	0.1	40.9	18.8	62.8	1.6	41.8
			35	0.01	28.9	18.8	62.8	0.2	31.6
	E10	PG 58-28	4	10	1367.4	18.7	63.1	4240.7	1486.9
			4	1	925.9	18.7	63.1	1801.5	1081.9
			4	0.1	575.4	18.7	63.1	658.6	698.4
			20	10	477.1	18.7	63.1	577.9	657.0
			20	1	230.4	18.7	63.1	177.6	366.5
			20	0.1	111.4	18.7	63.1	46.8	182.1
			40	10	118.3	18.7	63.1	47.9	184.4
			40	1	55.5	18.7	63.1	10.9	86.6
			40	0.1	33.2	18.7	63.1	2.2	45.4
			40	0.01	23.9	18.7	63.1	0.4	33.0
Christian/ Gade	E3	PG 58-28	4	10	1511.4	17.6	60.2	5875.8	1682.4
			4	1	1030.5	17.6	60.2	2074.4	1165.8
			4	0.1	640.5	17.6	60.2	591.1	677.2
			20	10	593.2	17.6	60.2	568.5	664.9
			20	1	307.3	17.6	60.2	130.9	319.5
			20	0.1	145.8	17.6	60.2	25.0	134.0
			35	10	203.0	17.6	60.2	60.2	212.4
			35	1	94.5	17.6	60.2	10.6	87.2
			35	0.1	54.8	17.6	60.2	1.6	42.6
			35	0.01	40.8	17.6	60.2	0.2	32.1
	E10	PG 58-28	4	10	1508.5	18.6	61.8	5875.8	1647.5
			4	1	1037.1	18.6	61.8	2074.4	1138.8
			4	0.1	650.5	18.6	61.8	591.1	660.0
			20	10	612.3	18.6	61.8	568.5	648.0
			20	1	320.2	18.6	61.8	130.9	310.9
			20	0.1	154.8	18.6	61.8	25.0	130.4
			35	10	217.8	18.6	61.8	60.2	206.6
			35	1	102.2	18.6	61.8	10.6	85.0
			35	0.1	60.5	18.6	61.8	1.6	41.8
			35	0.01	41.5	18.6	61.8	0.2	31.7
	E10	PG 70-28	4	10	1395.8	18.5	61.6	4240.7	1483.8
			4	1	970.8	18.5	61.6	1801.5	1078.7
			4	0.1	632.6	18.5	61.6	658.6	695.8
			20	10	598.4	18.5	61.6	577.9	654.5
			20	1	323.8	18.5	61.6	177.6	364.9
			20	0.1	163.6	18.5	61.6	46.8	181.3
			40	10	153.3	18.5	61.6	47.9	183.6
			40	1	78.9	18.5	61.6	10.9	86.3
			40	0.1	50.6	18.5	61.6	2.2	45.4
			40	0.01	41.1	18.5	61.6	0.4	33.0

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	VMA, %	VFA, %	Binder G*, psi	Estimated E*, ksi
Glenmore	E3	PG 58-28	4	10	1563.8	16.2	58.6	5875.8	1740.2
			4	1	1129.4	16.2	58.6	2074.4	1211.4
			4	0.1	745.7	16.2	58.6	591.1	706.9
			20	10	723.1	16.2	58.6	568.5	694.1
			20	1	394.1	16.2	58.6	130.9	334.5
			20	0.1	190.1	16.2	58.6	25.0	140.3
			35	10	254.7	16.2	58.6	60.2	222.5
			35	1	118.5	16.2	58.6	10.6	91.1
			35	0.1	68.4	16.2	58.6	1.6	44.0
			35	0.01	52.0	16.2	58.6	0.2	32.8
	E10	PG 58-28	4	10	1654.6	16.2	56.8	5875.8	1723.5
			4	1	1182.0	16.2	56.8	2074.4	1196.8
			4	0.1	783.5	16.2	56.8	591.1	696.6
			20	10	732.7	16.2	56.8	568.5	684.0
			20	1	409.8	16.2	56.8	130.9	329.1
			20	0.1	204.0	16.2	56.8	25.0	138.0
			35	10	279.3	16.2	56.8	60.2	218.8
			35	1	129.3	16.2	56.8	10.6	89.7
			35	0.1	71.7	16.2	56.8	1.6	43.7
			35	0.01	48.3	16.2	56.8	0.2	32.7
	E10	PG 58-28	4	10	1755.0	16.3	56.4	4240.7	1542.9
			4	1	1241.9	16.3	56.4	1801.5	1124.7
			4	0.1	808.0	16.3	56.4	658.6	727.2
			20	10	711.7	16.3	56.4	577.9	684.3
			20	1	388.4	16.3	56.4	177.6	382.2
			20	0.1	191.3	16.3	56.4	46.8	190.0
			40	10	194.1	16.3	56.4	47.9	192.4
			40	1	98.3	16.3	56.4	10.9	90.2
			40	0.1	64.1	16.3	56.4	2.2	47.1
			40	0.01	52.1	16.3	56.4	0.4	34.0
Wimmie	E3	PG 58-28	4	10	1491.4	17.5	60.6	5875.8	1690.9
			4	1	1000.3	17.5	60.6	2074.4	1172.8
			4	0.1	609.1	17.5	60.6	591.1	681.9
			20	10	588.7	17.5	60.6	568.5	669.6
			20	1	289.7	17.5	60.6	130.9	322.0
			20	0.1	126.2	17.5	60.6	25.0	135.0
			35	10	175.9	17.5	60.6	60.2	214.0
			35	1	72.5	17.5	60.6	10.6	87.8
			35	0.1	36.6	17.5	60.6	1.6	42.8
			35	0.01	26.8	17.5	60.6	0.2	32.2
	E10	PG 58-28	4	10	1982.3	17.7	62.7	5875.8	1698.8
			4	1	1368.2	17.7	62.7	2074.4	1180.4
			4	0.1	850.2	17.7	62.7	591.1	687.6
			20	10	799.9	17.7	62.7	568.5	675.1
			20	1	405.6	17.7	62.7	130.9	325.0
			20	0.1	174.1	17.7	62.7	25.0	136.3
			35	10	222.1	17.7	62.7	60.2	216.1
			35	1	89.6	17.7	62.7	10.6	88.6
			35	0.1	43.3	17.7	62.7	1.6	43.0
			35	0.01	28.3	17.7	62.7	0.2	32.1
	E10	PG 70-28	4	10	1434.5	17.9	62.0	4240.7	1514.5
			4	1	943.9	17.9	62.0	1801.5	1103.9
			4	0.1	571.3	17.9	62.0	658.6	713.8
			20	10	574.0	17.9	62.0	577.9	671.6
			20	1	293.5	17.9	62.0	177.6	375.1
			20	0.1	135.4	17.9	62.0	46.8	186.5
			40	10	135.7	17.9	62.0	47.9	188.8
			40	1	63.5	17.9	62.0	10.9	88.6
			40	0.1	37.2	17.9	62.0	2.2	46.3
			40	0.01	27.4	17.9	62.0	0.4	33.4

Table E2. Latest Witczak Equation Estimated Dynamic Moduli.

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	ρ_{200}, %	ρ_{4}, %	$\rho_{3/8}$, %	$\rho_{3/4}$, %	V_a, %	Vb_{eff}, %	Binder G*, psi	Binder Phase Angle, °	Estimated E*, ksi
Cisler	E3	PG 58-28	4	10	1611.2	4.1	37.0	15.0	0.0	6.9	10.3	2603.9	43.2	2632.5
			4	1	1096.1	4.1	37.0	15.0	0.0	6.9	10.3	774.7	51.6	1643.9
			4	0.1	670.7	4.1	37.0	15.0	0.0	6.9	10.3	186.9	59.5	880.7
			20	10	656.1	4.1	37.0	15.0	0.0	6.9	10.3	178.9	59.7	863.2
			20	1	336.6	4.1	37.0	15.0	0.0	6.9	10.3	35.4	66.7	402.2
			20	0.1	155.8	4.1	37.0	15.0	0.0	6.9	10.3	5.9	72.6	176.3
			35	10	168.5	4.1	37.0	15.0	0.0	6.9	10.3	15.2	69.7	270.3
			35	1	65.3	4.1	37.0	15.0	0.0	6.9	10.3	2.4	75.0	119.7
			35	0.1	31.8	4.1	37.0	15.0	0.0	6.9	10.3	0.3	79.1	58.9
			35	0.01	22.4	4.1	37.0	15.0	0.0	6.9	10.3	0.0	82.2	34.6
	E10	PG 58-28	4	10	1696.8	3.7	35.0	17.0	0.0	7.0	11.1	2603.9	43.2	2677.2
			4	1	1157.8	3.7	35.0	17.0	0.0	7.0	11.1	774.7	51.6	1663.3
			4	0.1	704.4	3.7	35.0	17.0	0.0	7.0	11.1	186.9	59.5	885.1
			20	10	621.1	3.7	35.0	17.0	0.0	7.0	11.1	178.9	59.7	867.4
			20	1	325.4	3.7	35.0	17.0	0.0	7.0	11.1	35.4	66.7	400.8
			20	0.1	157.1	3.7	35.0	17.0	0.0	7.0	11.1	5.9	72.6	174.1
			35	10	190.1	3.7	35.0	17.0	0.0	7.0	11.1	15.2	69.7	268.3
			35	1	79.9	3.7	35.0	17.0	0.0	7.0	11.1	2.4	75.0	117.8
			35	0.1	40.9	3.7	35.0	17.0	0.0	7.0	11.1	0.3	79.1	57.5
			35	0.01	28.9	3.7	35.0	17.0	0.0	7.0	11.1	0.0	82.2	33.6
	E10	PG 58-28	4	10	1367.4	3.7	35.0	17.0	0.0	6.9	11.1	2166.7	35.2	2835.2
			4	1	925.9	3.7	35.0	17.0	0.0	6.9	11.1	817.0	41.1	1947.4
			4	0.1	575.4	3.7	35.0	17.0	0.0	6.9	11.1	264.0	47.2	1195.0
			20	10	477.1	3.7	35.0	17.0	0.0	6.9	11.1	228.2	47.9	1118.2
			20	1	230.4	3.7	35.0	17.0	0.0	6.9	11.1	62.0	53.9	602.2
			20	0.1	111.4	3.7	35.0	17.0	0.0	6.9	11.1	14.5	59.6	296.7
			40	10	118.3	3.7	35.0	17.0	0.0	6.9	11.1	14.9	59.5	300.4
			40	1	55.5	3.7	35.0	17.0	0.0	6.9	11.1	3.0	64.7	144.1
			40	0.1	33.2	3.7	35.0	17.0	0.0	6.9	11.1	0.5	69.4	72.9
			40	0.01	23.9	3.7	35.0	17.0	0.0	6.9	11.1	0.1	73.4	41.8
Christian/ Gade	E3	PG 58-28	4	10	1511.4	3.5	36.0	14.0	0.0	7.0	10.6	2603.9	43.2	2570.1
			4	1	1030.5	3.5	36.0	14.0	0.0	7.0	10.6	774.7	51.6	1605.8
			4	0.1	640.5	3.5	36.0	14.0	0.0	7.0	10.6	186.9	59.5	860.8
			20	10	593.2	3.5	36.0	14.0	0.0	7.0	10.6	178.9	59.7	843.7
			20	1	307.3	3.5	36.0	14.0	0.0	7.0	10.6	35.4	66.7	393.4
			20	0.1	145.8	3.5	36.0	14.0	0.0	7.0	10.6	5.9	72.6	172.6
			35	10	203.0	3.5	36.0	14.0	0.0	7.0	10.6	15.2	69.7	264.5
			35	1	94.5	3.5	36.0	14.0	0.0	7.0	10.6	2.4	75.0	117.3
			35	0.1	54.8	3.5	36.0	14.0	0.0	7.0	10.6	0.3	79.1	57.7
			35	0.01	40.8	3.5	36.0	14.0	0.0	7.0	10.6	0.0	82.2	34.0
	E10	PG 58-28	4	10	1508.5	3.3	31.0	11.0	0.0	7.2	11.4	2603.9	43.2	2287.8
			4	1	1037.1	3.3	31.0	11.0	0.0	7.2	11.4	774.7	51.6	1432.0
			4	0.1	650.5	3.3	31.0	11.0	0.0	7.2	11.4	186.9	59.5	769.5
			20	10	612.3	3.3	31.0	11.0	0.0	7.2	11.4	178.9	59.7	754.3
			20	1	320.2	3.3	31.0	11.0	0.0	7.2	11.4	35.4	66.7	352.7
			20	0.1	154.8	3.3	31.0	11.0	0.0	7.2	11.4	5.9	72.6	155.2
			35	10	217.8	3.3	31.0	11.0	0.0	7.2	11.4	15.2	69.7	237.6
			35	1	102.2	3.3	31.0	11.0	0.0	7.2	11.4	2.4	75.0	105.6
			35	0.1	60.5	3.3	31.0	11.0	0.0	7.2	11.4	0.3	79.1	52.1
			35	0.01	41.5	3.3	31.0	11.0	0.0	7.2	11.4	0.0	82.2	30.7
	E10	PG 70-28	4	10	1395.8	3.3	31.0	11.0	0.0	7.1	11.4	2166.7	35.2	2421.3
			4	1	970.8	3.3	31.0	11.0	0.0	7.1	11.4	817.0	41.1	1672.9
			4	0.1	632.6	3.3	31.0	11.0	0.0	7.1	11.4	264.0	47.2	1034.4
			20	10	598.4	3.3	31.0	11.0	0.0	7.1	11.4	228.2	47.9	968.9
			20	1	323.8	3.3	31.0	11.0	0.0	7.1	11.4	62.0	53.9	526.8
			20	0.1	163.6	3.3	31.0	11.0	0.0	7.1	11.4	14.5	59.6	262.4
			40	10	153.3	3.3	31.0	11.0	0.0	7.1	11.4	14.9	59.5	265.7
			40	1	78.9	3.3	31.0	11.0	0.0	7.1	11.4	3.0	64.7	128.9
			40	0.1	50.6	3.3	31.0	11.0	0.0	7.1	11.4	0.5	69.4	65.9
			40	0.01	41.1	3.3	31.0	11.0	0.0	7.1	11.4	0.1	73.4	38.1

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	ρ_{200}, %	ρ_{4}, %	$\rho_{3/8}$, %	$\rho_{3/4}$, %	V_a, %	Vb_{eff}, %	Binder G*, psi	Binder Phase Angle, °	Estimated E*, ksi
Glenmore	E3	PG 58-28	4	10	1611.2	3.3	37.0	23.0	0.0	6.7	9.5	2603.9	43.2	3107.3
			4	1	1096.1	3.3	37.0	23.0	0.0	6.7	9.5	774.7	51.6	1925.8
			4	0.1	670.7	3.3	37.0	23.0	0.0	6.7	9.5	186.9	59.5	1021.5
			20	10	656.1	3.3	37.0	23.0	0.0	6.7	9.5	178.9	59.7	1000.8
			20	1	336.6	3.3	37.0	23.0	0.0	6.7	9.5	35.4	66.7	460.6
			20	0.1	155.8	3.3	37.0	23.0	0.0	6.7	9.5	5.9	72.6	199.2
			35	10	168.5	3.3	37.0	23.0	0.0	6.7	9.5	15.2	69.7	307.7
			35	1	65.3	3.3	37.0	23.0	0.0	6.7	9.5	2.4	75.0	134.5
			35	0.1	31.8	3.3	37.0	23.0	0.0	6.7	9.5	0.3	79.1	65.4
			35	0.01	22.4	3.3	37.0	23.0	0.0	6.7	9.5	0.0	82.2	38.1
	E10	PG 58-28	4	10	1696.8	2.6	41.0	23.0	0.0	7.0	9.2	2603.9	43.2	3186.8
			4	1	1157.8	2.6	41.0	23.0	0.0	7.0	9.2	774.7	51.6	1976.8
			4	0.1	704.4	2.6	41.0	23.0	0.0	7.0	9.2	186.9	59.5	1049.7
			20	10	621.1	2.6	41.0	23.0	0.0	7.0	9.2	178.9	59.7	1028.5
			20	1	325.4	2.6	41.0	23.0	0.0	7.0	9.2	35.4	66.7	474.0
			20	0.1	157.1	2.6	41.0	23.0	0.0	7.0	9.2	5.9	72.6	205.3
			35	10	190.1	2.6	41.0	23.0	0.0	7.0	9.2	15.2	69.7	316.8
			35	1	79.9	2.6	41.0	23.0	0.0	7.0	9.2	2.4	75.0	138.7
			35	0.1	40.9	2.6	41.0	23.0	0.0	7.0	9.2	0.3	79.1	67.5
			35	0.01	28.9	2.6	41.0	23.0	0.0	7.0	9.2	0.0	82.2	39.4
	E10	PG 58-28	4	10	1367.4	2.6	41.0	23.0	0.0	7.1	9.2	2166.7	35.2	3334.2
			4	1	925.9	2.6	41.0	23.0	0.0	7.1	9.2	817.0	41.1	2286.8
			4	0.1	575.4	2.6	41.0	23.0	0.0	7.1	9.2	264.0	47.2	1400.6
			20	10	477.1	2.6	41.0	23.0	0.0	7.1	9.2	228.2	47.9	1310.2
			20	1	230.4	2.6	41.0	23.0	0.0	7.1	9.2	62.0	53.9	703.8
			20	0.1	111.4	2.6	41.0	23.0	0.0	7.1	9.2	14.5	59.6	345.8
			40	10	118.3	2.6	41.0	23.0	0.0	7.1	9.2	14.9	59.5	350.1
			40	1	55.5	2.6	41.0	23.0	0.0	7.1	9.2	3.0	64.7	167.4
			40	0.1	33.2	2.6	41.0	23.0	0.0	7.1	9.2	0.5	69.4	84.5
			40	0.01	23.9	2.6	41.0	23.0	0.0	7.1	9.2	0.1	73.4	48.3
Wimmie	E3	PG 58-28	4	10	1511.4	3.8	37.0	17.0	0.0	6.9	10.6	2603.9	43.2	2737.3
			4	1	1030.5	3.8	37.0	17.0	0.0	6.9	10.6	774.7	51.6	1703.3
			4	0.1	640.5	3.8	37.0	17.0	0.0	6.9	10.6	186.9	59.5	908.3
			20	10	593.2	3.8	37.0	17.0	0.0	6.9	10.6	178.9	59.7	890.1
			20	1	307.3	3.8	37.0	17.0	0.0	6.9	10.6	35.4	66.7	412.3
			20	0.1	145.8	3.8	37.0	17.0	0.0	6.9	10.6	5.9	72.6	179.6
			35	10	203.0	3.8	37.0	17.0	0.0	6.9	10.6	15.2	69.7	276.3
			35	1	94.5	3.8	37.0	17.0	0.0	6.9	10.6	2.4	75.0	121.6
			35	0.1	54.8	3.8	37.0	17.0	0.0	6.9	10.6	0.3	79.1	59.5
			35	0.01	40.8	3.8	37.0	17.0	0.0	6.9	10.6	0.0	82.2	34.8
	E10	PG 58-28	4	10	1508.5	4.1	33.0	16.0	0.0	6.6	11.1	2603.9	43.2	2638.8
			4	1	1037.1	4.1	33.0	16.0	0.0	6.6	11.1	774.7	51.6	1642.3
			4	0.1	650.5	4.1	33.0	16.0	0.0	6.6	11.1	186.9	59.5	876.0
			20	10	612.3	4.1	33.0	16.0	0.0	6.6	11.1	178.9	59.7	858.4
			20	1	320.2	4.1	33.0	16.0	0.0	6.6	11.1	35.4	66.7	397.8
			20	0.1	154.8	4.1	33.0	16.0	0.0	6.6	11.1	5.9	72.6	173.4
			35	10	217.8	4.1	33.0	16.0	0.0	6.6	11.1	15.2	69.7	266.7
			35	1	102.2	4.1	33.0	16.0	0.0	6.6	11.1	2.4	75.0	117.4
			35	0.1	60.5	4.1	33.0	16.0	0.0	6.6	11.1	0.3	79.1	57.4
			35	0.01	41.5	4.1	33.0	16.0	0.0	6.6	11.1	0.0	82.2	33.7
	E10	PG 70-28	4	10	1395.8	4.1	33.0	16.0	0.0	6.8	11.1	2166.7	35.2	2742.4
			4	1	970.8	4.1	33.0	16.0	0.0	6.8	11.1	817.0	41.1	1885.7
			4	0.1	632.6	4.1	33.0	16.0	0.0	6.8	11.1	264.0	47.2	1158.8
			20	10	598.4	4.1	33.0	16.0	0.0	6.8	11.1	228.2	47.9	1084.5
			20	1	323.8	4.1	33.0	16.0	0.0	6.8	11.1	62.0	53.9	585.1
			20	0.1	163.6	4.1	33.0	16.0	0.0	6.8	11.1	14.5	59.6	288.9
			40	10	153.3	4.1	33.0	16.0	0.0	6.8	11.1	14.9	59.5	292.5
			40	1	78.9	4.1	33.0	16.0	0.0	6.8	11.1	3.0	64.7	140.6
			40	0.1	50.6	4.1	33.0	16.0	0.0	6.8	11.1	0.5	69.4	71.3
			40	0.01	41.1	4.1	33.0	16.0	0.0	6.8	11.1	0.1	73.4	40.9

Table E3. Viscosity Based Witczak Equation Estimated Dynamic Moduli.

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	$\rho_{200,}$ %	$\rho_{4,}$ %	$\rho_{3/8,}$ %	$\rho_{3/4,}$ %	V_a, %	Vb_{eff}, %	A	VTS	Estimated E*, ksi
Cisler	E3	PG 58-28	4	10	1611.2	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	1892.234
			4	1	1096.1	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	1341.312
			4	0.1	670.7	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	877.7423
			20	10	656.1	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	690.6325
			20	1	336.6	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	399.7337
			20	0.1	155.8	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	215.3305
			35	10	168.5	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	241.6213
			35	1	65.3	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	124.5325
			35	0.1	31.8	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	62.4084
			35	0.01	22.4	4.1	37.0	15.0	0.0	6.9	10.3	11.010	-3.701	31.42623
	E10	PG 58-28	4	10	1696.8	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	1809.967
			4	1	1157.8	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	1281.733
			4	0.1	704.4	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	837.7364
			20	10	621.1	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	658.7022
			20	1	325.4	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	380.6559
			20	0.1	157.1	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	204.6906
			35	10	190.1	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	229.7581
			35	1	79.9	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	118.1935
			35	0.1	40.9	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	59.11457
			35	0.01	28.9	3.7	35.0	17.0	0.0	7.0	11.1	11.010	-3.701	29.70916
	E10	PG 58-28	4	10	1367.4	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	2013.13
			4	1	925.9	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	1462.025
			4	0.1	575.4	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	982.317
			20	10	477.1	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	877.4772
			20	1	230.4	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	531.3828
			20	0.1	111.4	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	297.34
			40	10	118.3	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	266.4782
			40	1	55.5	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	138.5077
			40	0.1	33.2	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	69.518
			40	0.01	23.9	3.7	35.0	17.0	0.0	6.9	11.1	9.715	-3.217	34.79884
Christian/ Gade	E3	PG 58-28	4	10	1511.4	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	1755.529
			4	1	1030.5	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	1244.561
			4	0.1	640.5	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	814.5516
			20	10	593.2	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	640.9667
			20	1	307.3	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	371.0594
			20	0.1	145.8	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	199.9279
			35	10	203.0	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	224.329
			35	1	94.5	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	115.6471
			35	0.1	54.8	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	57.96978
			35	0.01	40.8	3.5	36.0	14.0	0.0	7.0	10.6	11.010	-3.701	29.19823
	E10	PG 58-28	4	10	1508.5	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	1698.682
			4	1	1037.1	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	1204.27
			4	0.1	650.5	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	788.1907
			20	10	612.3	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	620.2272
			20	1	320.2	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	359.0583
			20	0.1	154.8	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	193.4648
			35	10	217.8	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	217.0763
			35	1	102.2	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	111.9101
			35	0.1	60.5	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	56.09755
			35	0.01	41.5	3.3	31.0	11.0	0.0	7.2	11.4	11.010	-3.701	28.25573
	E10	PG 70-28	4	10	1395.8	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	1889.074
			4	1	970.8	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	1373.351
			4	0.1	632.6	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	923.926
			20	10	598.4	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	825.6195
			20	1	323.8	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	500.7908
			20	0.1	163.6	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	280.7489
			40	10	153.3	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	251.6984
			40	1	78.9	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	131.1029
			40	0.1	50.6	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	65.94839
			40	0.01	41.1	3.3	31.0	11.0	0.0	7.1	11.4	9.715	-3.217	33.08598

Source	Mix	Binder	Temp, C	Freq, Hz	Measured E*, ksi	ρ_{200}, %	ρ_{4}, %	$\rho_{3/8}$, %	$\rho_{3/4}$, %	V_a, %	Vb_{eff}, %	A	VTS	Estimated E*, ksi
Glenmore	E3	PG 58-28	4	10	1611.2	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	3107.3
			4	1	1096.1	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	1925.8
			4	0.1	670.7	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	1021.5
			20	10	656.1	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	1000.8
			20	1	336.6	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	460.6
			20	0.1	155.8	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	199.2
			35	10	168.5	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	307.7
			35	1	65.3	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	134.5
			35	0.1	31.8	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	65.4
			35	0.01	22.4	3.3	37.0	23.0	0.0	6.7	9.5	11.010	-3.701	38.1
	E10	PG 58-28	4	10	1696.8	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	3186.8
			4	1	1157.8	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	1976.8
			4	0.1	704.4	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	1049.7
			20	10	621.1	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	1028.5
			20	1	325.4	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	474.0
			20	0.1	157.1	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	205.3
			35	10	190.1	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	316.8
			35	1	79.9	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	138.7
			35	0.1	40.9	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	67.5
			35	0.01	28.9	2.6	41.0	23.0	0.0	7.0	9.2	11.010	-3.701	39.4
	E10	PG 58-28	4	10	1367.4	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	3334.2
			4	1	925.9	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	2286.8
			4	0.1	575.4	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	1400.6
			20	10	477.1	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	1310.2
			20	1	230.4	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	703.8
			20	0.1	111.4	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	345.8
			40	10	118.3	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	350.1
			40	1	55.5	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	167.4
			40	0.1	33.2	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	84.5
			40	0.01	23.9	2.6	41.0	23.0	0.0	7.1	9.2	9.715	-3.217	48.3
Wimmie	E3	PG 58-28	4	10	1511.4	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	2737.3
			4	1	1030.5	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	1703.3
			4	0.1	640.5	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	908.3
			20	10	593.2	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	890.1
			20	1	307.3	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	412.3
			20	0.1	145.8	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	179.6
			35	10	203.0	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	276.3
			35	1	94.5	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	121.6
			35	0.1	54.8	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	59.5
			35	0.01	40.8	3.8	37.0	17.0	0.0	6.9	10.6	11.010	-3.701	34.8
	E10	PG 58-28	4	10	1508.5	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	2638.8
			4	1	1037.1	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	1642.3
			4	0.1	650.5	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	876.0
			20	10	612.3	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	858.4
			20	1	320.2	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	397.8
			20	0.1	154.8	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	173.4
			35	10	217.8	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	266.7
			35	1	102.2	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	117.4
			35	0.1	60.5	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	57.4
			35	0.01	41.5	4.1	33.0	16.0	0.0	6.6	11.1	11.010	-3.701	33.7
	E10	PG 70-28	4	10	1395.8	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	2742.4
			4	1	970.8	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	1885.7
			4	0.1	632.6	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	1158.8
			20	10	598.4	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	1084.5
			20	1	323.8	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	585.1
			20	0.1	163.6	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	288.9
			40	10	153.3	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	292.5
			40	1	78.9	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	140.6
			40	0.1	50.6	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	71.3
			40	0.01	41.1	4.1	33.0	16.0	0.0	6.8	11.1	9.715	-3.217	40.9

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