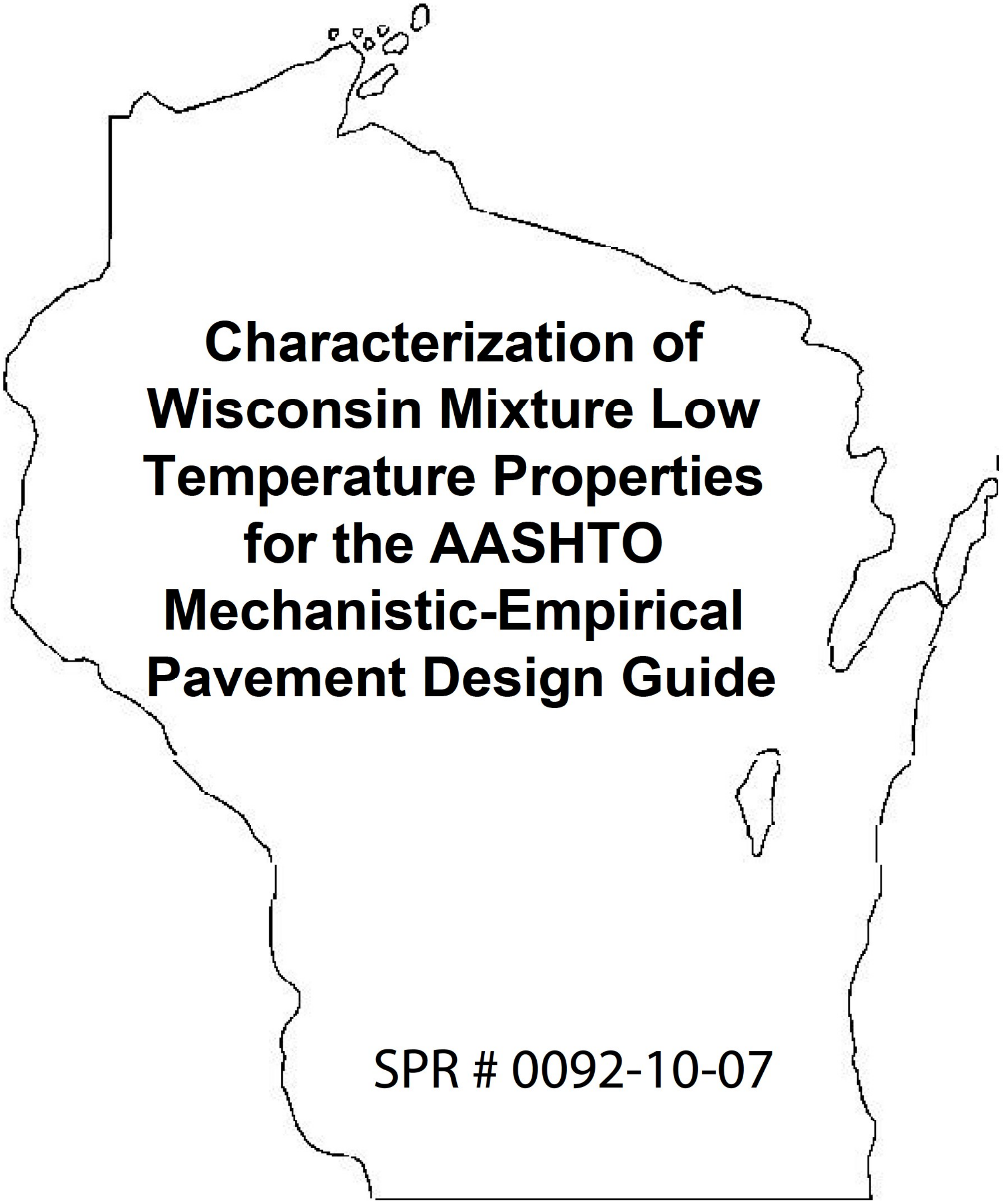
Wisconsin Highway Research Program



Characterization of Wisconsin Mixture Low Temperature Properties for the AASHTO Mechanistic-Empirical Pavement Design Guide

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Advanced Asphalt Technologies, LLC

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Disclaimer

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16. Abstract

This research evaluated the low temperature creep compliance and tensile strength properties of Wisconsin mixtures. Creep compliance and tensile strength data were collected for 16 Wisconsin mixtures representing commonly used aggregate sources and binder grades. Engineering and statistical analyses were performed on the data to provide recommendations for using measured mechanical properties in thermal cracking analyses with the Mechanistic-Empirical Pavement Design Guide (MEPDG), and to evaluate the thermal fracture resistance of Wisconsin mixtures.

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Executive Summary

Project Summary

This research evaluated the low temperature creep compliance and tensile strength properties of Wisconsin mixtures. Creep compliance and tensile strength data were collected for 16 Wisconsin mixtures representing commonly used aggregate sources and binder grades. Engineering and statistical analyses were performed on the data to provide recommendations for using measured mechanical properties in thermal cracking analyses with the Mechanistic-Empirical Pavement Design Guide (MEPDG), and to evaluate the thermal fracture resistance of Wisconsin mixtures.

Background

The thermal cracking model included in the MEPDG is an engineering tool that can be used by the Wisconsin Department of Transportation (WisDOT) to evaluate the potential for thermal cracking during design. This model performs, a thermo-viscoelastic analysis of a constrained asphalt layer to compute stresses within the layer as a function of depth. Pavement temperatures as a function of depth and time for the thermal stress analysis are obtained from the environmental effects model. The computed thermal stresses are used in a linear fracture mechanics model to compute the propagation of a vertical surface crack through the asphalt layer. Finally, the crack spacing at the surface of the pavement is determined from an empirical model that relates the crack spacing observed in the pavement to the average crack depth calculate by the analysis.

The asphalt concrete material property inputs needed to perform thermal cracking analyses using the MEPDG are: (1) the coefficient of thermal contraction, (2) creep compliance master curve data, and (3) the tensile strength at -10 °C. The coefficient of thermal contraction is estimated from mixture composition and the coefficient of thermal contraction for the binder and aggregates used in the mixture. For Level 1 analyses, creep compliance data are measured at three temperatures -20, -10, and 0 °C; and tensile strength data are measured at -10 °C using AASHTO T322.

To effectively evaluate and use the MEPDG, WisDOT needs low temperature creep compliance and strength data for mixtures representing current and future practice in Wisconsin. This project was conducted to address this need

Process

Low temperature creep compliance and strength data were collected on 16 Wisconsin mixtures. The mixtures included in the evaluation were the same mixtures used for dynamic modulus characterization in Wisconsin Highway Research Program (WHRP) Project 0092-08-06, "Wisconsin Mixture Characterization Using the Asphalt Mixture Performance Tester (AMPT) on Historical Aggregate Structures. This provides WisDOT with complete MEPDG Level 1 characterization of several mixtures representing current practice in Wisconsin. The experimental design included four aggregate sources: Cilser, Christian/Gade, Glenmore, and Wimmie. For each source WisDOT approved E-3 and E-10 mixture designs were used. Based on current WisDOT binder grade selection requirements, mixtures were produced using four different binders: (1) PG 58-34, (2) PG 58-28, (3) PG 58-34 with 25 percent reclaimed asphalt pavement (RAP) binder, and (4) PG 58-28 with 25 percent RAP binder.

Findings and Conclusions

Low Temperature Creep Compliance

For the mixtures tested, the low temperature creep compliance was found to be a function of only the low temperature performance grade of the binder in the mixture. Aggregate source and design traffic level did not have a significant effect on the low temperature compliance of the mixtures tested. As the low temperature grade of the binder increased, the compliance master curve becomes flatter, which results in an increase in thermal stresses in the pavement. For a typical thermal stress analysis, mixtures made with the PG 58-34 binder had the lowest thermal stresses. Over the temperature range of -28 to -34 °C, the thermal stresses are approximately 10 percent higher for the PG 58-34 with 25 % RAP compared to the PG 58-34; 20 percent higher for the PG 58-28 compared to the PG 58-34; and 60 percent higher for the PG 58-28 with 25 % RAP compared to the PG 58-34.

A predictive equation was developed to estimate the compliance of Wisconsin mixtures as a function of the low temperature continuous grade of the binder. This equation can be used to estimate the compliance values required by the MEPDG for thermal cracking analyses. The equation was developed for low temperature grades between -35.1 and -28.7 °C; therefore, it should be used with caution for binders with low temperature grades outside of this range.

The measured compliance values were compared to compliance values estimated by the MEPDG software for Level 3 analyses. The MEPDG Level 3 compliance values were generally lower than the measured values, with errors as high as 56 percent. These errors could result in difference in computed thermal stresses as high as 70 percent.

Low Temperature Tensile Strength

For the mixtures tested, the tensile strength at -10 °C was not significantly affected by low temperature binder grade, aggregate source, or design traffic level. The average tensile strength for the 16 mixtures tested was 430 psi with a standard deviation of 30 psi.

The measured tensile strengths were compared with those estimated by the MEPDG software for Level 3 analyses. The MEPDG estimates were generally higher than the measured tensile strengths, and exhibited irrational volumetric effects. The MEPDG estimated tensile strengths decrease with increasing voids filled with asphalt (VFA), while the measured tensile strengths and tensile strengths from other studies show a trend of increasing tensile strength with increasing VFA.

Linear Coefficient of Thermal Contraction

The evaluation of two equations for estimating the linear coefficient of thermal contraction produced similar results for the mixtures used in this study. The range of the estimated linear coefficient of thermal contraction was from 2.0×10^{-5}/°C to 3.0×10^{-5}/°C. This range in the coefficient of thermal contraction has a significant effect on computed thermal stresses in the pavement. The linear coefficient of thermal contraction is as important as the mixture compliance in thermal stress computations.

Recommendations

For thermal cracking analyses using the MEPDG, WisDOT should not rely on the MEPDG Level 3 estimated creep compliance and strength values. Instead, compliance values should be estimated based on the low temperature continuous grade of the binder using the predictive equation developed in this project. To aid in the implementation of this research, compliance values from the predictive equation for low temperature binder grades ranging from -22 to -36 were tabulated in Appendix C. These can be input directly into the MEPDG software. Since the low temperature tensile strength was not found to be a function of mixture or binder properties, the average measured tensile strength of 430 psi should be used for thermal cracking analyses.

The linear coefficient of thermal contraction was found to be of similar importance as the mixture compliance in thermal stress analyses. Because a standard test is not available, the linear coefficient of contraction is estimated using relationships that may have significant errors. Until measured linear coefficients of thermal contraction are available, WisDOT should use a representative linear coefficient of thermal contraction of 1.4×10^{-5}/°F (2.5×10^{-5}/°C) in thermal cracking analyses performed with the MEPDG.

The findings from this study do not suggest any needed changes to Wisconsin mixtures or specifications to improve low temperature cracking performance. The low temperature compliance of mixtures is primarily a function of the low temperature performance grade of the binder; therefore, changes to volumetric mixture design will have minimal impact on low temperature performance. Climate is appropriately considered in current Wisconsin binder grade selection, and WHRP Project 0092-10-06 is investigating the effect of recycled binders on performance grade properties and evaluating current WisDOT binder replacement criteria.

The findings from this study do suggest that the linear coefficient of thermal contraction is as important as the low temperature mixture compliance in thermal stress analyses. The linear coefficient of contraction will likely vary with aggregate source and perhaps with mixture composition; therefore, consideration should be given to measuring the linear coefficient of contraction on the mixtures used in this study. Possible tests include the Asphalt Mixture Glass Transition Test under development at the University of Wisconsin, Madison or the test developed at The Pennsylvania State University that uses the indirect tensile test instrumentation. This additional work may identify mixture compositions having high thermal contraction that will require higher compliance to maintain thermal stresses at acceptable levels.

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Chapter 1 Introduction and Research Approach

1.1 Background

1.1.1 Mechanistic-Empirical Pavement Design Guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is the product of National Cooperative Highway Research Program (NCHRP) Project 1-37A. The MEPDG is substantially different than most pavement design procedures used in the past by highway agencies. The MEPDG is based on mechanistic-empirical pavement design principles. Critical stresses and strains from vehicle and environmental loading are computed using mechanistic theory. These critical stresses and strains are then empirically related to the occurrence of distresses such as rutting and cracking in the pavement. Most agencies have used the 1993 AASHTO Pavement Design Guide, which is based on limited empirical pavement performance equations from the AASHO Road Test conducted in the late 1950's and early 1960's. The distress prediction models in the MEPDG have been calibrated using a large number of pavement sections from the Long-Term Pavement Performance database. Pavement sections used in the calibration were located throughout the United States. The MEPDG is an analysis tool. The output from the MEPDG is the predicted performance of a trial pavement section, not pavement thicknesses.

The MEPDG requires a large amount of information about the pavement being analyzed. This includes data concerning traffic, climate, subgrade soils, the condition of existing pavements for rehabilitation design, and the thicknesses and material properties for each layer of the pavement, including existing pavement layers for rehabilitation design. To provide flexibility for users with different capabilities, the MEPDG uses a hierarchical scheme for inputting the required data. Three levels are provided:

- **Level 1.** The input parameter is measured directly. This level provides the most accurate information about the input parameter.
- **Level 2.** The input parameter is estimated from correlations or regression equations that are embedded in the MEPDG.

- **Level 3.** The input parameter is based on default values provided by the MEPDG software.

Testing or data collection costs decrease as the hierarchical level increases from Level 1 to Level 3, but the accuracy of the input data also decreases.

The MEPDG has the capability to analyze flexible, semi-rigid, rigid, and composite pavements. For pavements with asphalt concrete surfaces, the MEPDG includes performance models to predict the following distresses:

- Rut depth for asphalt concrete layers, unbound aggregate layers, and the subgrade,
- Transverse thermal cracking,
- Alligator cracking due to bottom initiated fatigue,
- Longitudinal wheel path cracking due to surface initiated fatigue,
- Reflection cracking, and
- Roughness

1.1.2 Thermal Cracking Analysis in the MEPDG

Of particular interest to the Wisconsin Department of Transportation (WisDOT) is the thermal cracking model included in the MEPDG. This model is quite complex. It was originally developed during the Strategic Highway Research Program (SHRP) by researchers from The Pennsylvania State University (*1*). In this model, a thermo-viscoelastic analysis of a constrained asphalt layer is performed to compute stresses within the layer as a function of depth. Pavement temperatures as a function of depth and time for the thermal stress analysis are obtained from the environmental effects model. The computed thermal stresses are used in a linear fracture mechanics model to compute the propagation of a vertical surface crack through the asphalt layer. Finally, the crack spacing at the surface of the pavement is determined from an empirical model that relates the crack spacing observed in the pavement to the average crack depth calculate by the analysis.

An evaluation of the SHRP thermal cracking model that was conducted during NCHRP Project 9-19, found the model to be generally sound (*2*). This evaluation, however, identified several errors in the model that were subsequently improved by the NCHRP Project 9-19 research team (*3*). The improved model was calibrated using a number of pavement sections in NCHRP Project 9-37A (*4*). At this time, the thermal fracture model in the MEPDG is considered to be a valuable tool for evaluating the potential for thermal cracking in flexible pavements.

1.1.3 MEPDG Thermal Cracking Analysis Input Data

The asphalt concrete material property inputs needed to perform thermal cracking analyses using the MEPDG are: (1) the coefficient of thermal contraction, (2) creep compliance master curve data, and (3) the tensile strength at -10 °C. The coefficient of thermal contraction is estimated from mixture composition and the coefficient of thermal contraction for the binder and aggregates used in the mixture. For Level 1 analyses, creep compliance data are measured at three temperatures -20, -10, and 0 °C; and tensile strength data are measured at -10 °C using AASHTO T322. For Level 2 analyses, creep compliance and strength data are measured only at -10 °C using AASHTO T322. For Level 3 analyses, regression equations are used to estimate the creep compliance and tensile strength data.

1.2 Problem Statement and Objectives

To effectively evaluate and use the MEPDG, WisDOT needs low temperature creep compliance and strength data for mixtures representing current and future practice in Wisconsin. This project was conducted to address this need. The objectives of the research were to: (1) establish a range of tensile strength and creep compliance properties for representative Wisconsin asphalt concrete mixtures, (2) provide recommendations for using the measured mechanical properties in the MEPDG, and (3) evaluate the thermal fracture resistance of Wisconsin mixtures and recommend appropriate specification changes if warranted. These objectives were accomplished by characterizing the tensile strength and creep compliance properties of a number of asphalt concrete mixtures using AASHTO T322, summarizing the measured properties, and performing engineering and statistical analyses on the resulting data.

1.3 Research Approach

Low temperature strength and creep compliance data were collected on selected mixtures characterized in Wisconsin Highway Research Program (WHRP) Project 0092-08-06, “Wisconsin Mixture Characterization Using the Asphalt Mixture Performance Tester (AMPT) on Historical Aggregate Structures (*5*). This provides WisDOT with complete MEPDG Level 1 characterization of several mixtures representing current practice in Wisconsin. The experimental design included four aggregate sources: Cisler, Christian/Gade, Glenmore, and Wimmie. For each source WisDOT approved E-3 and E-10 mixture designs were used. Table 1 summarizes the experimental design. A total of 16 mixtures were characterized using AASHTO T322.

Table 1. Experimental Design.

Aggregate Source and Traffic Level	Binder Grade	RAP
Cisler E10	PG 58-28	0
	PG 58-28	25
Cisler E3	PG 58-34	0
	PG 58-34	25
Christian/Gade E3	PG 58-28	0
	PG 58-28	25
Christian/Gade E10	PG 58-34	0
	PG 58-34	25
Glenmore E10	PG 58-28	0
	PG 58-28	25
Glenmore E3	PG 58-34	0
	PG 58-34	25
Wimmie E3	PG 58-28	0
	PG 58-28	25
Wimmie E10	PG 58-34	0
	PG 58-34	25

The binder grades and the use of reclaimed asphalt pavement (RAP) binder in the mixtures was based on previous research that has shown the low temperature creep and strength properties measured using AASHTO T322 are most affected by the low temperature grade of the binder in the mixture (*6*). The evaluation included the most commonly used low temperature binder grades in Wisconsin, PG XX-28 and PG XX-34. These were selected based on the PG Binder Selection Criteria contained in Chapter 14, Section 10, Subject 5 of the WisDOT Facilities

Development Manual. The evaluation also included RAP binder because recycled binders are being used more commonly in mixtures. The RAP binder replacement value of 25 percent was based on Section 460.2.5 of the WisDOT Standard Specifications.

The mixtures incorporating RAP were prepared by extracting and recovering RAP binder from a single Wisconsin source, then replacing 25 percent of the binder in each mixture with the recovered RAP binder. This approach required less effort than redesigning the mixtures to include RAP. A sufficient amount of RAP binder for all of the mixtures was recovered and mixed in a single container prior to the start of specimen fabrication to ensure a consistent supply of RAP binder.

The AASHTO T322 indirect tensile (IDT) compliance and strength testing was conducted using an Interlaken 3310-55/37 servo-hydraulic load frame with an Interlaken DDC 4000 digital controller. Tests were conducted in an Bemco Model FTUM-40/70C-10 environmental chamber having temperature control from 70 to -30 °C. Deformations on the IDT specimens were measured using linear variable differential transformers (LVDTs) having 0.5 mm range, Schaevitz Model XS-B 099. Figure 1 is a photograph of the Interlaken IDT test system used to conduct the AASHTO T322 testing.

The IDT testing was conducted on 50 mm thick by 150 mm diameter IDT specimens. After mixing, the loose mix was conditioned in accordance with the short-term conditioning procedure for mixture mechanical property testing in AASHTO R30; four hours at 135 °C. The IDT test specimens were sawed from the middle of a 100 mm tall by 150 mm diameter gyratory specimen prepared in an Interlaken compactor meeting the requirements of AASHTO T312. The target air void content for the IDT test specimens was 7.0 ± 0.5 percent.

The data from the AASHTO T322 testing was reduced using the Excel application LTSTRESS.xls (*7*). LTSTRESS was developed at the Northeast Center of Excellence for Pavement Technology to reduce data from AASHTO T322 and to perform a simplified thermo-viscoelastic analysis (*7*). This analysis is similar to the thermal fracture model in the MEPDG. It provides an estimate of the expected thermal cracking temperature for the material tested. It does not consider thermal fatigue or crack propagation, and is strictly only accurate for single-event thermal cracking as occurs during extreme low temperature events.

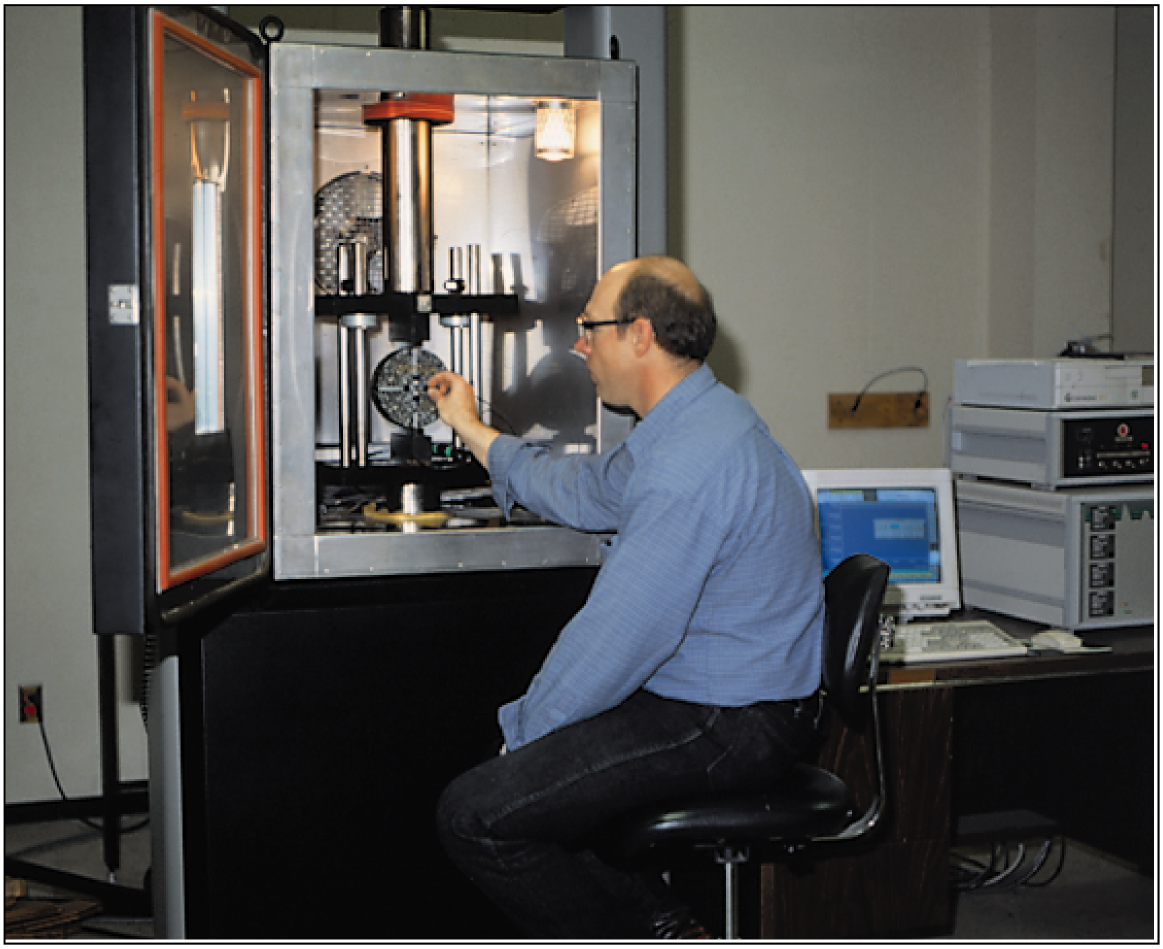

Figure 1. Interlaken IDT Test System.

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 the same mixtures used in WHRP Project 0092-08-06. Tables 2 and 3 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 2 and 3 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 4 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 than 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 5 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.

Table 2. 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 3. 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

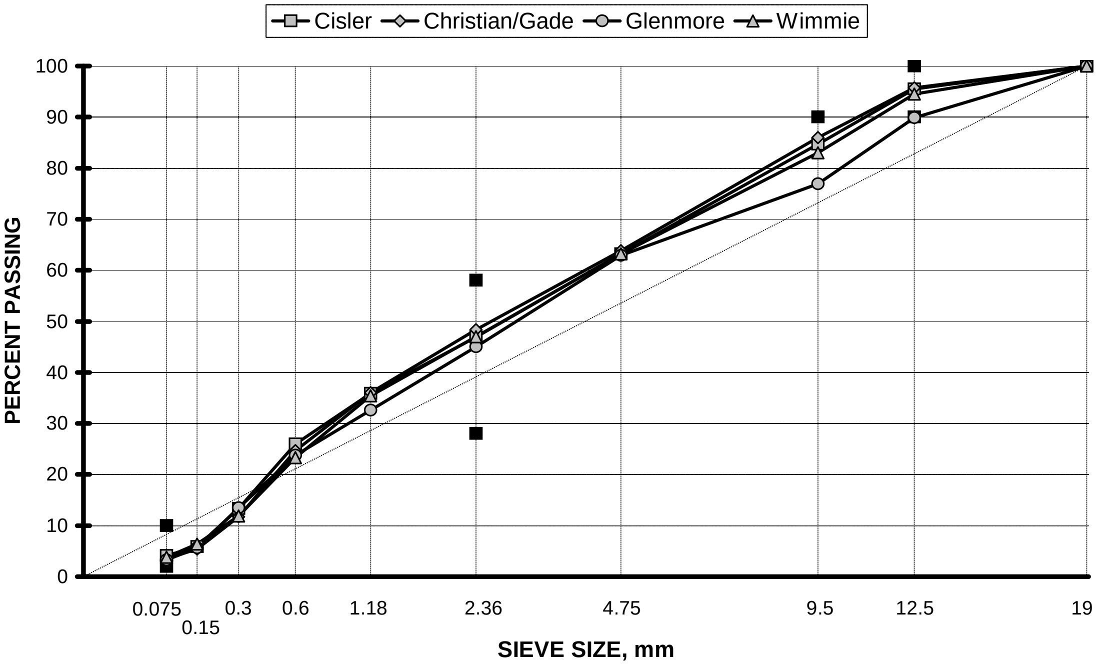

Figure 2. Gradation of E-3 Mixtures.

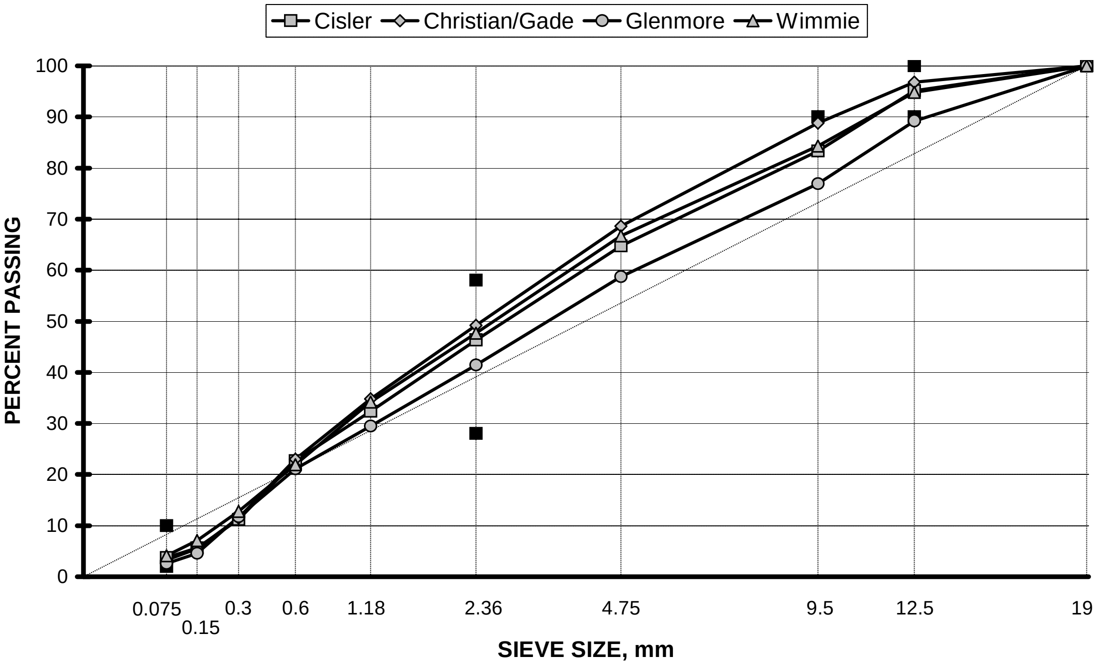

Figure 3. Gradation of E-10 Mixtures.

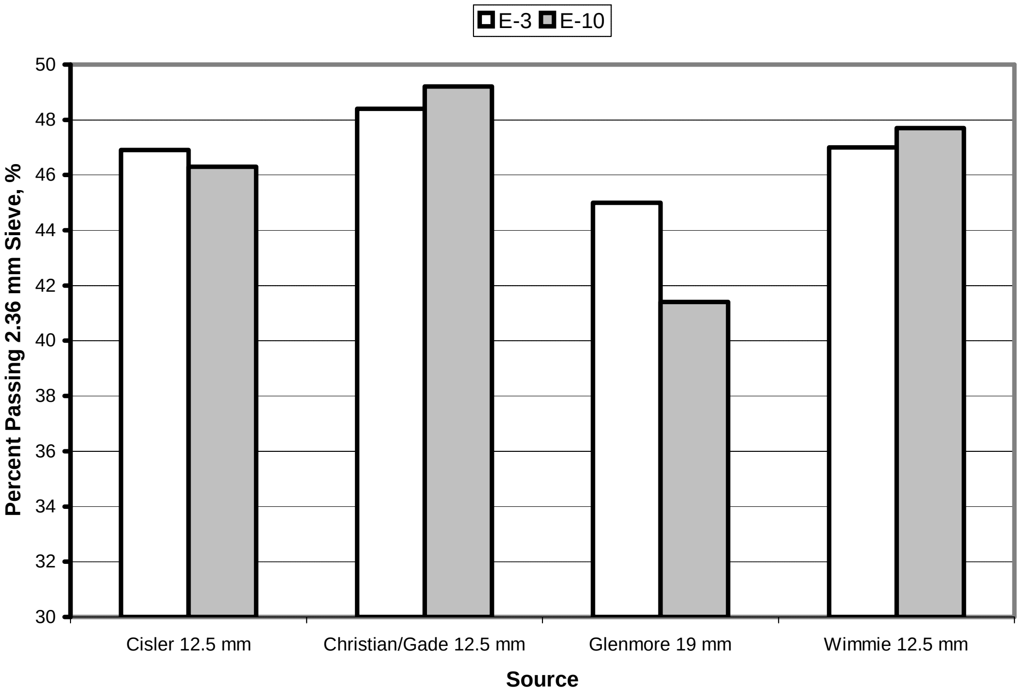

Figure 4. Percent Passing 2.36 mm Sieve (Control Sieve for 12.5 mm Mixtures).

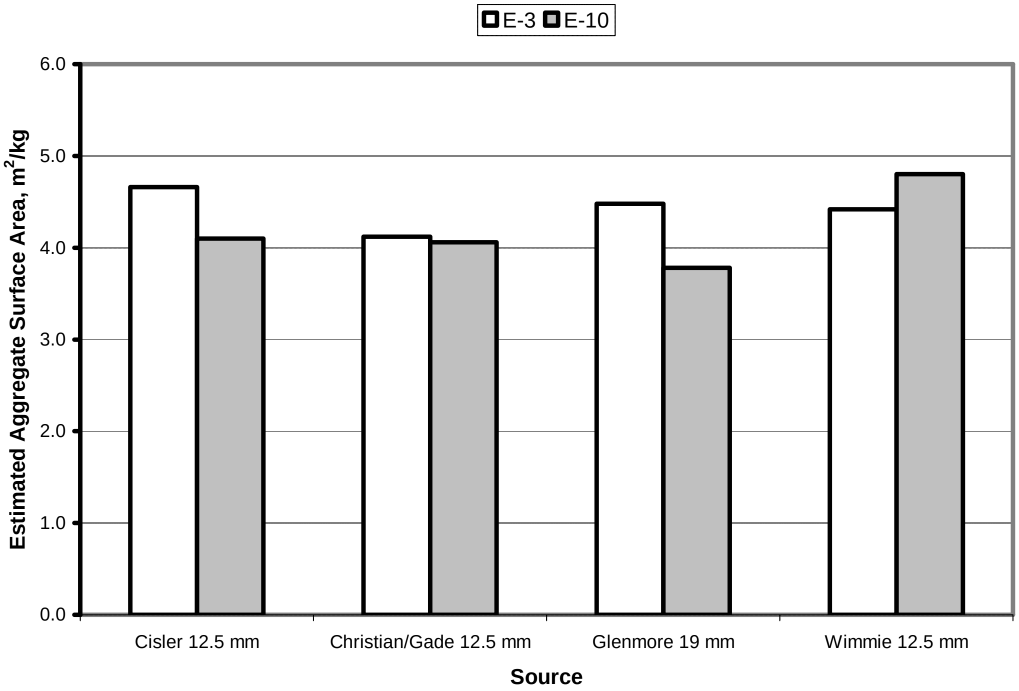

Figure 5. Estimated Aggregate Surface Area.

The major difference in the aggregate properties for the E-3 and E-10 mixtures is the angularity of the aggregates. Figure 6 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 7 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.

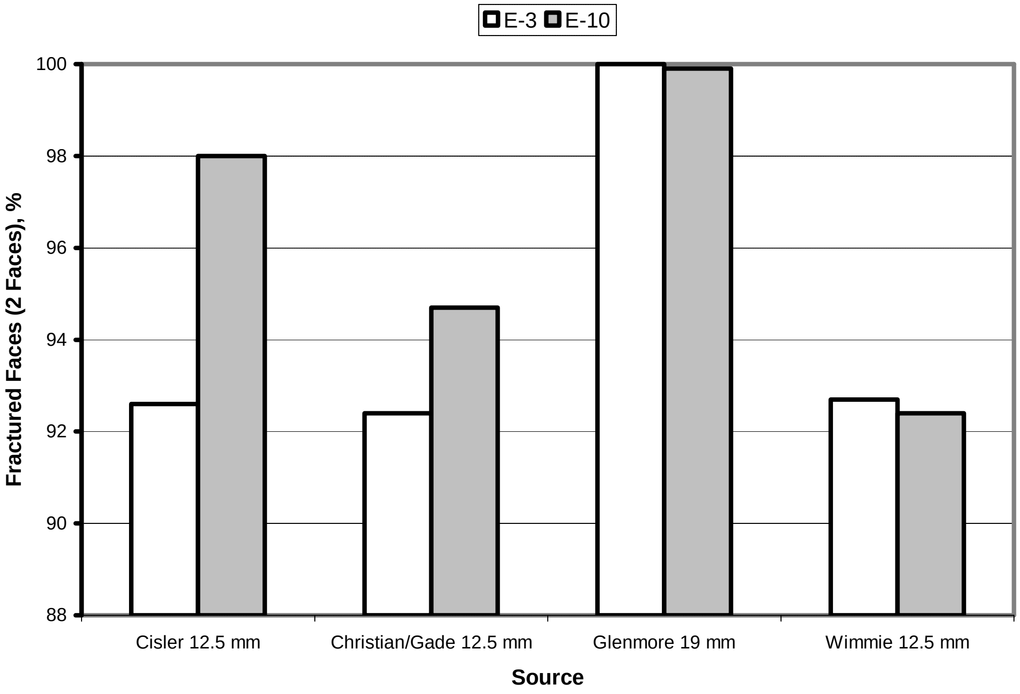

Figure 6. Coarse Aggregate Fractured Faces.

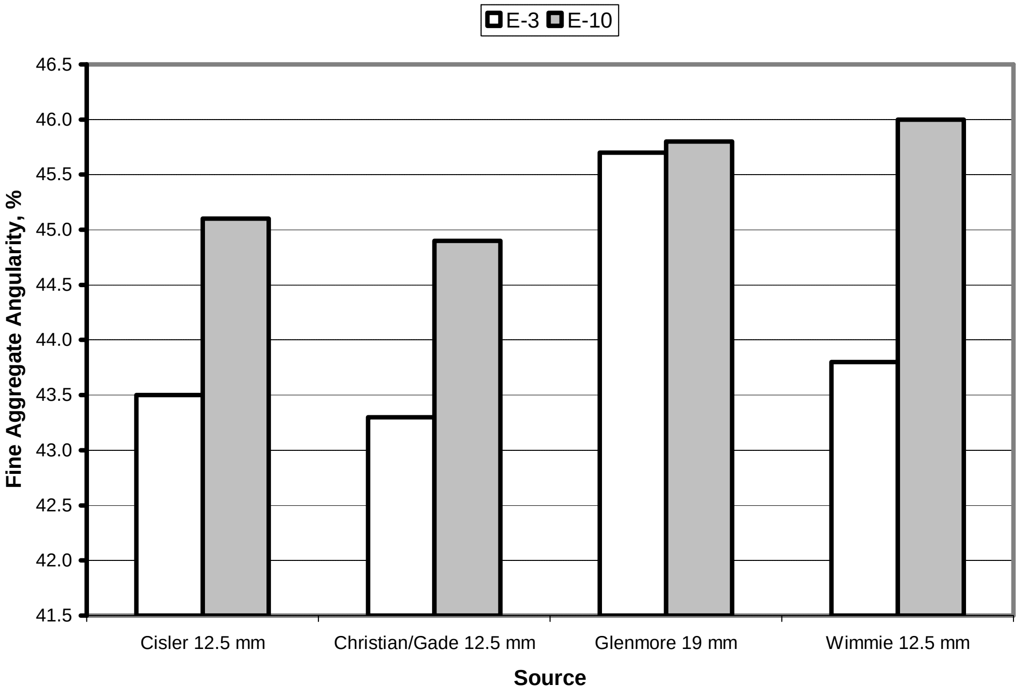

Figure 7. Fine Aggregate Angularity.

Figures 8 through 10 compare selected volumetric properties for the mixtures. Figure 8 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 9 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 10 compares the design binder content for the mixtures.

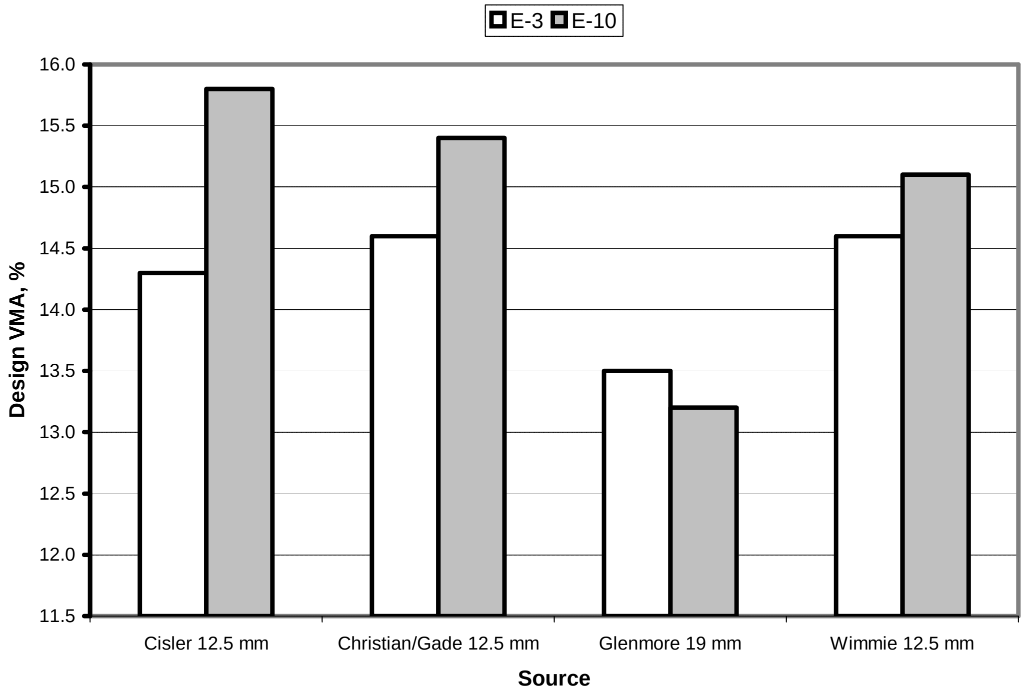

Figure 8. Design VMA.

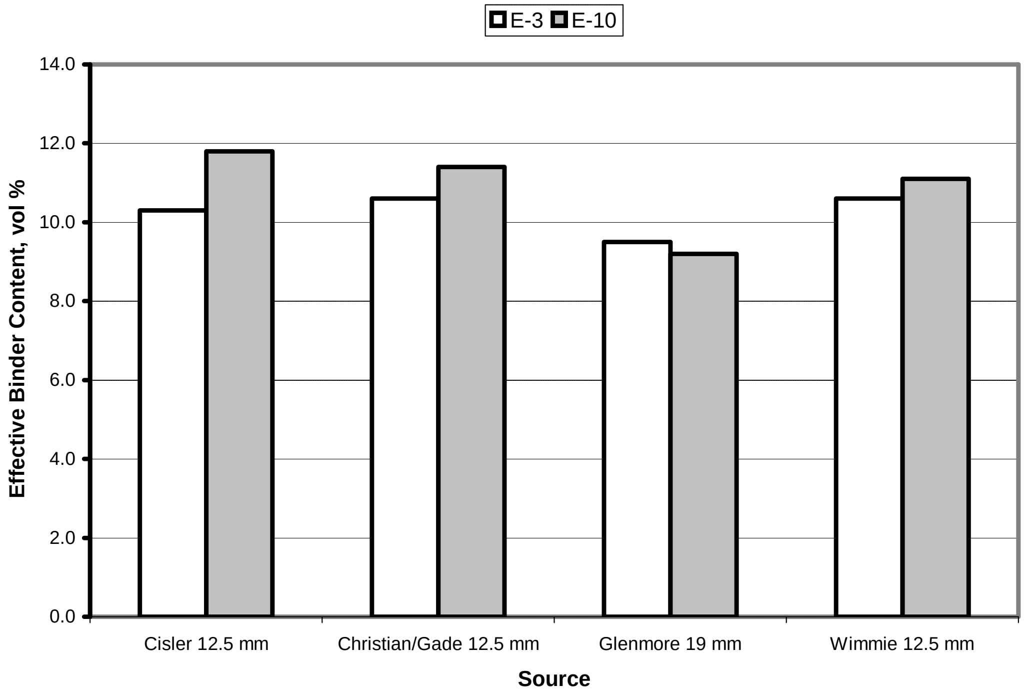

Figure 9. Effective Volumetric Binder Content.

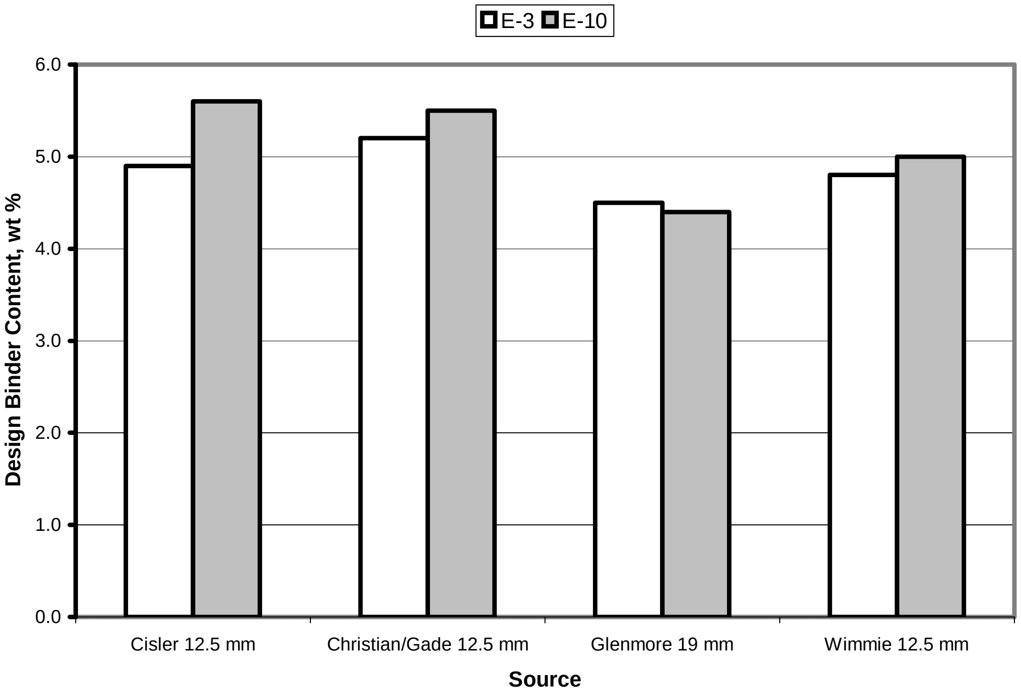

Figure 10. Design Binder Content.

Figures 11 and 12 compare the compactability of the mixtures. Figure 11 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 12 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.

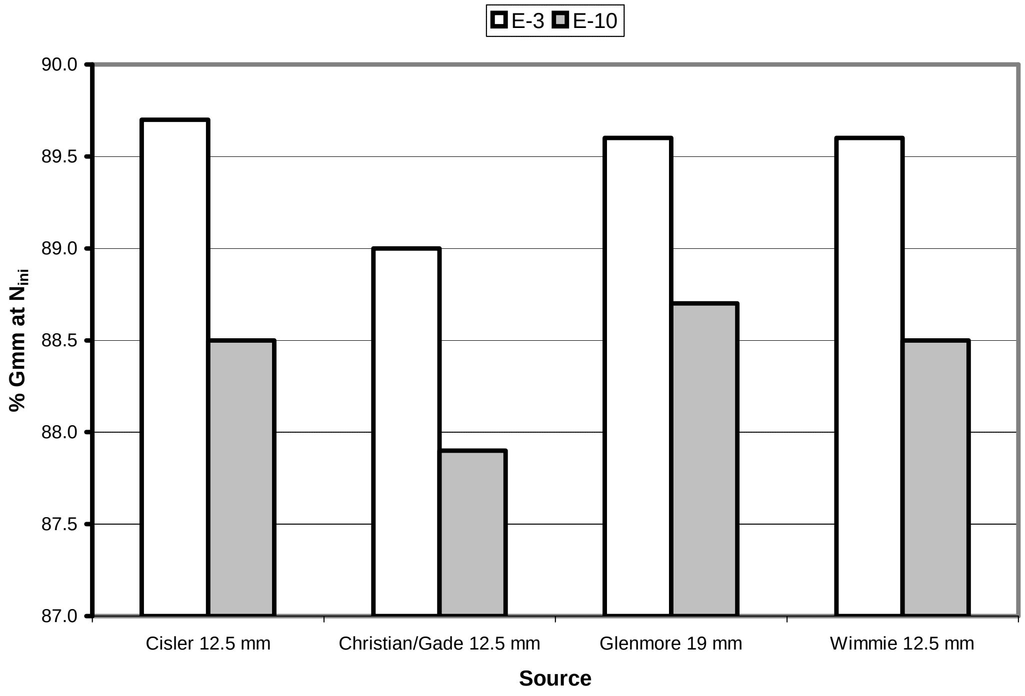

Figure 11. Density at $N_{initial}$.

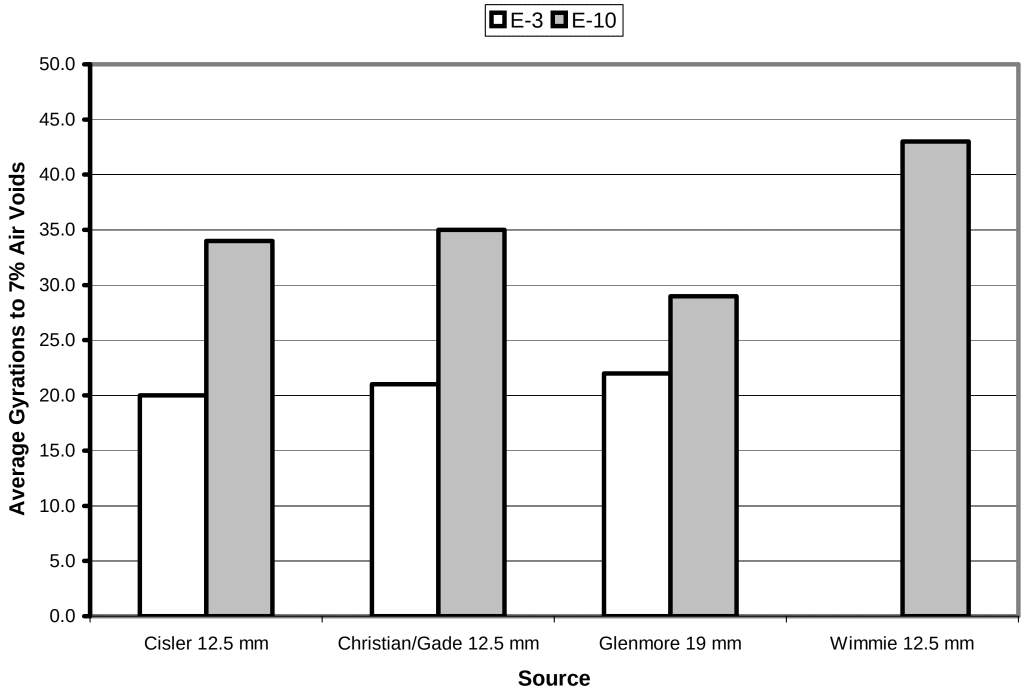

Figure 12. Gyrations to Reach 7 % Air Voids.

2.2 Binders

Two binders, PG 58-28 and PG 58-34, were used in the study. Both binders were provided by Mathy Technology and Engineering Services, Inc. Additionally, RAP binder was used at 25 percent in one-half of the mixtures. The RAP binder was extracted and recovered from RAP from the Badger Interchange Project. Table 4 presents performance grading properties for the two binders. Performance grading data for the recovered RAP binder is presented in Table 5. Finally performance grading data for the 25 percent RAP blends are presented in Table 6.

Figures 13, 14, and 15 compare the high, intermediate, and low temperature continuous grading data for the four binders used this study. The high temperature continuous grade for the virgin binders is approximately 60 °C. Adding 25 percent RAP binder increases the high temperature grade approximately one grade level to 66 °C. The RAP increases the intermediate temperature grade by about 3 °C. Of particular importance in this study is the low temperature grade. The range of the low temperature grade of the four binders is from approximately -35 °C for the virgin PG 58-34 to approximately -29 °C for the PG 58-28 with 25 percent RAP binder.

Table 4. Virgin Binder Performance Grading Properties.

Condition	**Test**	**Temp, °C**	**PG 58-28**	**PG 58-34**
Tank	G*/sinδ, kPa AASHTO T 315	58	1.39	1.36
		64	0.66	0.67
Rolling Thin Film Residue	G*/sinδ, kPa AASHTO T 315	58	4.11	3.73
		64	1.86	1.79
Pressure Aging Vessel Residue	G*sinδ, kPa AASHTO T 315	10		6750
		13	6170	4670
		16	4200	
	Creep Stiffness (MPa) / m AASHTO T 313	-30		535 / 0.266
		-24	463 / 0.255	262 / 0.312
		-18	229 / 0.322	
Grade	AASHTO M320	NA	PG 58-28	PG 58-34
Continuous Grade	NA	NA	60.8 (15.1) –30.5	60.6 (12.4) –35.1

Table 5. Recovered RAP Binder Performance Grading Properties.

Condition	Test	Temp, °C	Recovered Badger Interchange RAP
Recovered	G*/sinδ, kPa AASHTO T 315	82	1.07
		88	0.55
Rolling Thin Film Residue	G*/sinδ, kPa AASHTO T 315	76	4.46
		82	2.09
	G*sinδ, kPa AASHTO T 315	25	5690
		28	3960
	Creep Stiffness (MPa) / m AASHTO T 313	-18	462 / 0.251
		-12	245 / 0.321
Grade	AASHTO M320	NA	PG 76-22
Continuous Grade	NA	NA	81.6 (26.1) -23.7

Table 6. 25 Percent RAP Blend Performance Grading Properties.

Condition	Test	Temp, °C	PG 58-28 + 25 % RAP	PG 58-34 +25 % RAP
Tank	G*/sinδ, kPa AASHTO T 315	64	1.39	1.36
		70	0.66	0.67
Rolling Thin Film Residue	G*/sinδ, kPa AASHTO T 315	64	3.46	3.26
		70	1.59	1.57
Pressure Aging Vessel Residue	G*sinδ, kPa AASHTO T 315	13		6,880
		16		4,790
		19	5,910	
		22	4,180	
	Creep Stiffness (MPa) / m AASHTO T 313	-30		
		-24	556 / 0.255	373/ 0.289
		-18	279 / 0.307	179 / 0.347
Grade	AASHTO M320	NA	PG 64-28	PG 64-28
Continuous Grade	NA	NA	66.6 (17.4) –28.7	66.7 (15.6) –32.2

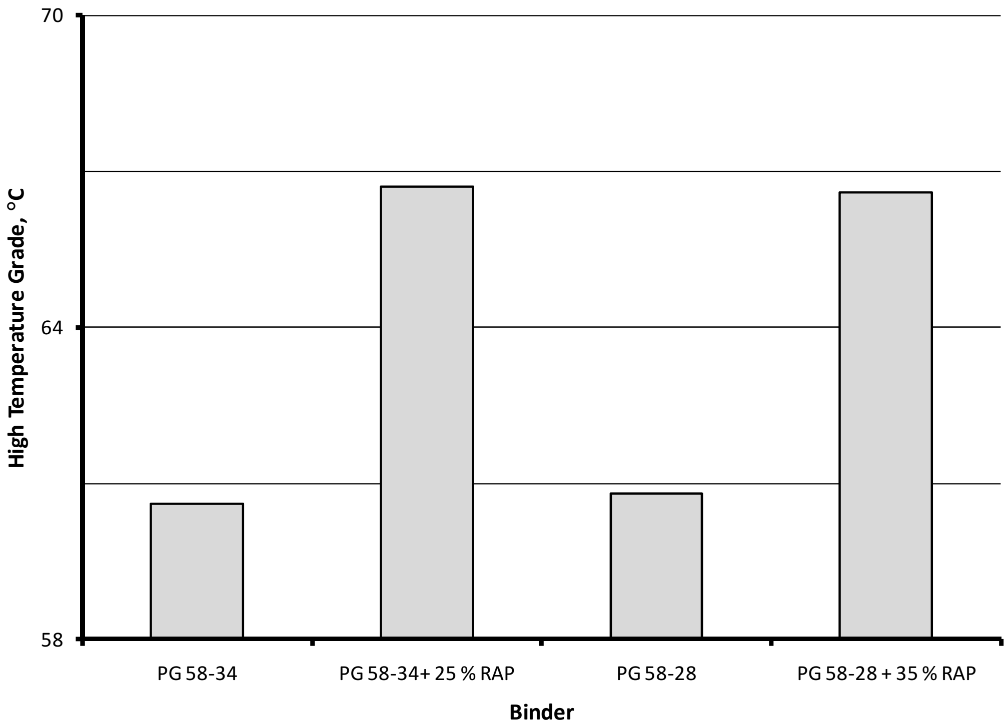

Figure 13. Continuous High Temperature Grade for the Four Binders.

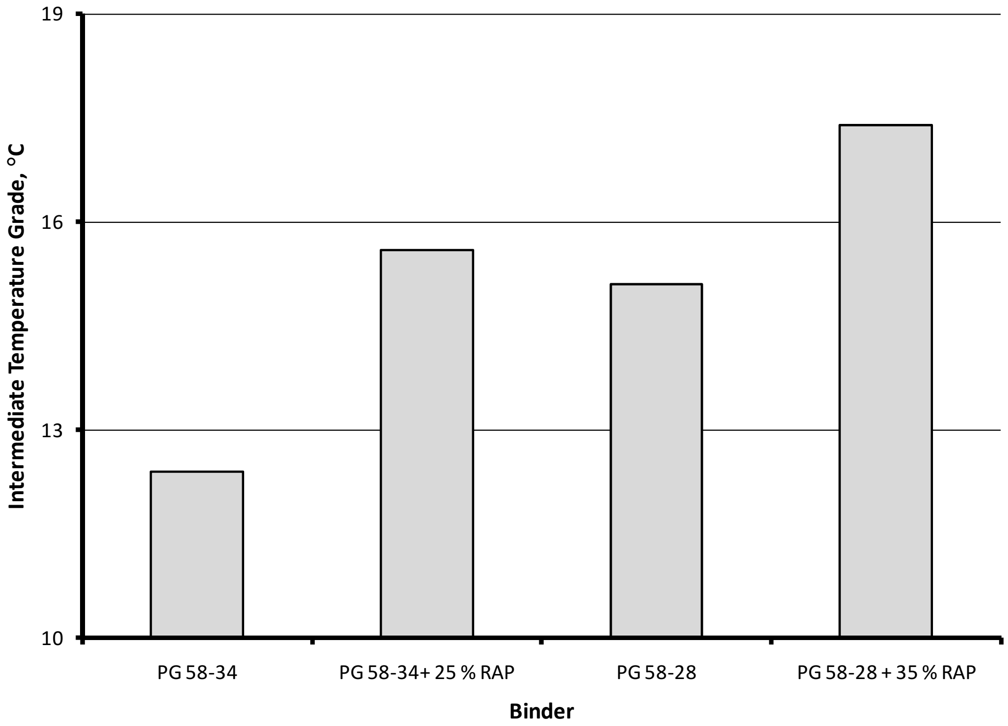

Figure 14. Continuous Intermediate Temperature Grade for the Four Binders.

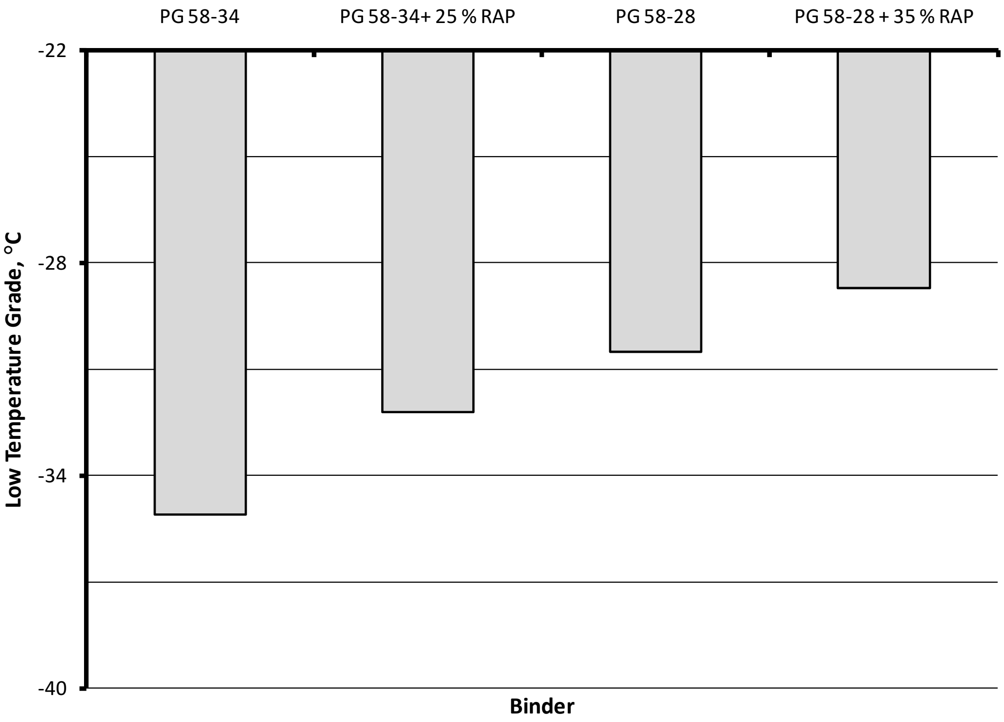

Figure 15. Continuous Low Temperature Grade for the Four Binders.

Chapter 3 Results and Analysis

3.1 Creep Compliance Master Curves

3.1.1 AASHTO T322 Measured

Creep tests were conducted on triplicate specimens at temperatures of 0, -10, and -20 °C in accordance with AASHTO T322. The target air void content for the specimens was 7.0 percent. The LTSTRESS spreadsheet was used to reduce the raw deformation and load data from the three specimens to obtain the average compliance as a function of time for each test temperature. This data reduction was performed in accordance with the calculations in Section 12 of AASHTO T322 except the deformation data from all six faces were used rather than the trimmed mean as outlined in AASHTO T322. The LTSTRESS spreadsheet was also used to generate a master creep compliance curve by shifting the compliance as a function of time data at each temperature to a reference temperature of -20 °C. This was done by numerical optimization using Equation 1 to model the master creep compliance curve of the mixture (*7*).

$$D(t) = D_0 + D_1\left[\frac{t}{10^{C_2(T_r - T)}}\right]^m \tag{1}$$

where:

$D(t)$ = creep compliance

D_0, D_1, m = fitting parameters

C_2 = time-temperature shift constant

T_r = reference temperature

T = temperature

t = time

Figure 16 shows a typical fitted compliance master curve. Appendix B contains the raw compliance data and fitted compliance master curves for all of the mixtures tested.

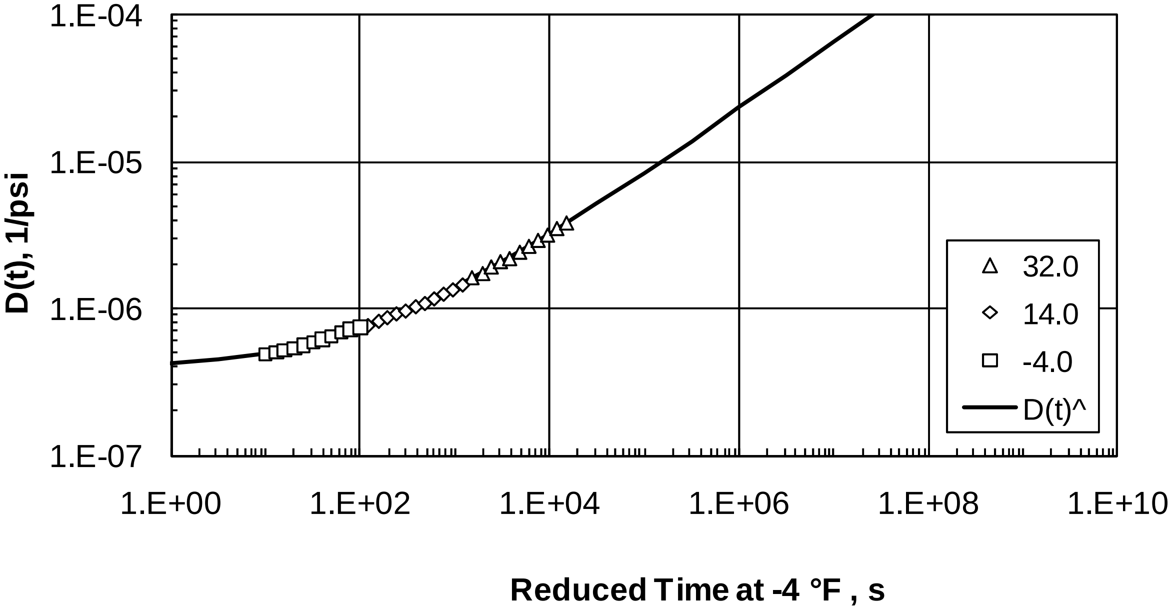

Figure 16. Fitted Compliance Master Curve for Glenmore E10 Mixture For PG 58-28 With 25 Percent RAP.

Table 7 summarizes the master curve fitting parameters for US customary units: compliance in 1/psi, temperature in °F, time in sec. The reference temperature is -4 °F (-20 °C). US customary units were selected to be consistent with the MEPDG. The standard error of the fitted master curves ranges from 0.8 to 4.1 percent indicating excellent fitting of the master curve equation to the raw compliance data.

To compare the master curves and determine the factors affecting the master curves, compliance values were calculated from the fitted master curves over the range of reduced times used in the AASHTO T322 testing, which is from approximately 10 to 100,000 sec. An analysis of variance was then performed on these compliance values to determine if the following factors affected the compliance master curves: (1) binder, (2) aggregate source, and (3) design traffic level. When factors were found to be significant, the Duncan multiple range test was used to determine which factor levels resulted in significant differences (*10*). The results of this analysis are summarized in Table 8.

Table 7. Compliance Master Curve Parameters and Fit.

Binder	Aggregate	Design Traffic Level	log D_0	log D_1	M	C_2	Standard Error, %
58-34	Cisler	E3	-6.517	-7.005	0.447	-0.076	2.4
	Christian/Gade	E10	-6.582	-6.947	0.393	-0.066	3.0
	Glenmore	E3	-6.376	-7.188	0.465	-0.066	1.2
	Wimmie	E10	-6.481	-7.007	0.432	-0.077	2.7
58-34 + 25 % RAP	Cisler	E3	-6.468	-7.197	0.468	-0.067	2.3
	Christian/Gade	E10	-6.409	-7.303	0.491	-0.057	1.7
	Glenmore	E3	-6.401	-7.244	0.476	-0.056	1.8
	Wimmie	E10	-6.523	-7.165	0.421	-0.067	2.9
58-28	Cisler	E10	-6.487	-7.424	0.510	-0.068	3.4
	Christian/Gade	E3	-6.429	-7.383	0.500	-0.057	1.7
	Glenmore	E10	-6.410	-7.205	0.438	-0.064	3.0
	Wimmie	E3	-6.439	-7.552	0.533	-0.065	3.2
58-28 + 25 % RAP	Cisler	E10	-6.424	-7.451	0.472	-0.068	0.8
	Christian/Gade	E3	-6.467	-7.509	0.435	-0.065	1.7
	Glenmore	E10	-6.428	-7.355	0.452	-0.060	1.7
	Wimmie	E3	-6.433	-7.652	0.502	-0.065	4.1

The analysis of variance shows the creep compliance is only affected by the low temperature grade of the binder. The compliance decreases as the low temperature grade of the binder increases. Figures 17 through 20 present the compliance master curves for the mixtures tested grouped by binder grade. Master curves for the PG 58-34 mixtures are shown in Figure 17, the PG 58-34 with RAP in Figure 18, the PG 58-28 in Figure 19, and the PG 58-28 with RAP in Figure 20. The master curves become flatter as the low temperature grade of the binder increases. This is illustrated by Figure 21, which shows compliance master curves averaged over all mixtures for each binder. For the materials tested, adding approximately 25 percent RAP binder to the PG 58-34 binder produces mixtures with similar compliance as those produced with PG 58-28 binder.

Table 8. Summary of Analysis of Variance on Compliance Master Curves.

<table>
<tr><td colspan="3">Reduced Time, -4 °F Reference Temp</td><td colspan="2">10 sec</td><td colspan="2">100 sec</td><td colspan="2">1000 sec</td><td colspan="2">10000 sec</td><td colspan="2">100000 sec</td></tr>
<tr><td>Binder</td><td>Aggregate</td><td>Design Traffic</td><td colspan="10">Creep Compliance, 1/psi</td></tr>
<tr><td rowspan="4">PG 58-34</td><td>Cisler</td><td>E3</td><td colspan="2">5.81E-07</td><td colspan="2">1.08E-06</td><td colspan="2">2.47E-06</td><td colspan="2">6.37E-06</td><td colspan="2">1.73E-05</td></tr>
<tr><td>Christian/Gade</td><td>E10</td><td colspan="2">5.41E-07</td><td colspan="2">9.52E-07</td><td colspan="2">1.97E-06</td><td colspan="2">4.48E-06</td><td colspan="2">1.07E-05</td></tr>
<tr><td>Glenmore</td><td>E3</td><td colspan="2">6.10E-07</td><td colspan="2">9.73E-07</td><td colspan="2">2.03E-06</td><td colspan="2">5.12E-06</td><td colspan="2">1.41E-05</td></tr>
<tr><td>Wimmie</td><td>E10</td><td colspan="2">5.96E-07</td><td colspan="2">1.05E-06</td><td colspan="2">2.28E-06</td><td colspan="2">5.59E-06</td><td colspan="2">1.46E-05</td></tr>
<tr><td rowspan="4">PG 58-34 + 25% RAP</td><td>Cisler</td><td>E3</td><td colspan="2">5.27E-07</td><td colspan="2">8.89E-07</td><td colspan="2">1.95E-06</td><td colspan="2">5.07E-06</td><td colspan="2">1.42E-05</td></tr>
<tr><td>Christian/Gade</td><td>E10</td><td colspan="2">5.44E-07</td><td colspan="2">8.67E-07</td><td colspan="2">1.87E-06</td><td colspan="2">4.97E-06</td><td colspan="2">1.46E-05</td></tr>
<tr><td>Glenmore</td><td>E3</td><td colspan="2">5.68E-07</td><td colspan="2">9.08E-07</td><td colspan="2">1.92E-06</td><td colspan="2">4.97E-06</td><td colspan="2">1.41E-05</td></tr>
<tr><td>Wimmie</td><td>E10</td><td colspan="2">4.80E-07</td><td colspan="2">7.75E-07</td><td colspan="2">1.55E-06</td><td colspan="2">3.60E-06</td><td colspan="2">9.01E-06</td></tr>
<tr><td rowspan="4">PG 58-28</td><td>Cisler</td><td>E10</td><td colspan="2">4.48E-07</td><td colspan="2">7.20E-07</td><td colspan="2">1.60E-06</td><td colspan="2">4.46E-06</td><td colspan="2">1.37E-05</td></tr>
<tr><td>Christian/Gade</td><td>E3</td><td colspan="2">5.03E-07</td><td colspan="2">7.86E-07</td><td colspan="2">1.68E-06</td><td colspan="2">4.51E-06</td><td colspan="2">1.35E-05</td></tr>
<tr><td>Glenmore</td><td>E10</td><td colspan="2">5.60E-07</td><td colspan="2">8.58E-07</td><td colspan="2">1.67E-06</td><td colspan="2">3.91E-06</td><td colspan="2">1.00E-05</td></tr>
<tr><td>Wimmie</td><td>E3</td><td colspan="2">4.60E-07</td><td colspan="2">6.91E-07</td><td colspan="2">1.48E-06</td><td colspan="2">4.17E-06</td><td colspan="2">1.33E-05</td></tr>
<tr><td rowspan="4">PG 58-28 +25 % RAP</td><td>Cisler</td><td>E10</td><td colspan="2">4.82E-07</td><td colspan="2">6.88E-07</td><td colspan="2">1.30E-06</td><td colspan="2">3.11E-06</td><td colspan="2">8.49E-06</td></tr>
<tr><td>Christian/Gade</td><td>E3</td><td colspan="2">4.26E-07</td><td colspan="2">5.71E-07</td><td colspan="2">9.66E-07</td><td colspan="2">2.04E-06</td><td colspan="2">4.98E-06</td></tr>
<tr><td>Glenmore</td><td>E10</td><td colspan="2">4.98E-07</td><td colspan="2">7.27E-07</td><td colspan="2">1.38E-06</td><td colspan="2">3.21E-06</td><td colspan="2">8.41E-06</td></tr>
<tr><td>Wimmie</td><td>E3</td><td colspan="2">4.40E-07</td><td colspan="2">5.94E-07</td><td colspan="2">1.08E-06</td><td colspan="2">2.64E-06</td><td colspan="2">7.58E-06</td></tr>
<tr><td colspan="13">Analysis of Variance Summary, 0.5 Percent Significance Level</td></tr>
<tr><td rowspan="3">Binder</td><td colspan="2">Significant Differences</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td><td colspan="2">Yes</td></tr>
<tr><td colspan="2" rowspan="2">Rank, highest to lowest compliance</td><td>Binder</td><td>Rank</td><td>Binder</td><td>Rank</td><td>Binder</td><td>Rank</td><td>Binder</td><td>Rank</td><td>Binder</td><td>Rank</td></tr>
<tr><td>-34
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-28
-28wRAP</td><td>1
2
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<tr><td>Design Traffic</td><td colspan="2">Design Traffic</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td></tr>
</table>

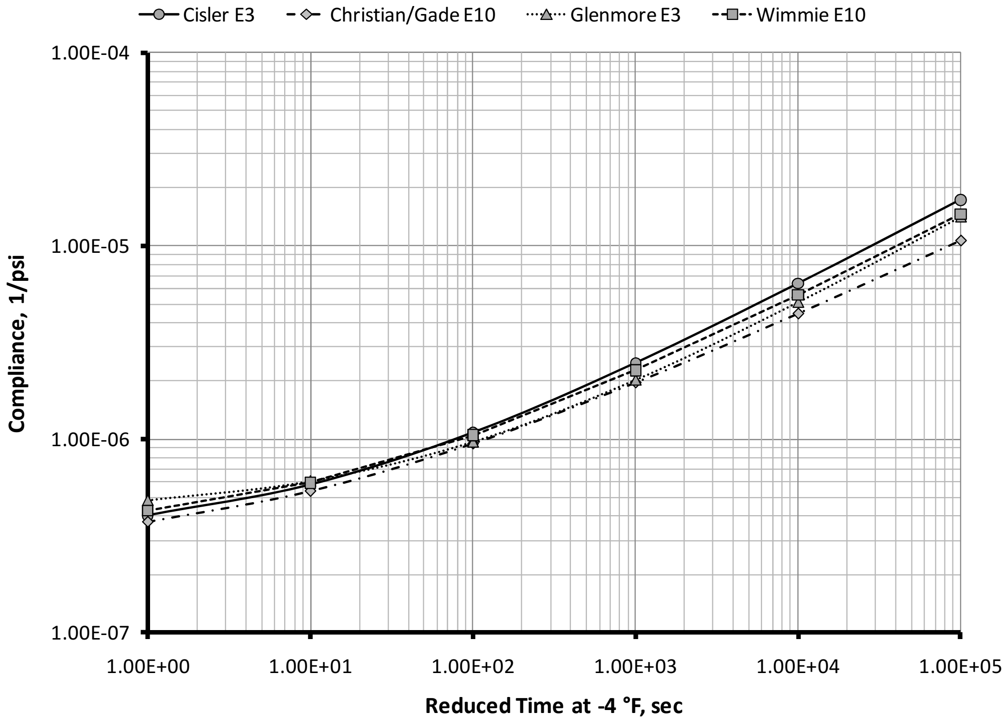

Figure 17. Compliance Master Curves for PG 58-34.

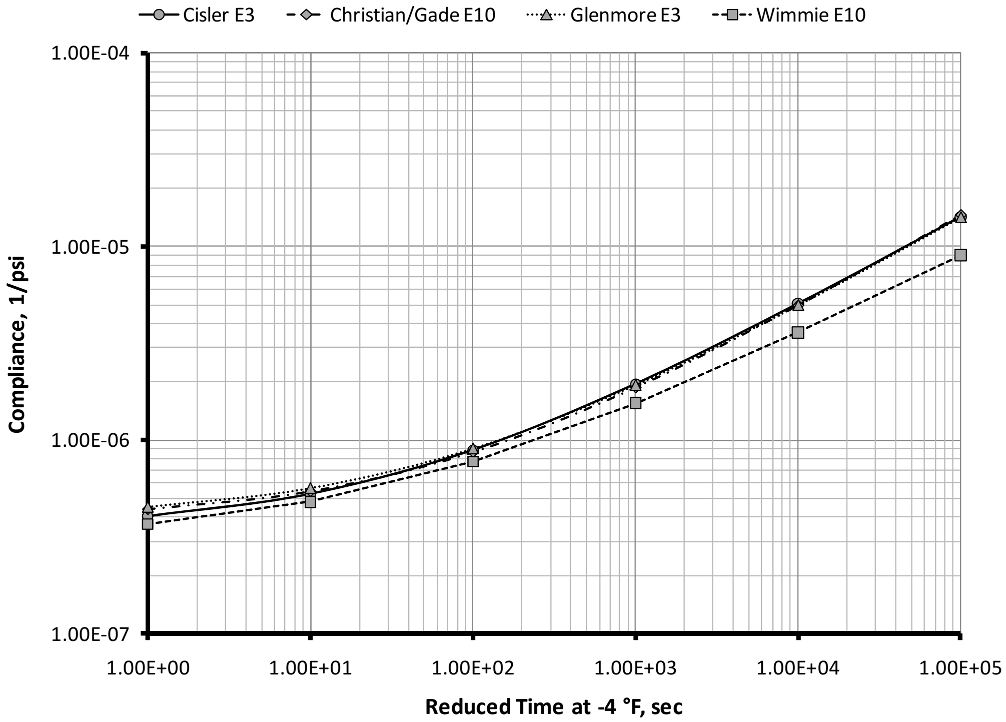

Figure 18. Compliance Master Curves for PG 58-34 With 25 Percent RAP.

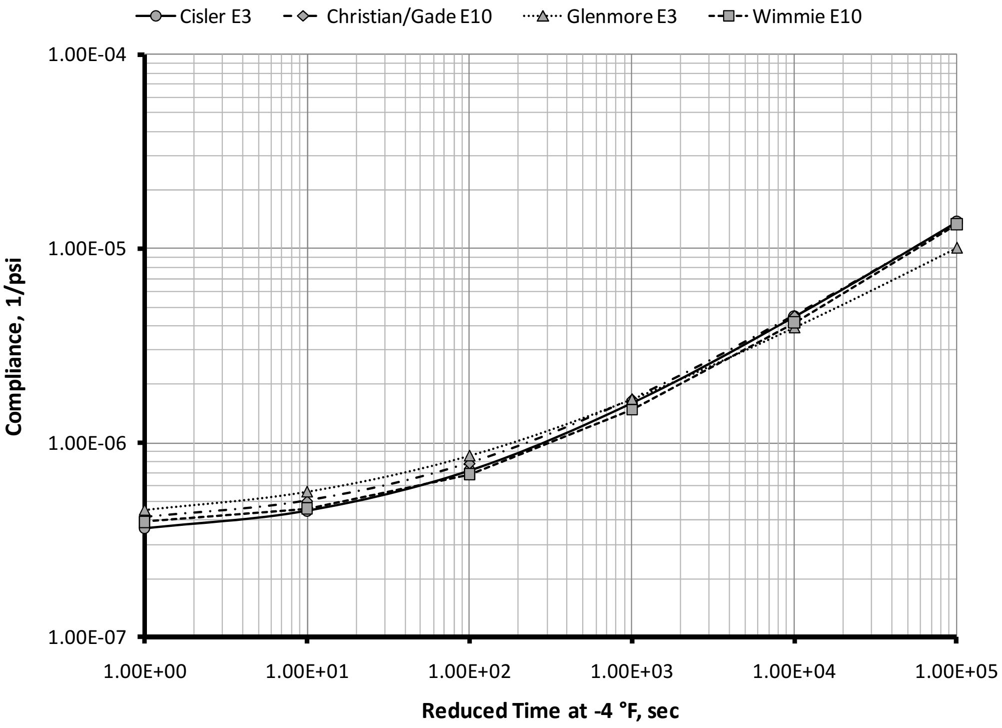

Figure 19. Compliance Master Curves for PG 58-28.

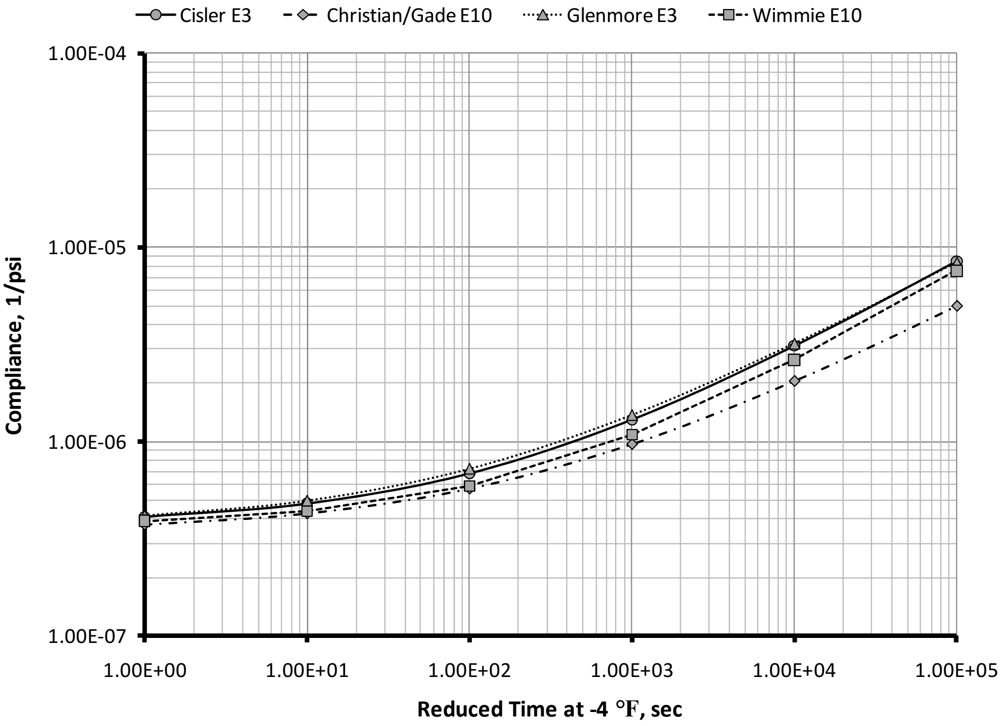

Figure 20. Compliance Master Curves for PG 58-28 With 25 Percent RAP.

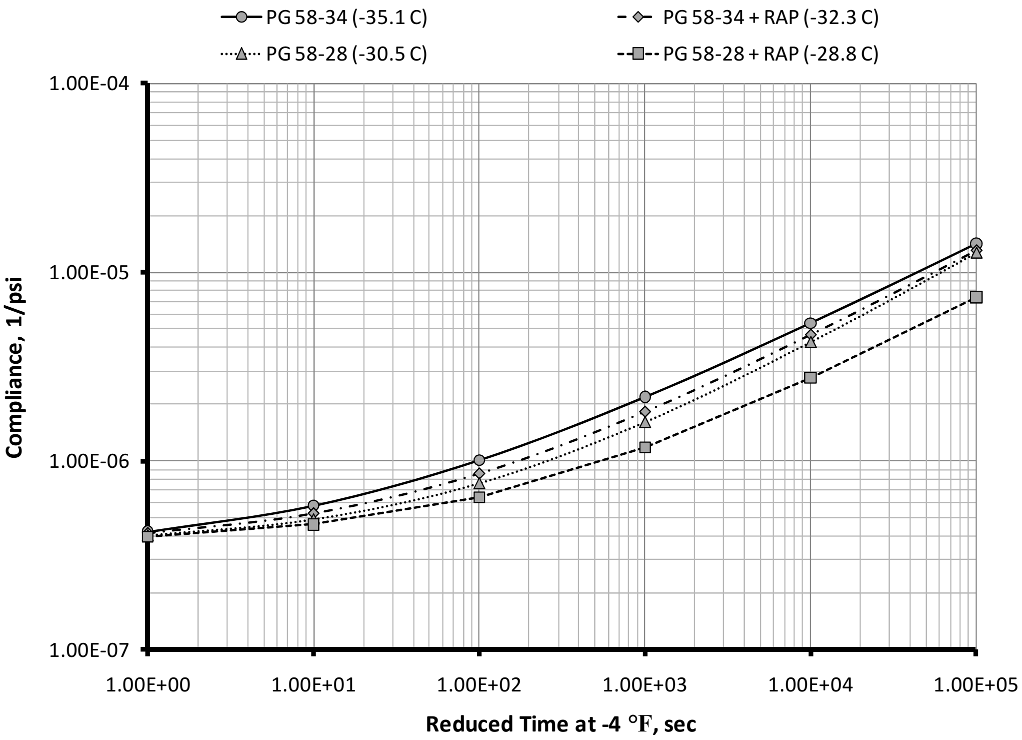

Figure 21. Compliance Master Curves Averaged Over Binder.

To evaluate the errors associated using average compliance values based on binder grade, compliance values computed with the average compliance models were compared to fitted compliance curves for each of the mixtures. The results are summarized in Tables 9 through 12 and compared graphically in Figure 22. Figure 22 shows that using binder average models results in an unbiased estimate of the compliance for the mixtures tested. The best fit regression line coincides with the line of equality. The errors increase with increasing reduced times. For the highest temperature and longest loading time, the errors can be as high as 40 percent. Errors in this portion of the compliance master curve have minimal effect on the computed thermal stresses. Figure 23 compares thermal stress calculated using the fitted compliance curve for the Cisler E3 mixture and the average PG 58-34 compliance curve. The fitted Cisler E3 mixture has the largest difference from the average PG 58-34 compliance curve. The stresses were calculated with the LTSTRESS spreadsheet using a typical thermal coefficient of contraction of 2.5×10^{-5} /°C and a typical cooling rate of 5.6 °C/hr. The difference in the thermal stresses between -28 to -34 °C is approximately 5 percent.

Table 9. Comparison of Fitted and Average PG 58-34 Compliance Values.

Aggregate Source		PG 58-34 Average	Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		NA	E3	E10	E3	E10
Time, sec	Temp, F	Compliance, 1/psi				
1	-4	4.40E-07	4.03E-07	3.75E-07	4.86E-07	4.29E-07
2	-4	4.71E-07	4.39E-07	4.10E-07	5.10E-07	4.63E-07
5	-4	5.30E-07	5.07E-07	4.74E-07	5.58E-07	5.28E-07
10	-4	5.94E-07	5.81E-07	5.41E-07	6.10E-07	5.96E-07
20	-4	6.79E-07	6.81E-07	6.29E-07	6.82E-07	6.89E-07
50	-4	8.42E-07	8.72E-07	7.87E-07	8.21E-07	8.64E-07
100	-4	1.02E-06	1.08E-06	9.52E-07	9.73E-07	1.05E-06
1	14	6.72E-07	7.08E-07	5.93E-07	6.52E-07	7.21E-07
2	14	7.86E-07	8.55E-07	6.97E-07	7.40E-07	8.57E-07
5	14	1.00E-06	1.13E-06	8.85E-07	9.10E-07	1.11E-06
10	14	1.23E-06	1.44E-06	1.08E-06	1.10E-06	1.39E-06
20	14	1.54E-06	1.85E-06	1.34E-06	1.35E-06	1.76E-06
50	14	2.13E-06	2.63E-06	1.80E-06	1.85E-06	2.45E-06
100	14	2.77E-06	3.47E-06	2.28E-06	2.39E-06	3.19E-06
1	32	1.52E-06	1.96E-06	1.23E-06	1.25E-06	1.88E-06
2	32	1.93E-06	2.56E-06	1.54E-06	1.56E-06	2.42E-06
5	32	2.71E-06	3.70E-06	2.09E-06	2.17E-06	3.44E-06
10	32	3.55E-06	4.93E-06	2.66E-06	2.83E-06	4.52E-06
20	32	4.69E-06	6.61E-06	3.41E-06	3.75E-06	5.99E-06
50	32	6.84E-06	9.80E-06	4.77E-06	5.51E-06	8.73E-06
100	32	9.16E-06	1.32E-05	6.19E-06	7.45E-06	1.17E-05

Table 10. Comparison of Fitted and Average PG 58-34 With 25 Percent RAP Compliance Values.

Aggregate Source		PG 58-34 With 25 % RAP Average	Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		NA	E3	E10	E3	E10
Time, sec	Temp, F	Compliance, 1/psi				
1	-4	4.30E-07	4.04E-07	4.40E-07	4.54E-07	3.68E-07
2	-4	4.52E-07	4.28E-07	4.60E-07	4.76E-07	3.91E-07
5	-4	4.93E-07	4.75E-07	5.00E-07	5.20E-07	4.35E-07
10	-4	5.39E-07	5.27E-07	5.44E-07	5.68E-07	4.80E-07
20	-4	6.03E-07	5.99E-07	6.07E-07	6.34E-07	5.41E-07
50	-4	7.27E-07	7.37E-07	7.30E-07	7.64E-07	6.55E-07
100	-4	8.63E-07	8.89E-07	8.67E-07	9.08E-07	7.75E-07
1	14	5.62E-07	5.73E-07	5.49E-07	5.69E-07	5.20E-07
2	14	6.34E-07	6.63E-07	6.13E-07	6.37E-07	5.95E-07
5	14	7.74E-07	8.35E-07	7.40E-07	7.67E-07	7.33E-07
10	14	9.28E-07	1.02E-06	8.82E-07	9.12E-07	8.80E-07
20	14	1.14E-06	1.29E-06	1.08E-06	1.11E-06	1.08E-06
50	14	1.56E-06	1.79E-06	1.47E-06	1.51E-06	1.44E-06
100	14	2.01E-06	2.35E-06	1.91E-06	1.94E-06	1.83E-06
1	32	1.00E-06	1.20E-06	8.96E-07	9.17E-07	1.01E-06
2	32	1.24E-06	1.52E-06	1.10E-06	1.12E-06	1.25E-06
5	32	1.71E-06	2.16E-06	1.51E-06	1.51E-06	1.70E-06
10	32	2.23E-06	2.85E-06	1.96E-06	1.95E-06	2.17E-06
20	32	2.94E-06	3.81E-06	2.59E-06	2.56E-06	2.80E-06
50	32	4.33E-06	5.67E-06	3.85E-06	3.74E-06	3.98E-06
100	32	5.85E-06	7.72E-06	5.25E-06	5.05E-06	5.23E-06

Table 11. Comparison of Fitted and Average PG 58-28 Compliance Values.

Aggregate Source		PG 58-28 Average	Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		NA	E10	E3	E10	E3
Time, sec	Temp, F	Compliance, 1/psi				
1	-4	4.29E-07	3.64E-07	4.14E-07	4.51E-07	3.92E-07
2	-4	4.45E-07	3.79E-07	4.31E-07	4.74E-07	4.05E-07
5	-4	4.76E-07	4.11E-07	4.65E-07	5.15E-07	4.3E-07
10	-4	5.11E-07	4.48E-07	5.03E-07	5.6E-07	4.6E-07
20	-4	5.61E-07	4.99E-07	5.58E-07	6.21E-07	5.02E-07
50	-4	6.59E-07	6.03E-07	6.65E-07	7.35E-07	5.9E-07
100	-4	7.71E-07	7.20E-07	7.86E-07	8.58E-07	6.91E-07
1	14	5.34E-07	4.84E-07	5.07E-07	5.88E-07	4.82E-07
2	14	5.93E-07	5.52E-07	5.63E-07	6.59E-07	5.35E-07
5	14	7.11E-07	6.86E-07	6.74E-07	7.92E-07	6.42E-07
10	14	8.44E-07	8.39E-07	7.99E-07	9.36E-07	7.66E-07
20	14	1.03E-06	1.06E-06	9.76E-07	1.13E-06	9.46E-07
50	14	1.41E-06	1.49E-06	1.33E-06	1.49E-06	1.31E-06
100	14	1.83E-06	1.99E-06	1.72E-06	1.89E-06	1.74E-06
1	32	9.31E-07	9.93E-07	8.12E-07	1.03E-06	8.6E-07
2	32	1.16E-06	1.28E-06	9.94E-07	1.25E-06	1.08E-06
5	32	1.60E-06	1.84E-06	1.36E-06	1.68E-06	1.53E-06
10	32	2.11E-06	2.49E-06	1.76E-06	2.14E-06	2.06E-06
20	32	2.82E-06	3.40E-06	2.34E-06	2.75E-06	2.81E-06
50	32	4.24E-06	5.23E-06	3.48E-06	3.92E-06	4.35E-06
100	32	5.85E-06	7.32E-06	4.77E-06	5.18E-06	6.13E-06

Table 12. Comparison of Fitted and Average PG 58-28 With 25 Percent RAP Compliance Values.

Aggregate Source		PG 58-28 With 25 % RAP Average	Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		NA	E3	E10	E3	E10
Time, sec	Temp, F	Compliance, 1/psi				
1	-4	4.06E-07	4.12E-07	3.72E-07	4.17E-07	3.91E-07
2	-4	4.18E-07	4.26E-07	3.83E-07	4.34E-07	4.01E-07
5	-4	4.41E-07	4.52E-07	4.04E-07	4.65E-07	4.19E-07
10	-4	4.67E-07	4.82E-07	4.26E-07	4.98E-07	4.4E-07
20	-4	5.03E-07	5.22E-07	4.55E-07	5.44E-07	4.69E-07
50	-4	5.71E-07	6.01E-07	5.11E-07	6.32E-07	5.28E-07
100	-4	6.47E-07	6.88E-07	5.71E-07	7.27E-07	5.94E-07
1	14	4.86E-07	5.11E-07	4.41E-07	5.09E-07	4.55E-07
2	14	5.28E-07	5.62E-07	4.76E-07	5.59E-07	4.91E-07
5	14	6.11E-07	6.63E-07	5.43E-07	6.55E-07	5.62E-07
10	14	7.02E-07	7.74E-07	6.13E-07	7.58E-07	6.43E-07
20	14	8.28E-07	9.27E-07	7.09E-07	9E-07	7.57E-07
50	14	1.07E-06	1.23E-06	8.89E-07	1.17E-06	9.83E-07
100	14	1.34E-06	1.55E-06	1.08E-06	1.46E-06	1.24E-06
1	32	7.68E-07	8.83E-07	6.64E-07	7.91E-07	7.02E-07
2	32	9.19E-07	1.08E-06	7.78E-07	9.45E-07	8.41E-07
5	32	1.21E-06	1.46E-06	9.91E-07	1.24E-06	1.12E-06
10	32	1.53E-06	1.88E-06	1.22E-06	1.56E-06	1.43E-06
20	32	1.98E-06	2.46E-06	1.53E-06	1.99E-06	1.87E-06
50	32	2.84E-06	3.59E-06	2.11E-06	2.82E-06	2.74E-06
100	32	3.79E-06	4.83E-06	2.73E-06	3.73E-06	3.73E-06

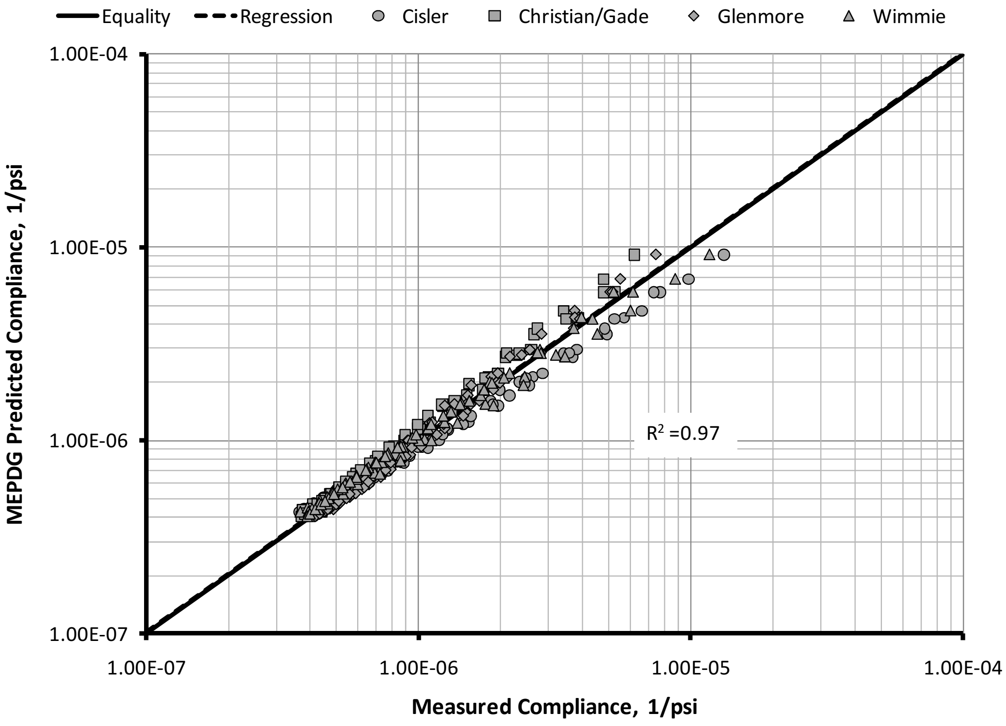

Figure 22. Comparison of Binder Average and Mixture Specific Compliance Values.

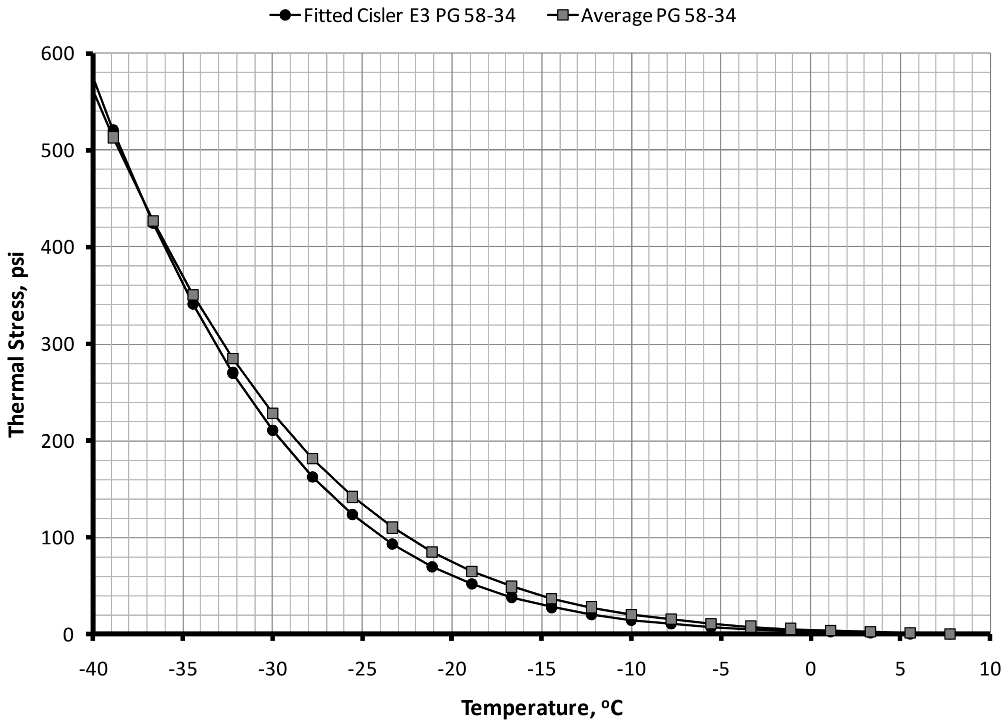

Figure 23. Comparison of Thermal Stresses for Cisler E3 With PG 58-34 Binder.

Figure 24 compares thermal stresses calculated with LTSTRESS for the different binders tested. This analysis also used a typical thermal coefficient of contraction of $2.5\text{x}10^{-5}$ /°C and a typical cooling rate of 5.6 °C/hr. Over the temperature range from -28 to -34 °C, the thermal stresses are approximately 10 percent higher for the PG 58-34 with 25 % RAP compared to the PG 58-34; 20 percent higher for the PG 58-28 compared to the PG 58-34; and 60 percent higher for the PG 58-28 with 25 % RAP compared to the PG 58-34. These analyses show that it is only necessary to consider the expected low temperature properties of the binder in the mixture when predicting thermal cracking for pavement design.

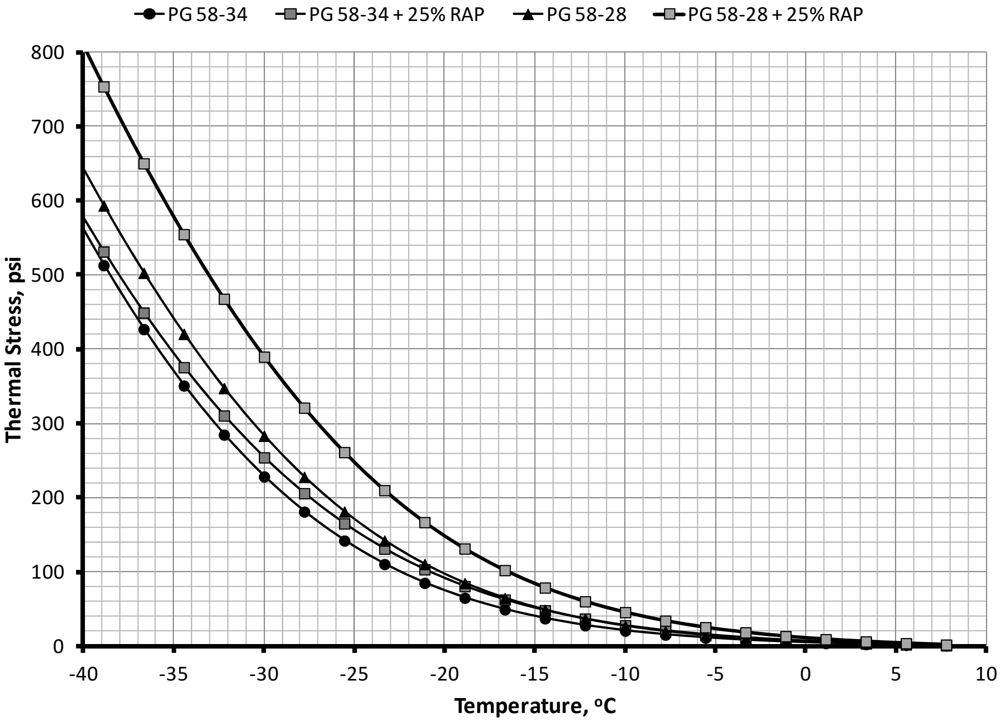

Figure 24. Comparison of Thermal Stresses For Binders Tested.

3.1.2 MEPDG Compliance Values

The MEPDG provides estimated compliance values for Level 3 analyses. These compliance values are estimated from binder properties and mixture volumetric properties using Equation 2.

$$D(t) = D_1 \times t^m \qquad (2)$$

Where:

$$\log D_1 = 8.524 + 0.01306 \times Temp + 0.7957 \times \log(Va) + 2.0103 \times \log(VFA) - 1.923 \times \log(A)$$

$$m = 1.1628 - 0.00185 \times Temp - 0.04596 \times Va - 0.01126 \times VFA + 0.00247 \times Pen77 + 0.001683 \times Temp \times (Pen77)^{0.4605}$$

Temp = temperature at which creep compliance is measured, ºF.
Va = as construction air voids, %
VFA = as construction voids filled with asphalt, %
Pen77 = binder penetration at 77 ºF, mm/10
A = viscosity-temperature susceptibility intercept.

Equation 2 uses binder properties that are no longer routinely measured. The MEPDG provides estimates of these properties based on the performance grade of the binder, so that estimates of compliance values can be made knowing the volumteric properties of the mixture and the performance grade of the binder. The discussion that follows compares these compliance values with those measured on Wisconsin mixtures in this project.

Tables 13 through 16 summarize compliance values estimated by the MEPDG. When computing the compliance values with the MEPDG, the performance grade of the binder in the mixture was used. Both binders with 25 percent RAP graded as PG 64-28. Figure 25 compares the MEDPG complaince values with the measured values for the 16 mixtures. Figure 25 includes the line of equality and the best fit regression line. For the mixtures tested, the MEPDG Level 3 compliance estimates are lower than the measured values. The bias is approximately 20 percent. The maximum deviation for any mixture is as high as approximately 56 percent. The effect of this deviation on thermal stresses is shown in Figure 26 which compares stresses calculated with LTSTRESS for the fitted compliance master curve for the Glenmore E10 mixture with PG 58-28 binder and the MEPDG Level 3 estimated compliance master curve. Like the stress analyses discussed earlier, this analysis used a typical thermal coefficient of contraction of $2.5\text{x}10^{-5}$ /°C and a typical cooling rate of 5.6 °C/hr. Over the temperature range of -28 to -34 °C, the lower MEPDG compliance values resulted in stresses that were approximately 70 percent higher. This indicates that the MEPDG Level 3 compliance values should be used with caution.

Table 13. Level 3 Compliance Values From MEPDG for PG 58-34 Mixtures.

Aggregate Source		Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		E3	E10	E3	E10
Binder Grade		PG 58-34	PG 58-34	PG 58-34	PG 58-34
Time, sec	Temp, F	Compliance, 1/psi			
1	-4	3.36E-07	4.02E-07	2.89E-07	3.84E-07
2	-4	3.83E-07	4.59E-07	3.3E-07	4.38E-07
5	-4	4.56E-07	5.46E-07	3.92E-07	5.21E-07
10	-4	5.21E-07	6.23E-07	4.48E-07	5.95E-07
20	-4	5.94E-07	7.11E-07	5.11E-07	6.79E-07
50	-4	7.07E-07	8.46E-07	6.08E-07	8.08E-07
100	-4	8.07E-07	9.65E-07	6.94E-07	9.22E-07
1	14	5.33E-07	6.13E-07	4.74E-07	5.91E-07
2	14	6.49E-07	7.46E-07	5.77E-07	7.19E-07
5	14	8.41E-07	9.66E-07	7.48E-07	9.32E-07
10	14	1.02E-06	1.18E-06	9.09E-07	1.13E-06
20	14	1.24E-06	1.43E-06	1.11E-06	1.38E-06
50	14	1.61E-06	1.85E-06	1.43E-06	1.79E-06
100	14	1.96E-06	2.25E-06	1.74E-06	2.18E-06
1	32	7.40E-07	8.33E-07	6.69E-07	8.08E-07
2	32	1.03E-06	1.16E-06	9.33E-07	1.13E-06
5	32	1.60E-06	1.80E-06	1.45E-06	1.75E-06
10	32	2.23E-06	2.51E-06	2.02E-06	2.44E-06
20	32	3.11E-06	3.50E-06	2.81E-06	3.40E-06
50	32	4.83E-06	5.44E-06	4.37E-06	5.27E-06
100	32	6.73E-06	7.58E-06	6.09E-06	7.35E-06

Table 14. Level 3 Compliance Values From MEPDG for PG 58-34 with 25 Percent RAP Mixtures.

Aggregate Source		Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		E3	E10	E3	E10
Binder Grade		PG 64-28	PG 64-28	PG 64-28	PG 64-28
Time, sec	Temp, F	Compliance, 1/psi			
1	-4	3.03E-07	5.03E-07	2.60E-07	3.46E-07
2	-4	3.36E-07	5.65E-07	2.89E-07	3.83E-07
5	-4	3.84E-07	6.58E-07	3.30E-07	4.39E-07
10	-4	4.26E-07	7.38E-07	3.66E-07	4.86E-07
20	-4	4.72E-07	8.28E-07	4.06E-07	5.39E-07
50	-4	5.40E-07	9.65E-07	4.65E-07	6.17E-07
100	-4	5.99E-07	1.08E-06	5.15E-07	6.84E-07
1	14	4.91E-07	7.31E-07	4.37E-07	5.45E-07
2	14	5.79E-07	8.74E-07	5.15E-07	6.42E-07
5	14	7.19E-07	1.11E-06	6.39E-07	7.97E-07
10	14	8.47E-07	1.32E-06	7.53E-07	9.39E-07
20	14	9.97E-07	1.58E-06	8.87E-07	1.11E-06
50	14	1.24E-06	2.00E-06	1.10E-06	1.37E-06
100	14	1.46E-06	2.39E-06	1.30E-06	1.62E-06
1	32	6.84E-07	9.89E-07	6.19E-07	7.47E-07
2	32	8.91E-07	1.33E-06	8.06E-07	9.74E-07
5	32	1.27E-06	1.96E-06	1.15E-06	1.38E-06
10	32	1.65E-06	2.63E-06	1.49E-06	1.80E-06
20	32	2.15E-06	3.53E-06	1.95E-06	2.35E-06
50	32	3.06E-06	5.22E-06	2.76E-06	3.34E-06
100	32	3.98E-06	7.00E-06	3.60E-06	4.35E-06

Table 15. Level 3 Compliance Values From MEPDG for PG 58-28 Mixtures.

Aggregate Source		Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		E3	E10	E3	E10
Binder Grade		PG 58-28	PG 58-28	PG 58-28	PG 58-28
Time, sec	Temp, F	Compliance, 1/psi			
1	-4	2.99E-07	2.48E-07	1.91E-07	2.48E-07
2	-4	3.35E-07	2.79E-07	2.14E-07	2.79E-07
5	-4	3.90E-07	3.24E-07	2.49E-07	3.24E-07
10	-4	4.37E-07	3.63E-07	2.79E-07	3.63E-07
20	-4	4.90E-07	4.07E-07	3.13E-07	4.07E-07
50	-4	5.70E-07	4.73E-07	3.63E-07	4.73E-07
100	-4	6.39E-07	5.31E-07	4.08E-07	5.31E-07
1	14	4.86E-07	4.20E-07	3.42E-07	4.20E-07
2	14	5.80E-07	5.02E-07	4.08E-07	5.02E-07
5	14	7.32E-07	6.34E-07	5.16E-07	6.34E-07
10	14	8.73E-07	7.56E-07	6.15E-07	7.56E-07
20	14	1.04E-06	9.02E-07	7.34E-07	9.02E-07
50	14	1.32E-06	1.14E-06	9.28E-07	1.14E-06
100	14	1.57E-06	1.36E-06	1.11E-06	1.36E-06
1	32	6.62E-07	5.85E-07	4.91E-07	5.85E-07
2	32	8.87E-07	7.84E-07	6.57E-07	7.84E-07
5	32	1.30E-06	1.15E-06	9.67E-07	1.15E-06
10	32	1.75E-06	1.54E-06	1.30E-06	1.54E-06
20	32	2.34E-06	2.07E-06	1.73E-06	2.07E-06
50	32	3.44E-06	3.04E-06	2.55E-06	3.04E-06
100	32	4.61E-06	4.07E-06	3.42E-06	4.07E-06

Table 16. Level 3 Compliance Values From MEPDG for PG 58-28 With 25 Percent RAP Mixtures.

Aggregate Source		Cisler	Christian/ Gade	Glenmore	Wimmie
Design Traffic Level		E3	E10	E3	E10
Binder Grade		PG 64-28	PG 64-28	PG 64-28	PG 64-28
Time, sec	Temp, F	Compliance, 1/psi			
1	-4	3.84E-07	3.19E-07	2.45E-07	3.19E-07
2	-4	4.25E-07	3.53E-07	2.71E-07	3.53E-07
5	-4	4.87E-07	4.05E-07	3.11E-07	4.05E-07
10	-4	5.40E-07	4.48E-07	3.44E-07	4.48E-07
20	-4	5.98E-07	4.97E-07	3.81E-07	4.97E-07
50	-4	6.85E-07	5.69E-07	4.37E-07	5.69E-07
100	-4	7.59E-07	6.30E-07	4.84E-07	6.30E-07
1	14	5.91E-07	5.12E-07	4.16E-07	5.12E-07
2	14	6.96E-07	6.03E-07	4.91E-07	6.03E-07
5	14	8.65E-07	7.48E-07	6.09E-07	7.48E-07
10	14	1.02E-06	8.81E-07	7.18E-07	8.81E-07
20	14	1.20E-06	1.04E-06	8.45E-07	1.04E-06
50	14	1.49E-06	1.29E-06	1.05E-06	1.29E-06
100	14	1.75E-06	1.52E-06	1.24E-06	1.52E-06
1	32	8.01E-07	7.08E-07	5.94E-07	7.08E-07
2	32	1.04E-06	9.23E-07	7.74E-07	9.23E-07
5	32	1.48E-06	1.31E-06	1.10E-06	1.31E-06
10	32	1.93E-06	1.71E-06	1.43E-06	1.71E-06
20	32	2.52E-06	2.23E-06	1.87E-06	2.23E-06
50	32	3.58E-06	3.16E-06	2.65E-06	3.16E-06
100	32	4.67E-06	4.12E-06	3.46E-06	4.12E-06

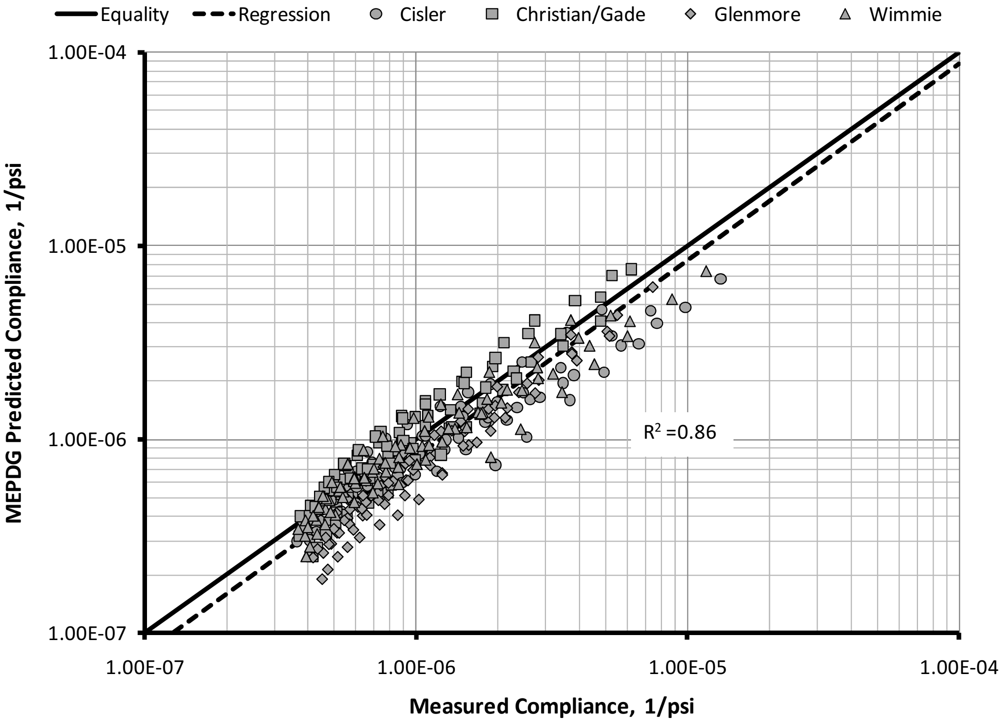

Figure 25. Comparison of Measured and MEPDG Level 3 Compliance Values.

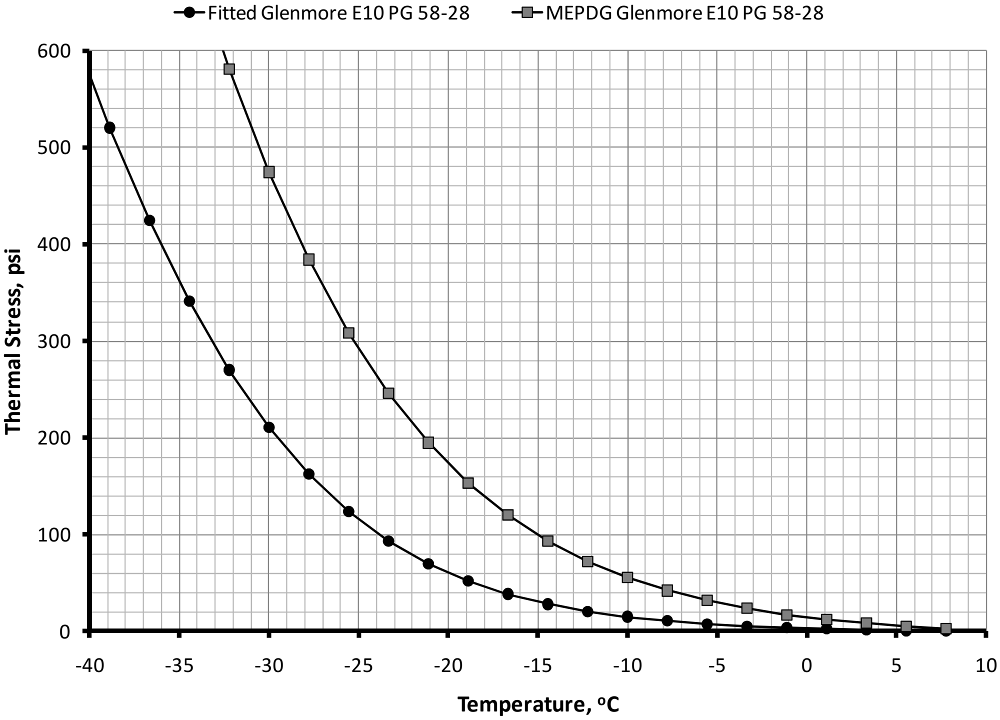

Figure 26. Comparison of Thermal Stresses For Glenmore E10 With PG 58-28 Binder.

3.2 Tensile Strength

3.2.1 AASHTO T322 Measured

Upon completion of the compliance testing, the tensile strength of each specimen was measured at -10 °C using a ram displacement rate of 12.5 mm/min. The tensile strength was calculated from the peak load using Equation 3 (*6*). Equation 3 was developed to estimate the true tensile strength without having to monitor deformation during strength testing. Indirect tensile specimens fail in a brittle manner at low temperature and often damage instrumentation attached to the specimen. Equation 3 allows the tensile strength to be estimated without having deformation instruments attached to the specimen.

$$S_{corr} = 0.78\, X\, S_{peak} + 38 \qquad (3)$$

Where:

S_{corr} = corrected tensile strength, psi

S_{peak} = peak tensile strength, psi

$= \frac{2 \times P_{peak}}{\pi \times t \times d}$

P_{peak} = peak load, lb

t = specimen thickness, in

d = specimen diameter, in.

The tensile strength results are summarized in Table 17. This table includes the peak and corrected tensile strength for each mixture. An analysis of variance was conducted on the data in Table 17 to determine the effect of binder, aggregate source, and design traffic level on the tensile strength. The results are summarized in Table 18. This analysis shows that the corrected indirect tensile strength is not strongly affected by these three factors and can be considered a constant for the surface mixtures tested. This finding may appear to contradict the finding for the compliance values which showed the compliance to be affected by binder grade. However, the loading rate for the tensile strength test is very fast in the range of the glassy (minimum) compliance for the mixtures. From Figures 17 trough 21, the glassy compliance is very similar for the mixtures tested.

Table 17. AASHTO T322 Tensile Strength Measurements.

Binder	Aggregate Source	Design Traffic Level	Peak Tensile Strength, psi			Corrected Tensile Strength, psi				
			1	2	3	1	2	3	Avg	Std. Dev.
PG 58-34	Cisler	E3	469.2	461.8	458.9	403.9	398.2	396.0	399.4	4.1
	Christian/Gade	E10	464.8	500.0	513.2	400.5	428.0	438.3	422.3	19.5
	Glenmore	E3	414.9	404.6	500.8	361.6	353.6	428.6	381.2	41.2
	Wimmie	E10	542.6	542.6	585.9	461.2	461.2	495.0	472.5	19.5
PG 58-34 + RAP	Cisler	E3	530.8	558.0	533.1	452.0	473.2	453.8	459.7	11.8
	Christian/Gade	E10	517.7	471.4	547.7	441.8	405.7	465.2	437.6	30.0
	Glenmore	E3	459.6	500.8	485.3	396.5	428.6	416.6	413.9	16.2
	Wimmie	E10	462.6	441.3	465.5	398.8	382.2	401.1	394.0	10.3
PG 58-28	Cisler	E10	539.7	515.5	511.6	459.0	440.1	437.1	445.4	11.9
	Christian/Gade	E3	494.1	475.1	514.0	423.4	408.5	438.9	423.6	15.2
	Glenmore	E10	481.5	517.3	471.9	413.5	441.5	406.1	420.4	18.7
	Wimmie	E3	459.6	475.8	522.8	396.5	409.1	445.8	417.1	25.6
PG 58-34 + RAP	Cisler	E10	517.7	530.8	565.4	441.8	452.0	479.0	457.6	19.2
	Christian/Gade	E3	498.6	525.0	529.4	426.9	447.5	450.9	441.8	13.0
	Glenmore	E10	535.3	502.9	483.2	455.5	430.3	414.9	433.6	20.5
	Wimmie	E3	559.5	585.2	500.8	474.4	494.4	428.6	465.8	33.8
								Grand Average	430.4	29.6

Table 18. Summary of Analysis of Variance.

Binder						
Source	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	10578.91	3	3526.302	2.390	0.081	2.816
Within Groups	64895.64	44	1474.901			
Total	75474.54	47				
Aggregate Source						
Source	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	9475.826	3	3158.609	2.105	0.113	2.816
Within Groups	65998.72	44	1499.971			
Total	75474.54	47				
Traffic Level						
Source	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	2008.179	1	2008.179	1.257	0.268	4.052
Within Groups	73466.37	46	1597.095			

3.2.2 MEPDG Strength Values

The MEPDG provides estimated strength values for Level 3 analyses. These strength values are estimated from binder properties and mixture volumetric properties using Equation 4.

$$\begin{aligned} TS &= 7416.712 - 114.016 * Va - 0.304 Va^2 - 122.592 VFA + 0.704 VFA^2 \\ &\quad + 405.71 Log_{10}(Pen77) - 2039.297 Log_{10}(A) \end{aligned} \tag{4}$$

where:
TS = indirect tensile strength at 14 ºF, psi
Va = as construction air voids, %
VFA = as construction voids filled with asphalt, %
$Pen77$ = binder penetration at 77 ºF, mm/10
A = viscosity-temperature susceptibility intercept.

Equation 4 uses binder properties that are no longer routinely measured. Like the compliance values, the MEPDG provides estimates of these properties based on the performance grade of the binder, so that estimates of tensile strength compliance values can be made knowing the mixture volumteric properties and the performance grade of the binder. Table 19 and Figure 27 compare the MEPDG estimated tensile strengths with the corrected tensile strength from the AASHTO T322 testing. As shown the MEPDG generally overestimates the corrected tensile strength from the AASHTO T322 testing. The largest differences occur for the Glenmore mixtures which have lower VFA than the other mixtures. This suggests that volumetric effects in the MEPDG predictive equation over estimate the effect of VFA on the tensile strength of the mixtures. Figure 28 compares the measured and MEPDG estimated tensile strengths as a function of VFA. There is a slight trend of increasing strength with increasing VFA in the measured data, while the MEPDG estimates a significant reduction in tensile strength with increasing VFA. The MEPDG effect is irrational suggesting that the mixtures having greater amounts of air rather than binder in the aggregate void structure will have higher tensile strengths. Other published low temperature tensile strength data show a trend of increasing tensile strength with increasing VFA (*6*) supporting the data measured in this project.

Table 19. MEPDG Estimated Tensile Strength.

Binder	Aggregate Source	Design Traffic Level	Tensile Strength, psi	
			MEPDG	Corrected
PG 58-34	Cisler	E3	541.0	399.4
	Christian/Gade	E10	482.7	422.3
	Glenmore	E3	592.3	381.2
	Wimmie	E10	497.4	472.5
PG 58-34 + RAP	Cisler	E3	481.5	459.7
	Christian/Gade	E10	423.1	437.6
	Glenmore	E3	532.8	413.9
	Wimmie	E10	437.8	394.0
PG 58-28	Cisler	E10	391.4	445.4
	Christian/Gade	E3	450.9	423.6
	Glenmore	E10	540.9	420.4
	Wimmie	E3	450.9	417.1
PG 58-34 + RAP	Cisler	E10	404.8	457.6
	Christian/Gade	E3	464.3	441.8
	Glenmore	E10	554.3	433.6
	Wimmie	E3	464.3	465.8
		Average	481.9	430.4

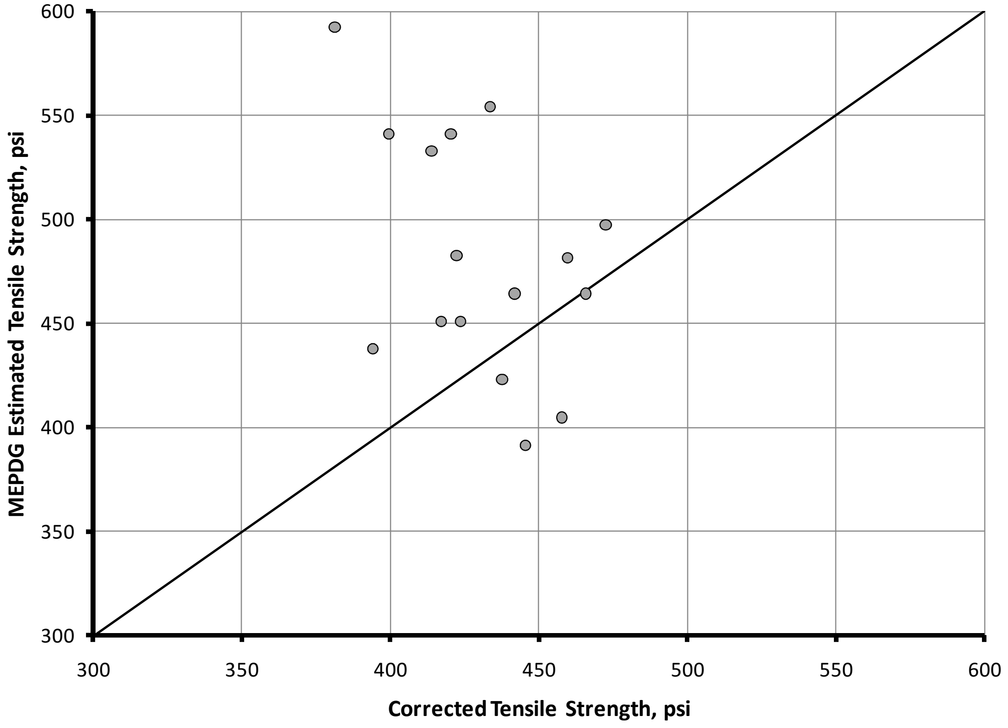

Figure 27. Comparison of Corrected Tensile Strength With MEPDG Estimated Tensile Strength.

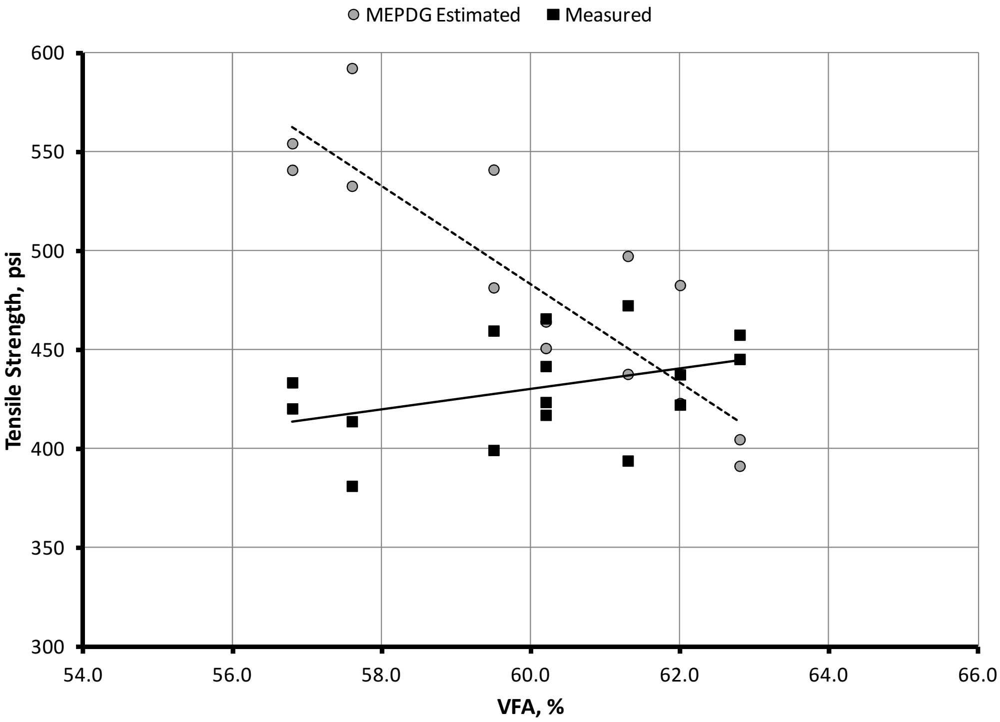

Figure 28. Effect of VFA on Measured and MEPDG Estimated Tensile Strengths.

3.3 Coefficient of Thermal Contraction

The final analysis that was conducted was a comparison of various methods for estimating the coefficient of thermal contraction. This is an important input parameter for thermal cracking analyses; however, a test for measuring it has not been standardized. Since coefficients of thermal contraction were not measured during the project, this analysis was limited to comparing two methods for estimating it: (1) MEPDG equation, and (2) Christensen equation (*6*).

Equation 5 presents the MEPDG equation for estimating the thermal coefficient of contraction of a mixture. The thermal coefficient of contraction is estimated from the thermal coefficient of contraction for the binder and aggregates, and the volumetric properties of the mixture.

$$\alpha_{mix} = \frac{VMA \times B_{ac} + (100 - VMA) \times B_{agg}}{300} \tag{5}$$

Where:

α_{mix} = linear coefficient of thermal contraction of the asphalt concrete mixture, (1/°C)
B_{ac} = volumetric coefficient of thermal contraction of the asphalt cement in the solid state (1/°C)
B_{agg} = volumetric coefficient of thermal contraction of the aggregate (1/°C)
VMA = voids in mineral aggregate, %

The volumetric coefficient of thermal contraction for asphalt binders in the glassy state range from 3.0 to 4.0 x 10^{-4}/°C (*11*). The volumetric coefficient of thermal contraction for the aggregates depends on the type of aggregate ranging from about 1.0 to 4.0 x 10^{-5}/°C (*4, 11*).

Estimated coefficients of thermal contract using Equation 5 are listed in Table 20. For these calculations an average of 3.5 x10^{-4}/°C was used for the asphalt binder volumetric coefficient of thermal contraction. The volumetric coefficient of thermal contraction for the aggregates was the average value in Reference 4 for the type of aggregate for each source. The estimated linear coefficients of thermal contraction range from 2.31 to 3.01 x10^{-5}/°C with the Glenmore E10 mixtures having the lowest value (limestone with low VMA) and the Christian/Gade E10 (gravel with high VMA) having the highest value.

Equation 6 presents the Christensen equation for estimating the coefficient of linear expansion of asphalt concrete mixtures. Christensen observed that because the coefficient of thermal contraction of asphalt binders is greater than that for aggregates, the estimated coefficient of thermal contraction for mixtures is largely independent of the coefficient of thermal contraction of the aggregates (*6*). It was hypothesized that the coefficient of thermal contraction for the binder should be related to some property of the binder. The best relationship was found with the m-value (slope of the log compliance versus log time) at -20 °C. This is the reason for the m-value in Equation 6.

$$\alpha_{mix} = \frac{1}{100} \times \left[\left(5.3 \times 10^{-4} \times m + 7.7 \times 10^{-5}\right) \times VBE + 7 \times 10^{-6} \times (100 - VMA)\right] \tag{6}$$

Where:

α_{mix} = linear coefficient of thermal contraction of the asphalt concrete mixture, (1/°C)
m = log-log slope of the mixture creep compliance with respect to time from 5 to 100 sec at -20 °C.
VBE = effective volumetric binder content, %
VMA = voids in mineral aggregate, %

Table 20. Estimated Linear Thermal Coefficients of Contraction Using the MEPDG Equation.

Source	Design Traffic	Binder	VMA at 7% Air Voids	B_{ac} /°C	Aggregate Type	B_{agg} /°C	α_{mix}/°C	α_{mix}/°F
Cisler	E3	58-34	17.3	0.00035	Granite	0.000023	2.65E-05	1.47E-05
		58-34 + RAP	17.3	0.00035	Granite	0.000023	2.65E-05	1.47E-05
	E10	58-28	18.8	0.00035	Granite	0.000023	2.82E-05	1.56E-05
		58-28 +RAP	18.8	0.00035	Granite	0.000023	2.82E-05	1.56E-05
Christian/ Gade	E3	58-28	17.6	0.00035	Gravel	0.000034	2.99E-05	1.66E-05
		58-28 + RAP	17.6	0.00035	Gravel	0.000034	2.99E-05	1.66E-05
	E10	58-34	18.4	0.00035	Gravel	0.000034	3.07E-05	1.71E-05
		58-34 +RAP	18.4	0.00035	Gravel	0.000034	3.07E-05	1.71E-05
Glenmore	E3	58-34	16.5	0.00035	Limestone	0.000015	2.34E-05	1.3E-05
		58-34 +RAP	16.5	0.00035	Limestone	0.000015	2.34E-05	1.3E-05
	E10	58-28	16.2	0.00035	Limestone	0.000015	2.31E-05	1.28E-05
		58-28 +RAP	16.2	0.00035	Limestone	0.000015	2.31E-05	1.28E-05
Wimmie	E3	58-28	17.6	0.00035	Gravel	0.000034	2.99E-05	1.66E-05
		58-28 +RAP	17.6	0.00035	Gravel	0.000034	2.99E-05	1.66E-05
	E10	58-34	18.1	0.00035	Gravel	0.000034	3.04E-05	1.69E-05
		58-34 + RAP	18.1	0.00035	Gravel	0.000034	3.04E-05	1.69E-05

Estimated linear coefficients of thermal contract using Equation 6 are listed in Table 21. The estimated linear coefficients of thermal contraction from the two equations are compared in Figure 29. The Christensen equation produces somewhat lower values than the MEPDG equation. The range of estimated coefficients of thermal contraction are similar for the two equations ranging from about 2×10^{-5} to 3×10^{-5}/°C.

Figure 30 shows the effect of variations in the linear coefficient of thermal contraction on the thermal stresses in the pavement. The analysis was performed with LTSTRESS using the average compliance curves for the PG 58-34 binder and the PG 58-28 with 25 percent RAP. A typical cooling rate of 5.6 °C/hr was used.

Table 21. Estimated Linear Thermal Coefficients of Contraction Using the Christensen Equation.

Aggregate	Design Traffic	Binder	VMA	VBE	m	α $_{mix}$/°C	α $_{mix}$/°F
Cisler	E3	58-34	17.3	10.3	0.27	2.85E-05	1.58E-05
		58-34 + RAP	17.3	10.3	0.21	2.52E-05	1.40E-05
	E10	58-28	18.8	11.8	0.18	2.6E-05	1.45E-05
		58-28 +RAP	18.8	11.8	0.17	2.54E-05	1.41E-05
Christian/Gade	E3	58-28	17.6	10.6	0.19	2.46E-05	1.37E-05
		58-28 + RAP	17.6	10.6	0.14	2.18E-05	1.21E-05
	E10	58-34	18.4	11.4	0.22	2.78E-05	1.54E-05
		58-34 +RAP	18.4	11.4	0.23	2.84E-05	1.58E-05
Glenmore	E3	58-34	16.5	9.5	0.21	2.37E-05	1.32E-05
		58-34 +RAP	16.5	9.5	0.21	2.37E-05	1.32E-05
	E10	58-28	16.2	9.2	0.16	2.08E-05	1.15E-05
		58-28 +RAP	16.2	9.2	0.16	2.08E-05	1.15E-05
Wimmie	E3	58-28	17.6	10.6	0.18	2.4E-05	1.34E-05
		58-28 +RAP	17.6	10.6	0.21	2.57E-05	1.43E-05
	E10	58-34	18.1	11.1	0.23	2.78E-05	1.55E-05
		58-34 + RAP	18.1	11.1	0.18	2.49E-05	1.38E-05

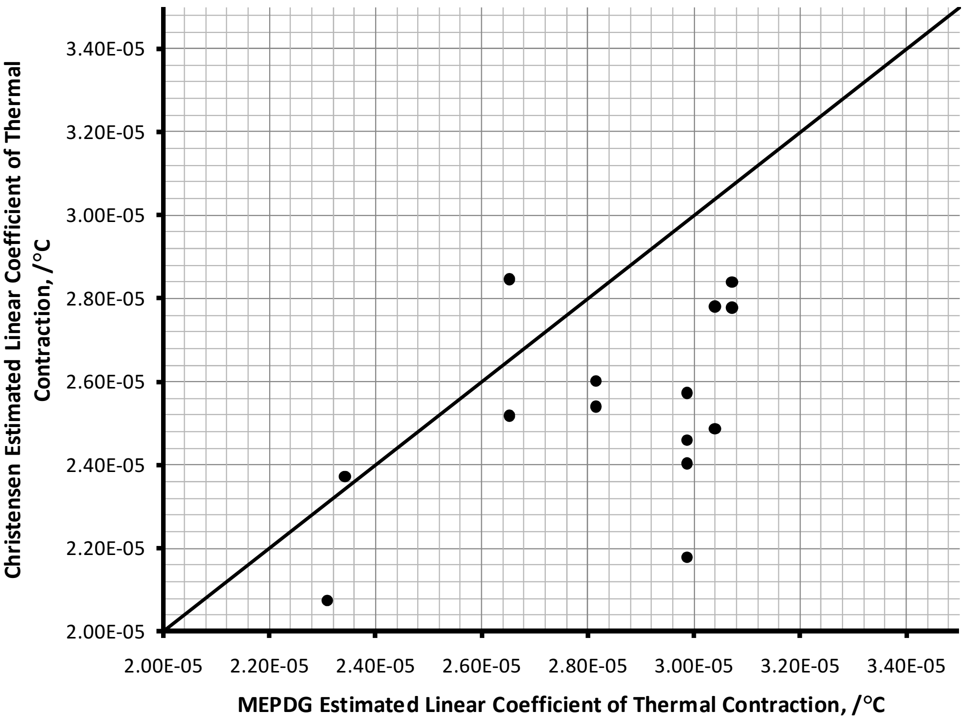

Figure 29. Comparison of MEPDG and Christensen Estimated Linear Coefficients of Thermal Contraction.

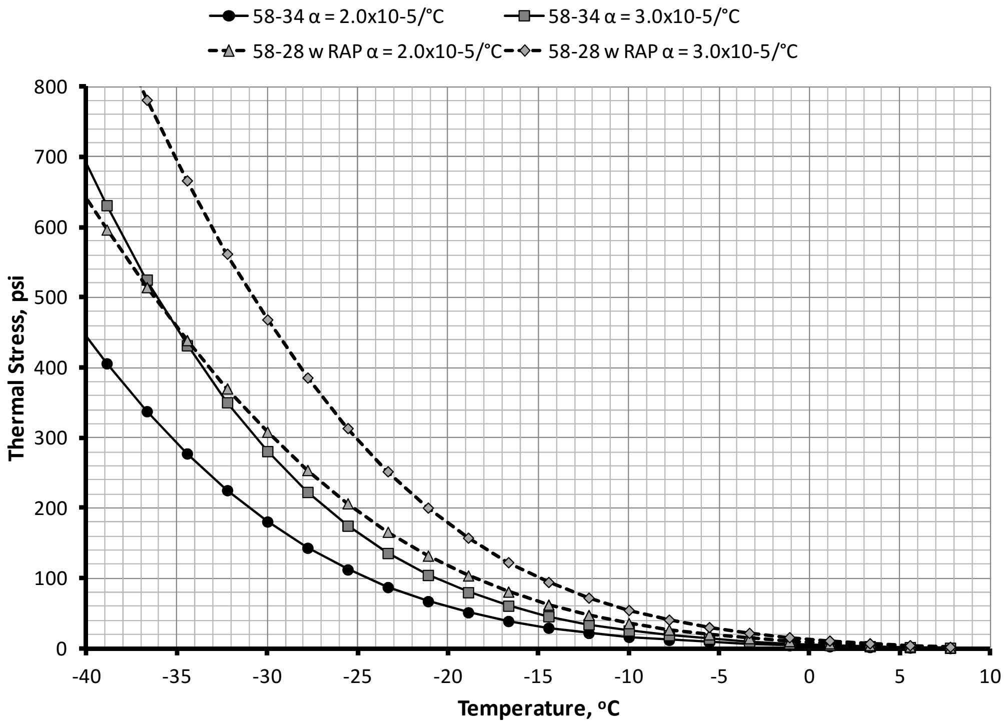

Figure 30. Effect of Linear Coefficient of Thermal Contraction on Thermal Stresses.

Figure 30 shows that the effect of the linear coefficient of thermal contraction is similar to that for changes in binder grade. Recall from Figure 24 that over the temperature range from -28 to -34 °C, the thermal stresses are approximately 10 percent higher for the PG 58-34 with 25 % RAP compared to the PG 58-34; 20 percent higher for the PG 58-28 compared to the PG 58-34; and 60 percent higher for the PG 58-28 with 25 % RAP compared to the PG 58-34. Increasing the linear coefficient of contraction from 2×10^{-5} /°C to 3×10^{-5}/°C increases the thermal stresses approximately 50 percent.

Nam and Bahia reported measured linear coefficient of thermal contract values ranging from 0.5×10^{-5} /°C to 3.4×10^{-5}/°C for temperatures below the glass transition temperature to from 5.7×10^{-5}/°C to 9.6×10^{-5}/°C for temperatures above the glass transition temperature (*12*). They recommended using linear coefficients above the glass transition temperature in typical thermal cracking studies. For this temperature range, the measured values were 50 to 65 percent higher than estimated using the MEPDG equation.

Chapter 4 Conclusions and Recommendations

4.1 Conclusions

The primary objective of this project was to develop representative asphalt concrete material properties for Wisconsin mixtures for use in thermal cracking analysis with the MEPDG. The asphalt concrete material properties required by the MEPDG for thermal cracking analyses are: (1) creep compliance master curve data, (2) the tensile strength at -10 °C, and (3) the linear coefficient of thermal contraction. To establish a database of compliance and strength data, low temperature compliance and strength measurements were made in accordance with AASHTO T322 on 16 mixtures representing 4 aggregate sources, two design traffic levels, and four binders. The binders considered were virgin PG 58-34, virgin PG 58-28, PG 58-34 with 25 percent RAP, and PG 58-28 with 25 percent RAP. Measurements of the linear coefficient of thermal contraction were not performed because a standard procedure the measuring this property for asphalt concrete is not available. Two different equations for estimating the linear coefficient of thermal contraction were evaluated. The sections that follow described the conclusions drawn from the testing and analysis.

4.1.1 Creep Compliance

For the mixtures tested, the low temperature creep compliance was found to be a function of only the low temperature performance grade of the binder in the mixture. Aggregate source and design traffic level did not have a significant effect on the low temperature compliance of the mixtures tested. As the low temperature grade of the binder increased, the compliance master curve becomes flatter, which results in an increase in thermal stresses in the pavement. For a typical thermal stress analysis, mixtures made with the PG 58-34 binder had the lowest thermal stresses. Over the temperature range of -28 to -34 °C, the thermal stresses are approximately 10 percent higher for the PG 58-34 with 25 % RAP compared to the PG 58-34; 20 percent higher for the PG 58-28 compared to the PG 58-34; and 60 percent higher for the PG 58-28 with 25 % RAP compared to the PG 58-34.

Equation 7 was developed to estimate the compliance of Wisconsin mixtures as a function of the low temperature continuous grade of the binder. The reference temperature for this Equation is 4 ºF (-20 ºC). This equation can be used to estimate the compliance values required by the MEPDG for thermal cracking analyses. The use of Equation 7 is explained in Appendix C, which is a tutorial on the development of inputs for MEPDG thermal cracking analysis. Equation 7 was developed for low temperature grades between -35.1 and -28.7 °C; therefore, it should be used with caution for binders with low temperature grades outside of this range.

$$D(t) = 3.729 \times 10^{-7} + 10^{-9.3552-0.0645 \times PG_{Low}} \left[\frac{t}{10^{0.0655(T+4)}} \right]^{0.4705} \tag{7}$$

where:

$D(t)$ = creep compliance, 1/psi

T = temperature, °F

PG_{Low} = low temperature continuous grade of the binder in the mixture, °C

t = time

The measured compliance values were compared to compliance values estimated by the MEPDG software for Level 3 analyses. The MEPDG Level 3 compliance values were generally lower than the measured values, with errors as high as 56 percent. These errors could result in difference in computed thermal stresses as high as 70 percent.

4.1.2 Tensile Strength

For the mixtures tested, the tensile strength at -10 °C was not significantly affected by low temperature binder grade, aggregate source, or design traffic level. The average tensile strength for the 16 mixtures tested was 430 psi with a standard deviation of 30 psi.

The measured tensile strengths were compared with those estimated by the MEPDG software for Level 3 analyses. The MEPDG estimates were generally higher than the measured tensile strengths, and exhibited irrational volumetric effects. The MEPDG estimated tensile strengths decrease with increasing VFA, while the measured tensile strengths and tensile strengths from other studies show a trend of increasing tensile strength with increasing VFA.

4.1.3 Linear Coefficient of Thermal Contraction

The evaluation of two equations for estimating the linear coefficient of thermal contraction produced similar results for the mixtures used in this study. The range of the estimated linear coefficient of thermal contraction was from 2.0×10^{-5}/°C to 3.0×10^{-5}/°C. This range in the coefficient of thermal contraction has a significant effect on computed thermal stresses in the pavement. The linear coefficient of thermal contraction is as important as the mixture compliance in thermal stress computations.

4.2 Recommendations

For thermal cracking analyses using the MEPDG, WisDOT should not rely on the MEPDG Level 3 estimated creep compliance and strength values. Instead, compliance values should be estimated based on the low temperature continuous grade of the binder using Equation 7. Compliance values from Equation 7 for low temperature binder grades ranging from -22 to -36 have been tabulated in Appendix C. These can be input directly into the MEPDG software. Since the low temperature tensile strength was not found to be a function of mixture or binder properties, the average measured tensile strength of 430 psi should be used.

Since the linear coefficient of thermal contraction was found to be of similar importance as the mixture compliance in thermal stress analyses, linear coefficients of thermal contraction should be measured for the mixtures used in this study. Possible tests include the Asphalt Mixture Glass Transition Test under development at the University of Wisconsin, Madison (*13*) or the test developed at the Pennsylvania State University that uses the IDT instrumentation (*14*). Until this additional work is completed, WisDOT should use a representative linear coefficient of thermal contraction of 1.4×10^{-5}/°F (2.5×10^{-5}/°C) in thermal cracking analyses performed with the MEPDG.

The findings from this study do not suggest any needed changes to Wisconsin mixtures or specifications to improve low temperature cracking performance. The low temperature compliance of mixtures is primarily a function of the low temperature performance grade of the binder; therefore, changes to volumetric mixture design will have minimal impact on low temperature performance. Climate is appropriately considered in current Wisconsin binder grade selection, and WHRP Project 0092-10-06 is investigating the effect of recycled binders on performance grade properties and evaluating current WisDOT binder replacement criteria.

The findings from this study do suggest that the linear coefficient of thermal contraction is as important as the low temperature mixture compliance in thermal stress analyses. Because a standard test is not available, the linear coefficient of contraction is estimated using relationships that may have significant errors (*12, 14*). The linear coefficient of contraction will likely vary with aggregate source and perhaps with mixture composition; therefore, consideration should be given to measuring the linear coefficient of contraction on the mixtures used in this study. This additional work may identify mixture compositions having high thermal contraction that will require higher compliance to maintain thermal stresses at acceptable levels.

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Appendix A. WisDOT Approved Mixture Designs

Contents

Source	Mixture	Page
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Christian/Gade	E-3	58-59
Glenmore	E-3	60-61
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Glenmore	E-10	67-68
Wimmie	E-10	69

MATHY CONSTRUCTION CO.

GENERAL CONTRACTORS

920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650

PHONE 608-781-4683 FAX 608-781-4694

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

AASHTO R18

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

43 Min
40 Min

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

Report of Bituminous Mix Design

AASHTO R18

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:	**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

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	**% Air Voids:**	4.02%	**Agg. Angularity (Fines):**	43.3
Grade:	PG 58-28	**Gmm:**	2.565	**Gmm Dryback Correction:**	
Source:	AMOCO-MILW	**Gmb:**	2.462	**Unit Wt (PCF):**	153.23
AC Sp. Gr:	1.029 @ 25/25°C	**Gse:**	2.794	**Fracture:**	95.2 1F 92.4 2F
RAP % AC:		**%VMA**	14.6	**Thin/Elong:**	0.5
Mixing Temp (°C):	135-149	**% VFB:**	72.5	**TSR:**	87.8
Compaction Temp (°C):		**Sand Equiv. (%):**	0.0	**TSR Comp. Effort:**	21.0 N
Design Comp. Effort:	75 Ndes	**Stability (N):**		**Anitstrip:**	NONE

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

Test Number: 0 - 250 - 0053 - 2002

Labsite:

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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

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: 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:**

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	**% Air Voids:** 4.01%	**FAA:** 45.7	**Mixing Temp (°C):** 135-149
Grade: PG 58-28	**Gmm:** 2.592	**Gmm Corr:**	**Compaction Temp (°C):**
Source: KOCH-GREEN BAY	**Gmb:** 2.488	**Unit Wt (PCF):** 154.85	**Moisture Absorption:** 1.00
AC Sp. Gr: 1.031 @ 25/25°C	**Gse:** 2.791		**Dust Proportion:** 1.00
RAP % AC:	**Nini:** 7	**% Gmm:** 89.6	**Fracture:** 100.0 1F 100.0 2F
%VMA: 13.5	**Ndes:** 75		**Thin/Elong:** 0.8
% VFB: 70.3	**Nmax:** 115	**% Gmm:** 96.7	**TSR:** 73.9 **Comp. Effort:** 22.0 N
Sand Equiv. (%): 80.0			**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

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:

Page 1 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

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	**% Air Voids:** 3.98%	**FAA:** 43.8	**Mixing Temp (°C):** 275-300 F
Grade: PG 58-28	**Gmm:** 2.536	**Gmm Corr:**	**Compaction Temp (°C):**
Source: MIF, LACROSSE	**Gmb:** 2.435	**Unit Wt (PCF):** 151.55	**Moisture Absorption:** 0.60
AC Sp. Gr: 1.030 @ 25/25°C	**Gse:** 2.738		**Dust Proportion:** 1.00
RAP % AC:	**Nini:** 7	**% Gmm:** 89.6	**Fracture:** 94.2 1F 92.7 2F
%VMA: 14.6	**Ndes:** 75		**Thin/Elong:** 3.0
% VFB: 72.6	**Nmax:** 115	**% Gmm:** 96.8	**TSR:** 91.5 **Comp. Effort:** N
Sand Equiv. (%): 84.0			**Anitstrip:** NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.0	4.00	2.568	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:

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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

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

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

Page 2 of 2

Test Number: 0 - 250 - 0186 - 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

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	88.6
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 AMOC	**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

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: 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:**

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

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

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

USH 41

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

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:**

Remarks: Satisfactory

Test Number: 0 - 250 - 0047 - 2005

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

Labsite:
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:
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 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.

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	94.8
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

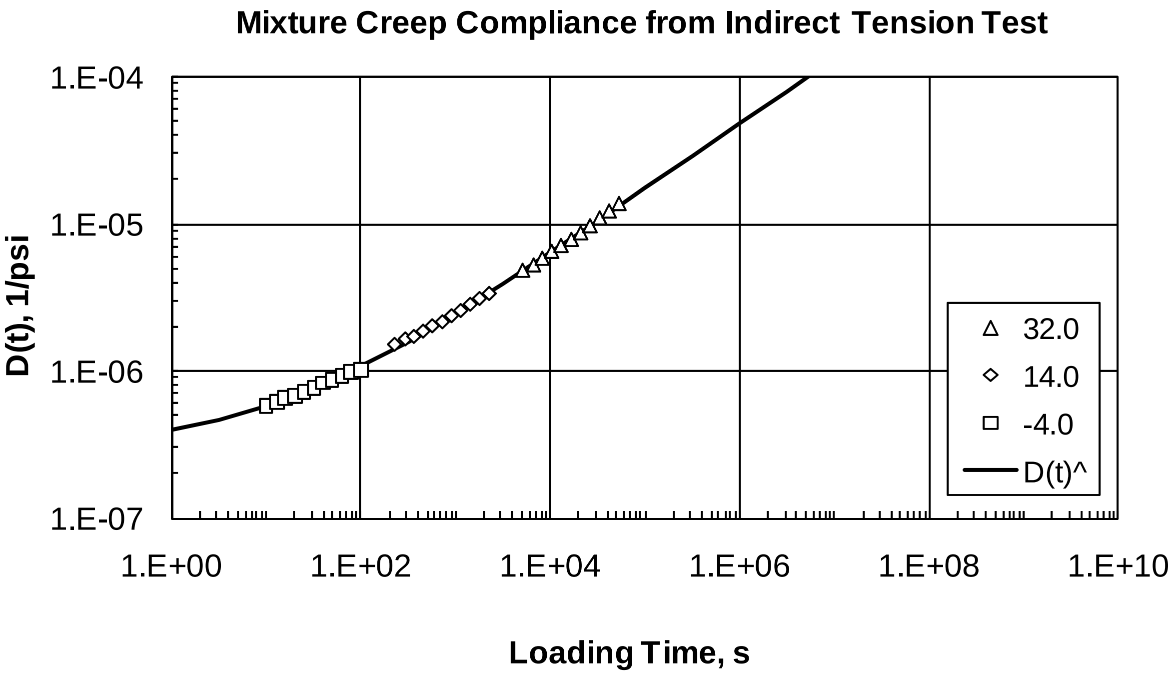
Verified Date: 06/04/2008 **Verified By:** JUDIE RYAN

Appendix B. Creep Compliance Data.

Cisler E3, PG 58-34

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.4	-6.517	-7.005	0.447	-0.076	2.4

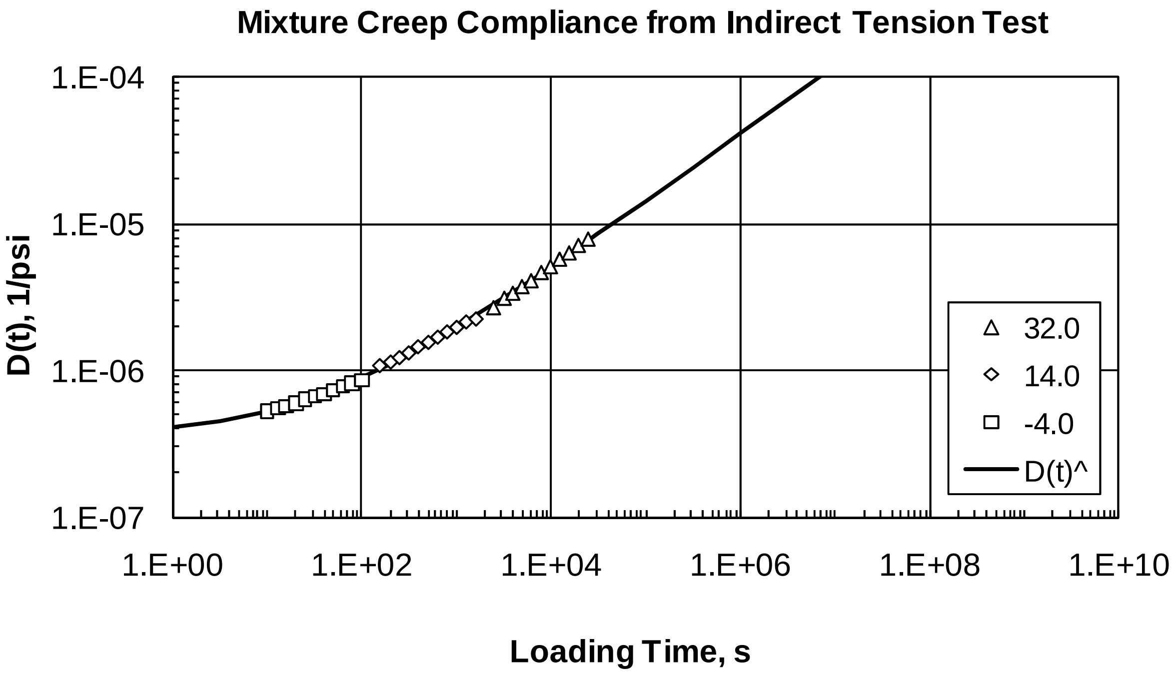
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	5.77E-07	0.21	0.20	1.51E-06	0.25	0.18	4.78E-06	0.37	0.18
13	6.12E-07	0.22	0.20	1.65E-06	0.28	0.18	5.19E-06	0.39	0.18
16	6.52E-07	0.23	0.20	1.71E-06	0.30	0.18	5.77E-06	0.41	0.18
20	6.81E-07	0.24	0.20	1.87E-06	0.32	0.18	6.44E-06	0.43	0.18
25	7.22E-07	0.26	0.20	2.03E-06	0.34	0.18	7.06E-06	0.44	0.18
32	7.62E-07	0.27	0.20	2.17E-06	0.37	0.18	7.77E-06	0.46	0.18
40	8.26E-07	0.28	0.20	2.39E-06	0.39	0.18	8.61E-06	0.48	0.18
50	8.71E-07	0.29	0.20	2.59E-06	0.41	0.18	9.64E-06	0.50	0.18
63	9.30E-07	0.30	0.20	2.87E-06	0.43	0.18	1.09E-05	0.51	0.18
79	9.93E-07	0.32	0.20	3.14E-06	0.45	0.18	1.22E-05	0.53	0.18
100	1.02E-06	0.33	0.20	3.41E-06	0.48	0.18	1.37E-05	0.55	0.18



Cisler E3, PG 58-34 +25 % RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.0	-6.468	-7.197	0.468	-0.067	2.3

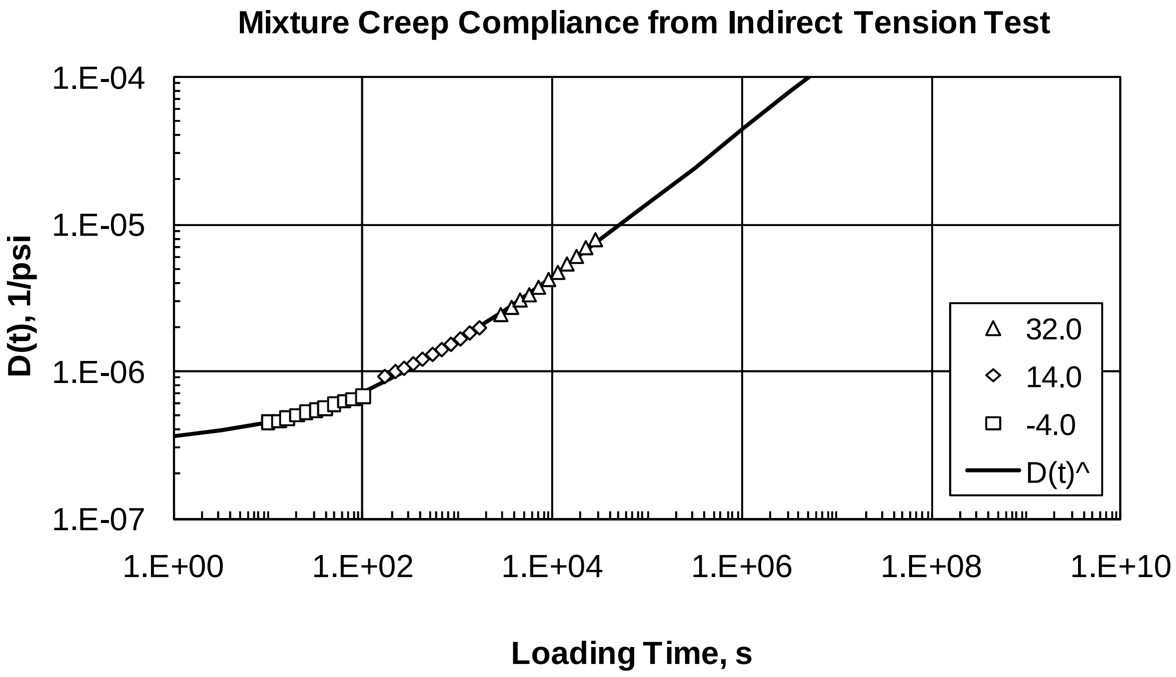
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	5.29E-07	0.19	0.18	1.07E-06	0.29	0.16	2.66E-06	0.48	0.16
13	5.50E-07	0.19	0.18	1.13E-06	0.30	0.16	3.08E-06	0.47	0.16
16	5.71E-07	0.20	0.18	1.21E-06	0.31	0.16	3.33E-06	0.47	0.16
20	5.96E-07	0.20	0.18	1.31E-06	0.32	0.16	3.70E-06	0.47	0.16
25	6.30E-07	0.21	0.18	1.44E-06	0.33	0.16	4.05E-06	0.47	0.16
32	6.68E-07	0.21	0.18	1.54E-06	0.34	0.16	4.61E-06	0.47	0.16
40	6.89E-07	0.22	0.18	1.67E-06	0.35	0.16	5.05E-06	0.47	0.16
50	7.31E-07	0.22	0.18	1.82E-06	0.35	0.16	5.68E-06	0.47	0.16
63	7.77E-07	0.22	0.18	1.95E-06	0.36	0.16	6.26E-06	0.47	0.16
79	8.14E-07	0.23	0.18	2.12E-06	0.37	0.16	7.04E-06	0.47	0.16
100	8.53E-07	0.23	0.18	2.22E-06	0.38	0.16	7.77E-06	0.47	0.16



Cisler E10, PG 58-28

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.2	-6.487	-7.424	0.510	-0.068	3.4

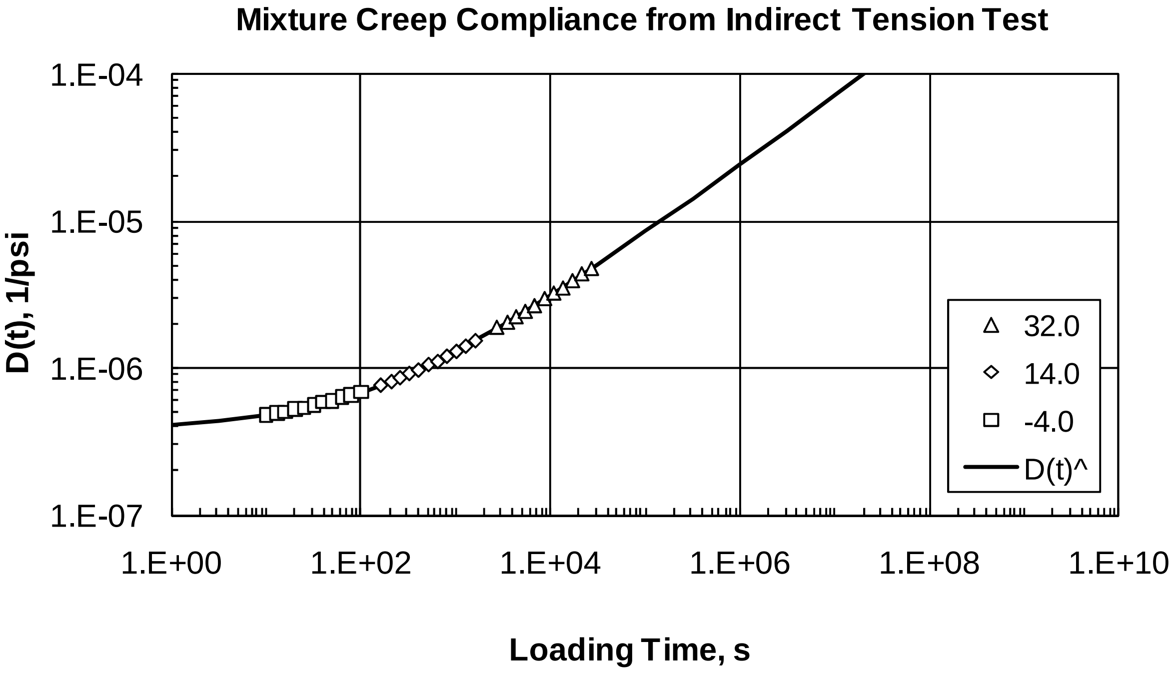
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.48E-07	0.17	0.21	9.10E-07	0.26	0.18	2.42E-06	0.43	0.18
13	4.59E-07	0.17	0.21	9.85E-07	0.27	0.18	2.71E-06	0.45	0.18
16	4.81E-07	0.17	0.21	1.03E-06	0.29	0.18	3.05E-06	0.47	0.18
20	5.03E-07	0.17	0.21	1.11E-06	0.30	0.18	3.31E-06	0.49	0.18
25	5.26E-07	0.18	0.21	1.19E-06	0.32	0.18	3.73E-06	0.50	0.18
32	5.48E-07	0.18	0.21	1.29E-06	0.34	0.18	4.22E-06	0.52	0.18
40	5.63E-07	0.18	0.21	1.39E-06	0.35	0.18	4.72E-06	0.54	0.18
50	5.96E-07	0.19	0.21	1.50E-06	0.37	0.18	5.39E-06	0.56	0.18
63	6.26E-07	0.19	0.21	1.64E-06	0.39	0.18	6.08E-06	0.58	0.18
79	6.48E-07	0.19	0.21	1.79E-06	0.40	0.18	6.98E-06	0.59	0.18
100	6.77E-07	0.19	0.21	1.94E-06	0.42	0.18	7.93E-06	0.61	0.18



Cisler E10, PG 58-28 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.0	-6.424	-7.451	0.472	-0.068	0.8

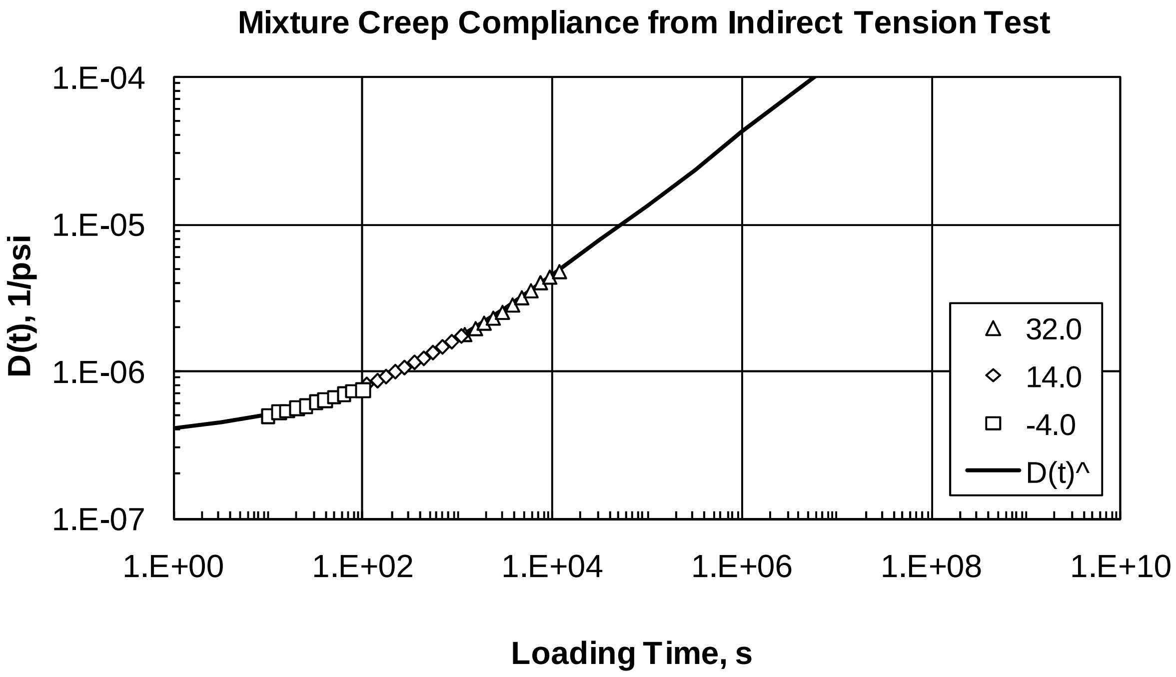
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.75E-07	0.12	0.13	7.75E-07	0.25	0.18	1.88E-06	0.36	0.18
13	4.91E-07	0.13	0.13	8.19E-07	0.26	0.18	2.03E-06	0.38	0.18
16	5.03E-07	0.14	0.13	8.69E-07	0.27	0.18	2.22E-06	0.38	0.18
20	5.28E-07	0.15	0.13	9.28E-07	0.28	0.18	2.41E-06	0.39	0.18
25	5.36E-07	0.16	0.13	9.78E-07	0.29	0.18	2.64E-06	0.40	0.18
32	5.61E-07	0.17	0.13	1.06E-06	0.30	0.18	2.95E-06	0.41	0.18
40	5.85E-07	0.18	0.13	1.12E-06	0.30	0.18	3.22E-06	0.42	0.18
50	5.98E-07	0.18	0.13	1.21E-06	0.31	0.18	3.48E-06	0.43	0.18
63	6.34E-07	0.19	0.13	1.30E-06	0.32	0.18	3.91E-06	0.44	0.18
79	6.63E-07	0.20	0.13	1.41E-06	0.33	0.18	4.36E-06	0.45	0.18
100	6.86E-07	0.21	0.13	1.54E-06	0.34	0.18	4.73E-06	0.46	0.18



Christian/Gade E3, PG 58-28

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.2	-6.429	-7.383	0.500	-0.057	1.7

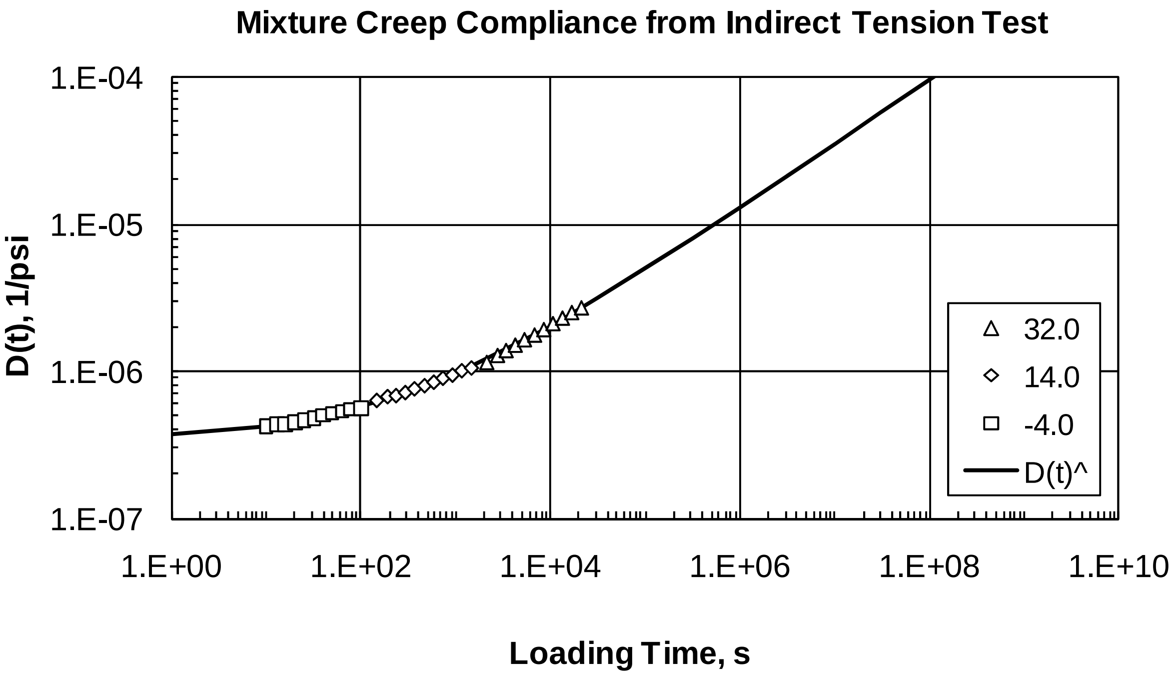
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.93E-07	0.19	0.14	8.23E-07	0.26	0.14	1.78E-06	0.35	0.14
13	5.22E-07	0.19	0.14	8.72E-07	0.27	0.14	1.96E-06	0.37	0.14
16	5.35E-07	0.19	0.14	9.28E-07	0.28	0.14	2.13E-06	0.39	0.14
20	5.60E-07	0.19	0.14	1.00E-06	0.30	0.14	2.31E-06	0.41	0.14
25	5.84E-07	0.19	0.14	1.07E-06	0.31	0.14	2.53E-06	0.43	0.14
32	6.13E-07	0.19	0.14	1.15E-06	0.32	0.14	2.84E-06	0.45	0.14
40	6.38E-07	0.19	0.14	1.23E-06	0.34	0.14	3.19E-06	0.47	0.14
50	6.63E-07	0.19	0.14	1.34E-06	0.35	0.14	3.56E-06	0.49	0.14
63	7.00E-07	0.19	0.14	1.46E-06	0.36	0.14	4.05E-06	0.51	0.14
79	7.29E-07	0.19	0.14	1.58E-06	0.37	0.14	4.42E-06	0.53	0.14
100	7.45E-07	0.19	0.14	1.73E-06	0.39	0.14	4.82E-06	0.55	0.14



Christian/Gade E3, PG 58-28 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.0	-6.467	-7.509	0.435	-0.065	1.7

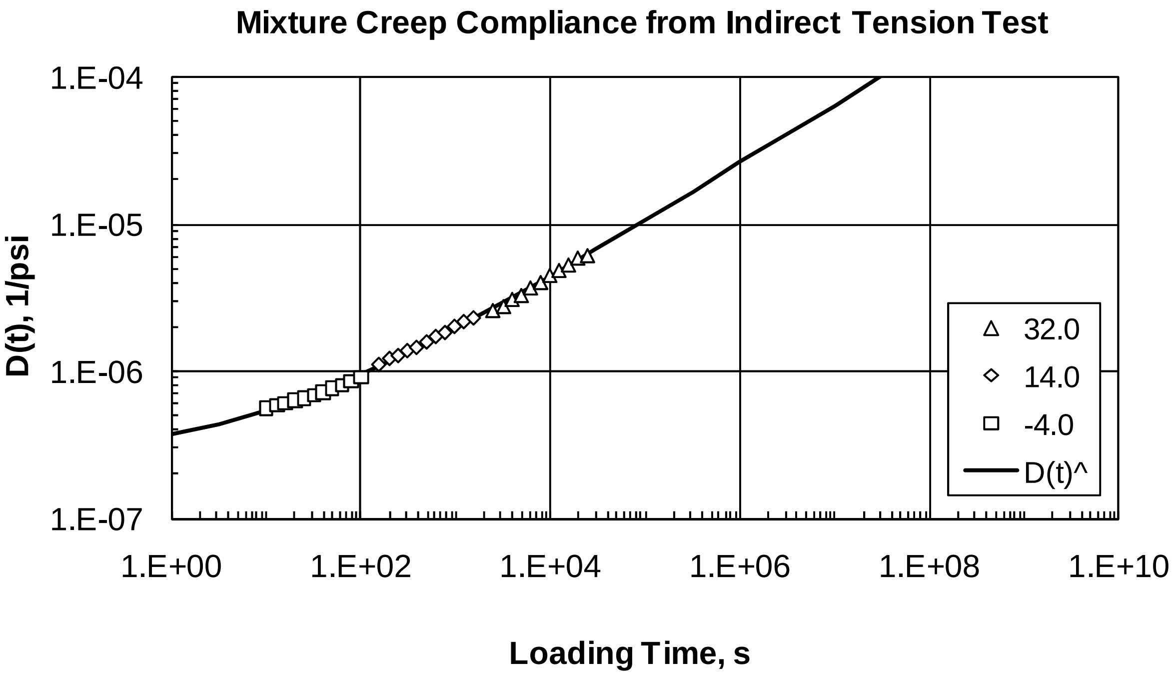
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.19E-07	0.10	0.22	6.33E-07	0.16	0.27	1.17E-06	0.35	0.27
13	4.34E-07	0.11	0.22	6.71E-07	0.18	0.27	1.30E-06	0.36	0.27
16	4.37E-07	0.11	0.22	6.82E-07	0.19	0.27	1.40E-06	0.36	0.27
20	4.51E-07	0.12	0.22	7.14E-07	0.20	0.27	1.52E-06	0.37	0.27
25	4.63E-07	0.13	0.22	7.57E-07	0.21	0.27	1.66E-06	0.37	0.27
32	4.81E-07	0.14	0.22	7.94E-07	0.23	0.27	1.78E-06	0.38	0.27
40	5.02E-07	0.15	0.22	8.37E-07	0.24	0.27	1.94E-06	0.38	0.27
50	5.19E-07	0.16	0.22	8.91E-07	0.25	0.27	2.13E-06	0.39	0.27
63	5.34E-07	0.17	0.22	9.34E-07	0.27	0.27	2.32E-06	0.39	0.27
79	5.55E-07	0.18	0.22	9.98E-07	0.28	0.27	2.53E-06	0.40	0.27
100	5.59E-07	0.18	0.22	1.04E-06	0.29	0.27	2.72E-06	0.40	0.27



Christian/Gade E10, PG 58-34

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.0	-6.582	-6.947	0.393	-0.066	3.0

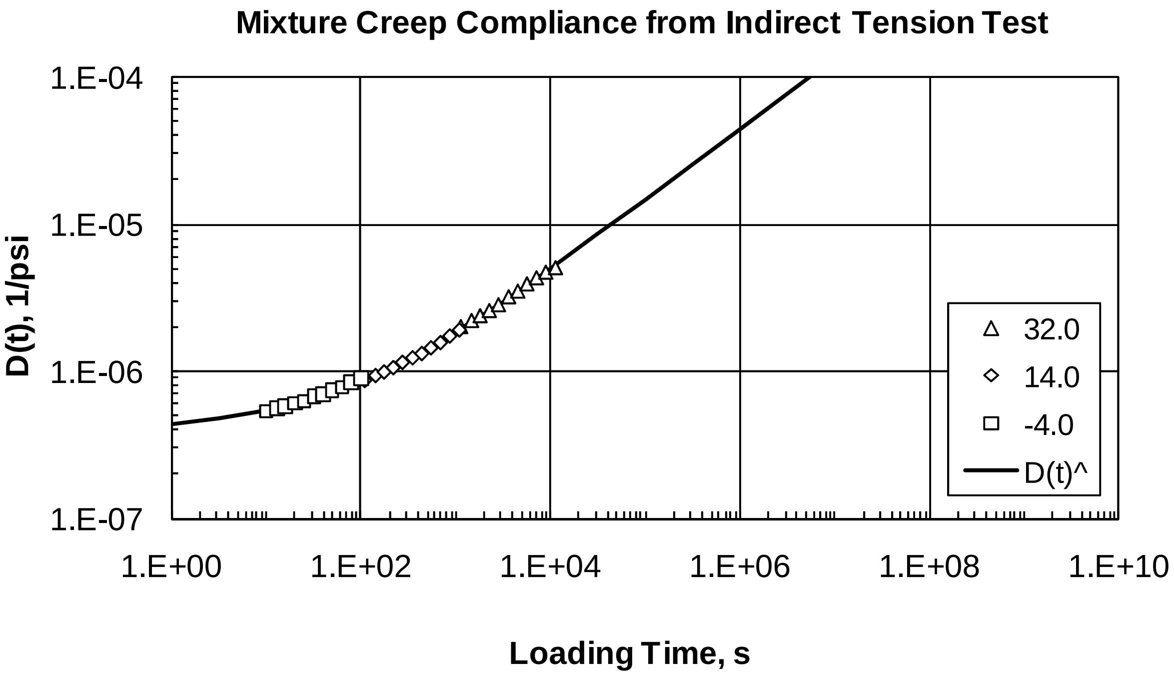
Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	5.58E-07	0.14	0.25	1.12E-06	0.27	0.24	2.60E-06	0.36	0.24
13	5.86E-07	0.16	0.25	1.23E-06	0.29	0.24	2.76E-06	0.37	0.24
16	6.06E-07	0.17	0.25	1.29E-06	0.30	0.24	3.10E-06	0.38	0.24
20	6.31E-07	0.19	0.25	1.39E-06	0.31	0.24	3.29E-06	0.39	0.24
25	6.59E-07	0.20	0.25	1.46E-06	0.32	0.24	3.72E-06	0.40	0.24
32	6.88E-07	0.22	0.25	1.59E-06	0.33	0.24	4.05E-06	0.41	0.24
40	7.20E-07	0.23	0.25	1.73E-06	0.34	0.24	4.53E-06	0.42	0.24
50	7.60E-07	0.24	0.25	1.84E-06	0.35	0.24	4.90E-06	0.43	0.24
63	8.04E-07	0.26	0.25	2.02E-06	0.36	0.24	5.34E-06	0.44	0.24
79	8.57E-07	0.27	0.25	2.18E-06	0.37	0.24	5.96E-06	0.45	0.24
100	9.12E-07	0.29	0.25	2.31E-06	0.38	0.24	6.19E-06	0.46	0.24



Christian/Gade E10, PG 58-34 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.0	-6.409	-7.303	0.491	-0.057	1.7

Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	5.34E-07	0.18	0.17	8.78E-07	0.26	0.18	2.02E-06	0.39	0.18
13	5.57E-07	0.19	0.17	9.46E-07	0.28	0.18	2.22E-06	0.40	0.18
16	5.81E-07	0.20	0.17	1.00E-06	0.29	0.18	2.40E-06	0.40	0.18
20	6.05E-07	0.21	0.17	1.07E-06	0.31	0.18	2.60E-06	0.41	0.18
25	6.25E-07	0.22	0.17	1.16E-06	0.32	0.18	2.85E-06	0.41	0.18
32	6.76E-07	0.23	0.17	1.24E-06	0.34	0.18	3.23E-06	0.42	0.18
40	7.03E-07	0.24	0.17	1.33E-06	0.36	0.18	3.54E-06	0.43	0.18
50	7.39E-07	0.25	0.17	1.45E-06	0.37	0.18	3.96E-06	0.43	0.18
63	7.78E-07	0.26	0.17	1.57E-06	0.39	0.18	4.37E-06	0.44	0.18
79	8.46E-07	0.27	0.17	1.74E-06	0.40	0.18	4.77E-06	0.44	0.18
100	8.96E-07	0.28	0.17	1.91E-06	0.42	0.18	5.12E-06	0.45	0.18

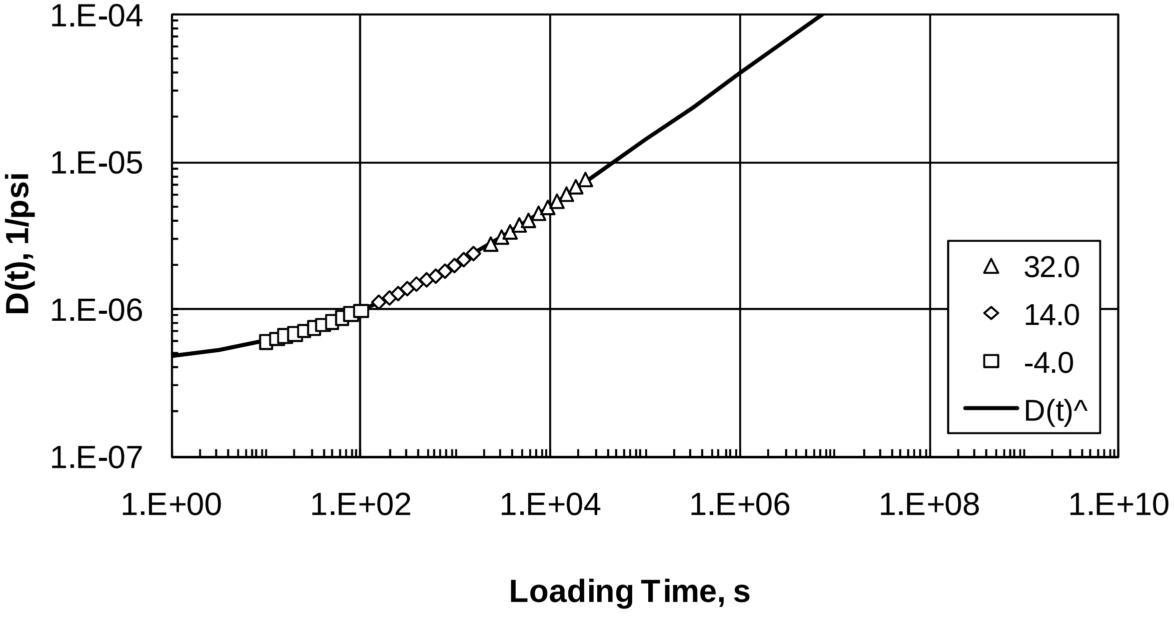


Glenmore E3, PG 58-34

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.5	-6.376	-7.188	0.465	-0.066	1.2

Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	6.03E-07	0.15	0.25	1.11E-06	0.27	0.29	2.77E-06	0.38	0.29
13	6.27E-07	0.17	0.25	1.19E-06	0.28	0.29	3.09E-06	0.40	0.29
16	6.56E-07	0.18	0.25	1.27E-06	0.29	0.29	3.35E-06	0.40	0.29
20	6.76E-07	0.19	0.25	1.37E-06	0.30	0.29	3.73E-06	0.41	0.29
25	7.08E-07	0.20	0.25	1.47E-06	0.31	0.29	4.00E-06	0.42	0.29
32	7.46E-07	0.21	0.25	1.57E-06	0.32	0.29	4.46E-06	0.43	0.29
40	7.78E-07	0.23	0.25	1.66E-06	0.33	0.29	4.89E-06	0.44	0.29
50	8.22E-07	0.24	0.25	1.80E-06	0.34	0.29	5.38E-06	0.45	0.29
63	8.72E-07	0.25	0.25	1.96E-06	0.36	0.29	6.00E-06	0.46	0.29
79	9.24E-07	0.26	0.25	2.15E-06	0.37	0.29	6.73E-06	0.47	0.29
100	9.75E-07	0.27	0.25	2.36E-06	0.38	0.29	7.53E-06	0.48	0.29

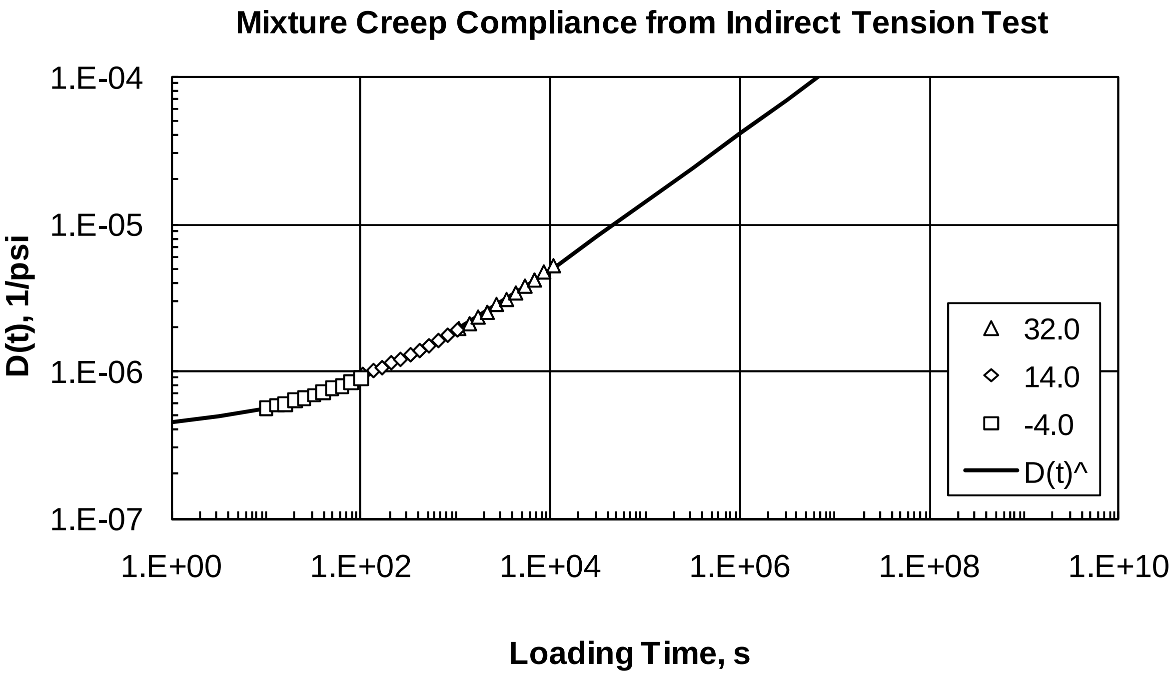
Mixture Creep Compliance from Indirect Tension Test



Glenmore E3, PG 58-34 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.6	-6.401	-7.244	0.476	-0.056	1.8

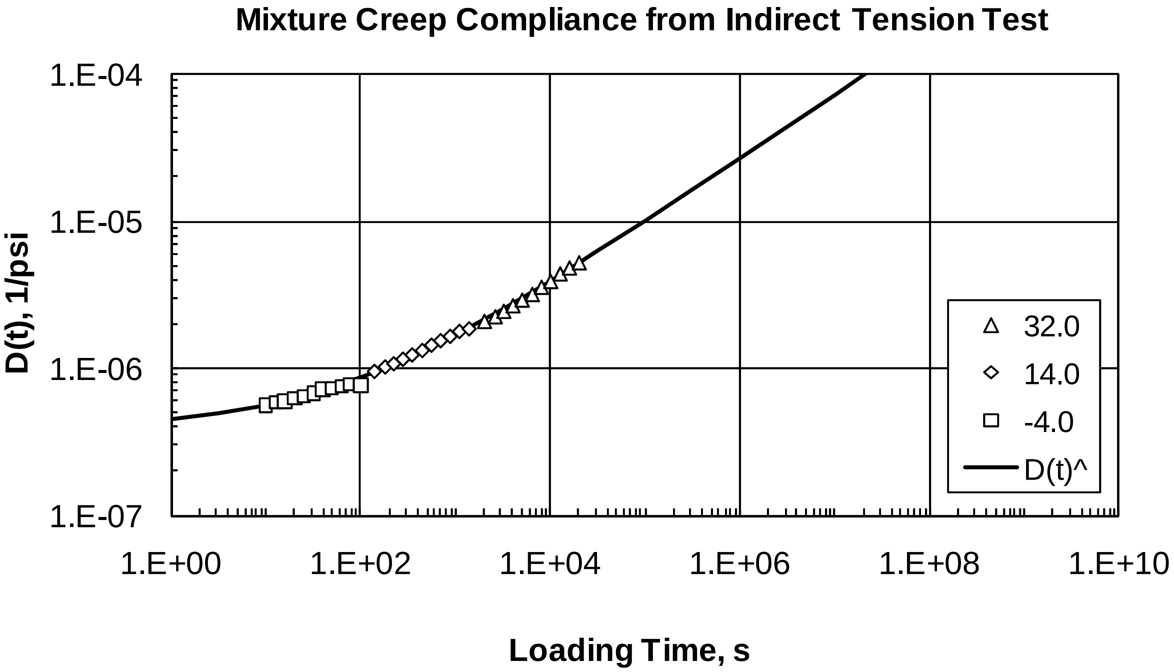
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	5.65E-07	0.14	0.15	9.60E-07	0.22	0.17	1.95E-06	0.34	0.17
13	5.89E-07	0.15	0.15	1.02E-06	0.24	0.17	2.10E-06	0.37	0.17
16	6.01E-07	0.17	0.15	1.07E-06	0.26	0.17	2.33E-06	0.38	0.17
20	6.33E-07	0.18	0.15	1.15E-06	0.27	0.17	2.51E-06	0.40	0.17
25	6.58E-07	0.19	0.15	1.21E-06	0.29	0.17	2.85E-06	0.42	0.17
32	6.90E-07	0.21	0.15	1.31E-06	0.30	0.17	3.08E-06	0.44	0.17
40	7.22E-07	0.22	0.15	1.39E-06	0.32	0.17	3.41E-06	0.46	0.17
50	7.62E-07	0.23	0.15	1.50E-06	0.33	0.17	3.79E-06	0.48	0.17
63	7.91E-07	0.25	0.15	1.63E-06	0.35	0.17	4.18E-06	0.50	0.17
79	8.51E-07	0.26	0.15	1.77E-06	0.37	0.17	4.74E-06	0.52	0.17
100	8.96E-07	0.27	0.15	1.92E-06	0.38	0.17	5.23E-06	0.54	0.17



Glenmore E10, PG 58-28

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.4	-6.410	-7.205	0.438	-0.064	3.0

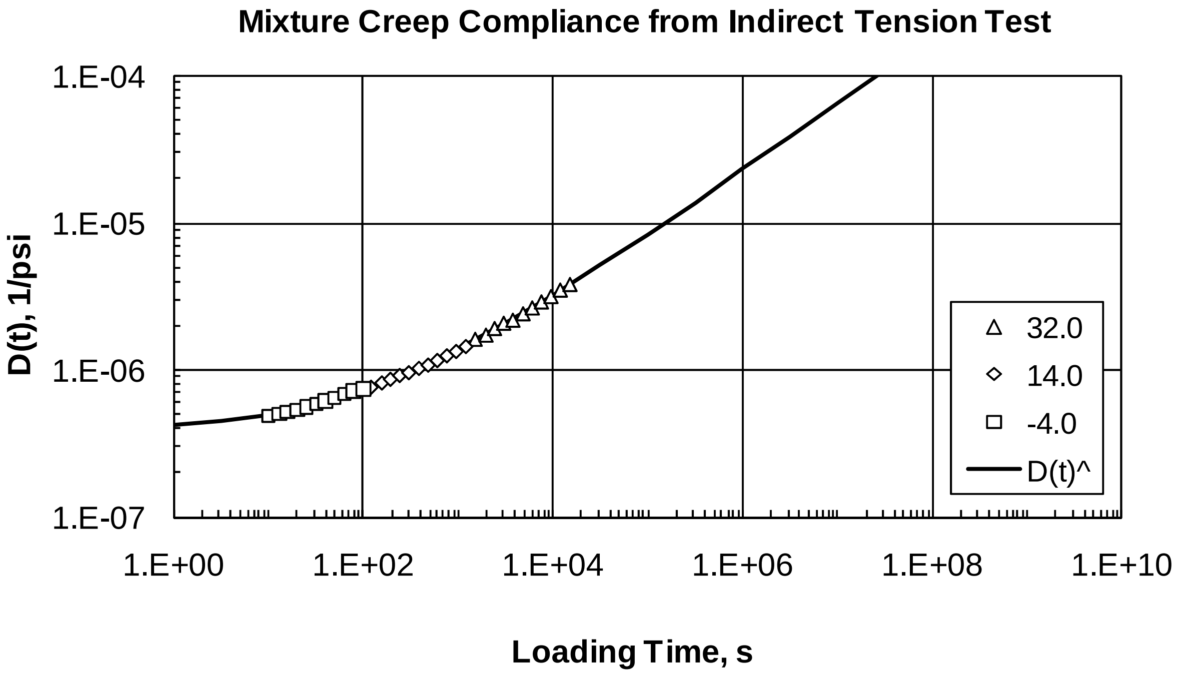
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	5.63E-07	0.16	0.15	9.58E-07	0.25	0.14	2.11E-06	0.31	0.14
13	5.86E-07	0.16	0.15	1.03E-06	0.26	0.14	2.26E-06	0.33	0.14
16	5.98E-07	0.16	0.15	1.08E-06	0.27	0.14	2.47E-06	0.35	0.14
20	6.25E-07	0.16	0.15	1.16E-06	0.28	0.14	2.69E-06	0.37	0.14
25	6.48E-07	0.16	0.15	1.24E-06	0.29	0.14	2.94E-06	0.39	0.14
32	6.79E-07	0.16	0.15	1.32E-06	0.31	0.14	3.21E-06	0.41	0.14
40	7.14E-07	0.16	0.15	1.44E-06	0.32	0.14	3.59E-06	0.44	0.14
50	7.29E-07	0.16	0.15	1.54E-06	0.33	0.14	3.92E-06	0.46	0.14
63	7.52E-07	0.16	0.15	1.65E-06	0.34	0.14	4.42E-06	0.48	0.14
79	7.84E-07	0.16	0.15	1.78E-06	0.35	0.14	4.84E-06	0.50	0.14
100	7.64E-07	0.16	0.15	1.85E-06	0.36	0.14	5.25E-06	0.52	0.14



Glenmore E10, PG 58-28 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.3	-6.428	-7.355	0.452	-0.060	1.7

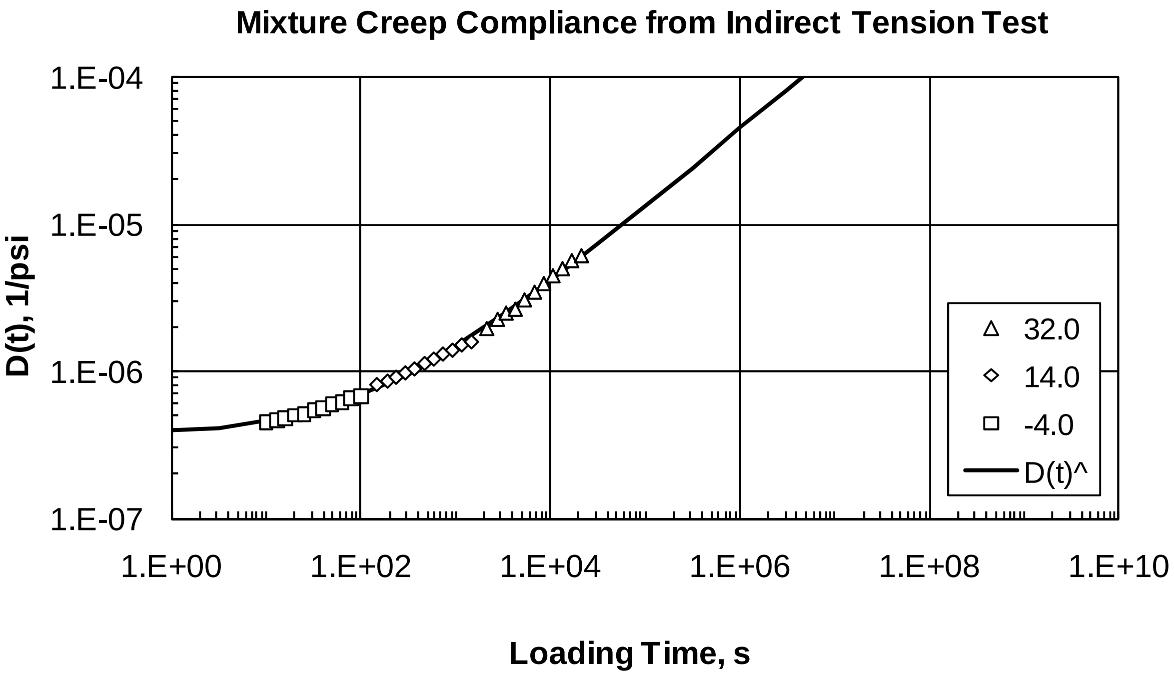
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.88E-07	0.13	0.16	7.59E-07	0.23	0.14	1.60E-06	0.31	0.14
13	5.04E-07	0.15	0.16	8.13E-07	0.24	0.14	1.71E-06	0.33	0.14
16	5.21E-07	0.16	0.16	8.60E-07	0.25	0.14	1.90E-06	0.34	0.14
20	5.37E-07	0.17	0.16	9.14E-07	0.26	0.14	2.06E-06	0.35	0.14
25	5.60E-07	0.18	0.16	9.54E-07	0.27	0.14	2.16E-06	0.37	0.14
32	5.89E-07	0.19	0.16	1.02E-06	0.28	0.14	2.39E-06	0.38	0.14
40	6.19E-07	0.21	0.16	1.07E-06	0.28	0.14	2.63E-06	0.40	0.14
50	6.48E-07	0.22	0.16	1.16E-06	0.29	0.14	2.89E-06	0.41	0.14
63	6.84E-07	0.23	0.16	1.24E-06	0.30	0.14	3.14E-06	0.43	0.14
79	7.17E-07	0.24	0.16	1.33E-06	0.31	0.14	3.48E-06	0.44	0.14
100	7.36E-07	0.25	0.16	1.44E-06	0.32	0.14	3.80E-06	0.46	0.14



Wimmie E3, PG 58-28

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.4	-6.439	-7.552	0.533	-0.065	3.2

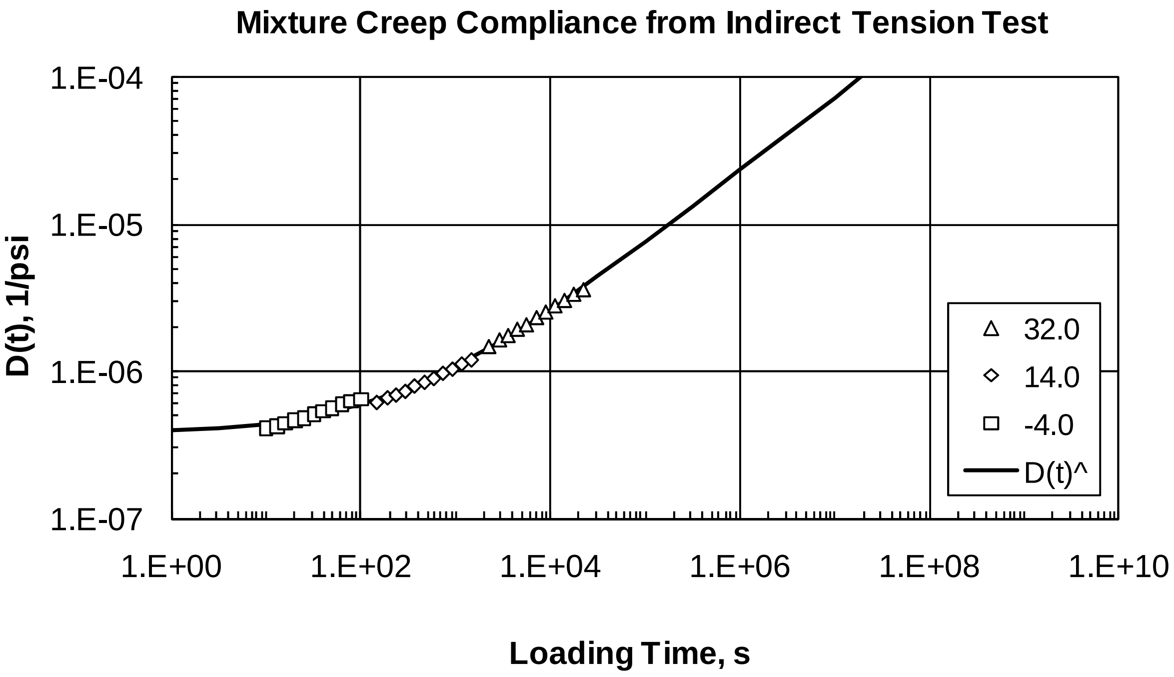
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.49E-07	0.16	0.17	8.16E-07	0.26	0.15	1.94E-06	0.46	0.15
13	4.65E-07	0.16	0.17	8.61E-07	0.27	0.15	2.25E-06	0.48	0.15
16	4.77E-07	0.17	0.17	9.16E-07	0.28	0.15	2.48E-06	0.49	0.15
20	5.00E-07	0.17	0.17	9.80E-07	0.29	0.15	2.64E-06	0.50	0.15
25	5.16E-07	0.18	0.17	1.04E-06	0.30	0.15	3.06E-06	0.51	0.15
32	5.47E-07	0.18	0.17	1.14E-06	0.31	0.15	3.46E-06	0.53	0.15
40	5.63E-07	0.19	0.17	1.22E-06	0.31	0.15	3.96E-06	0.54	0.15
50	5.99E-07	0.19	0.17	1.32E-06	0.32	0.15	4.48E-06	0.55	0.15
63	6.22E-07	0.19	0.17	1.40E-06	0.33	0.15	5.01E-06	0.56	0.15
79	6.50E-07	0.20	0.17	1.52E-06	0.34	0.15	5.68E-06	0.58	0.15
100	6.77E-07	0.20	0.17	1.60E-06	0.35	0.15	6.15E-06	0.59	0.15


Mixture Creep Compliance from Indirect Tension Test

Wimmie E3, PG 58-28 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.2	-6.433	-7.652	0.502	-0.065	4.1

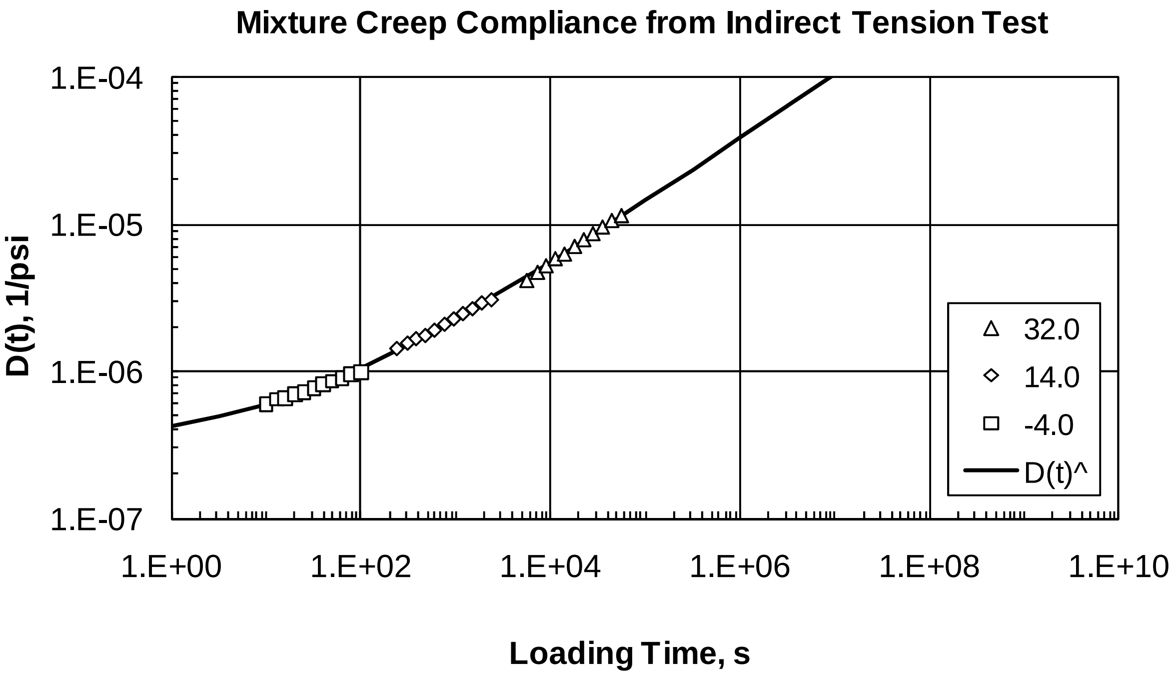
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.11E-07	0.16	0.10	6.14E-07	0.24	0.19	1.47E-06	0.38	0.19
13	4.26E-07	0.17	0.10	6.60E-07	0.25	0.19	1.64E-06	0.39	0.19
16	4.42E-07	0.18	0.10	6.89E-07	0.26	0.19	1.75E-06	0.39	0.19
20	4.65E-07	0.19	0.10	7.29E-07	0.27	0.19	1.94E-06	0.39	0.19
25	4.84E-07	0.20	0.10	7.93E-07	0.28	0.19	2.08E-06	0.40	0.19
32	5.07E-07	0.21	0.10	8.39E-07	0.29	0.19	2.33E-06	0.40	0.19
40	5.35E-07	0.22	0.10	8.90E-07	0.30	0.19	2.54E-06	0.40	0.19
50	5.58E-07	0.23	0.10	9.65E-07	0.31	0.19	2.80E-06	0.41	0.19
63	5.97E-07	0.24	0.10	1.03E-06	0.32	0.19	3.05E-06	0.41	0.19
79	6.24E-07	0.25	0.10	1.11E-06	0.33	0.19	3.36E-06	0.41	0.19
100	6.46E-07	0.26	0.10	1.19E-06	0.34	0.19	3.61E-06	0.42	0.19



Wimmie E10, PG 58-34

Va, %	Log D_o	Log D_1	m	C_2	SE, %
7.1	-6.481	-7.007	0.432	-0.077	2.7

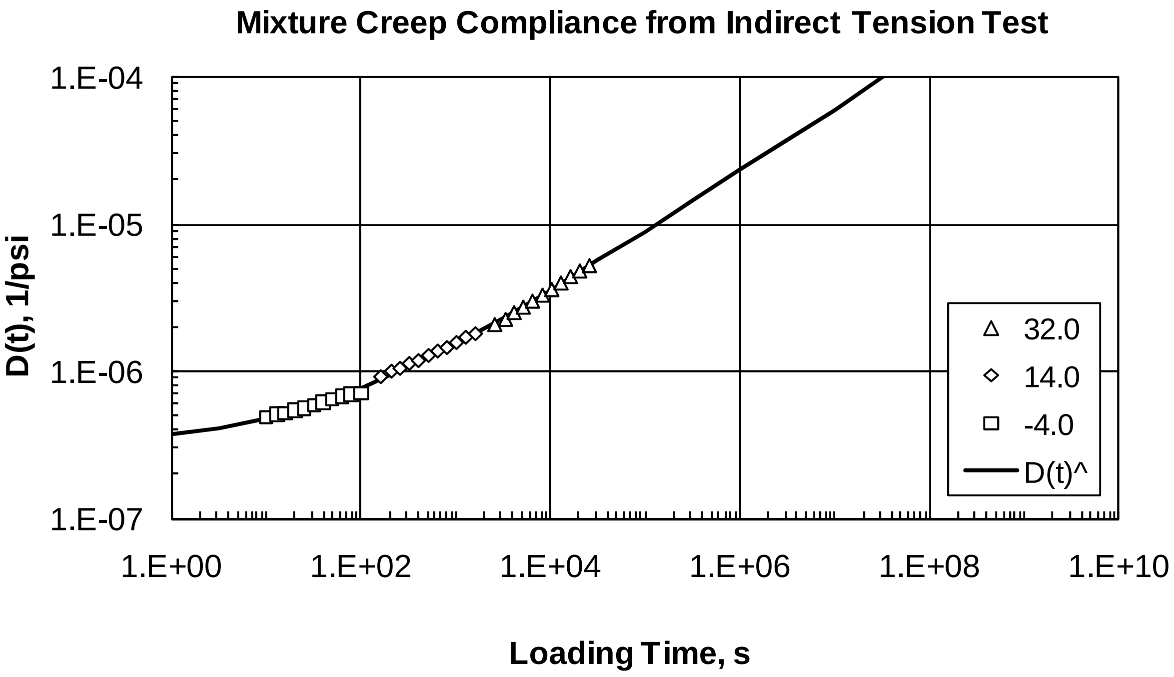
Temp., F:	-4			14			32		
Loading Time s	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$	Creep Comp. 1/psi	m(t)	$\mu(t)$
10	6.00E-07	0.20	0.17	1.43E-06	0.30	0.18	4.15E-06	0.47	0.18
13	6.43E-07	0.20	0.17	1.56E-06	0.31	0.18	4.71E-06	0.46	0.18
16	6.61E-07	0.21	0.17	1.67E-06	0.32	0.18	5.23E-06	0.46	0.18
20	6.92E-07	0.21	0.17	1.76E-06	0.33	0.18	5.85E-06	0.46	0.18
25	7.17E-07	0.22	0.17	1.91E-06	0.34	0.18	6.28E-06	0.46	0.18
32	7.66E-07	0.23	0.17	2.09E-06	0.35	0.18	7.09E-06	0.46	0.18
40	8.09E-07	0.23	0.17	2.28E-06	0.36	0.18	7.88E-06	0.45	0.18
50	8.58E-07	0.24	0.17	2.47E-06	0.37	0.18	8.67E-06	0.45	0.18
63	8.89E-07	0.25	0.17	2.67E-06	0.38	0.18	9.62E-06	0.45	0.18
79	9.51E-07	0.25	0.17	2.92E-06	0.39	0.18	1.07E-05	0.45	0.18
100	9.80E-07	0.26	0.17	3.07E-06	0.40	0.18	1.15E-05	0.44	0.18



Wimmie E10, PG 58-34 + 25 Percent RAP

Va, %	Log D_o	Log D_1	m	C_2	SE, %
6.7	-6.523	-7.165	0.421	-0.067	2.9

Temp., F:	-4			14			32		
Loading Time S	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)	Creep Comp. 1/psi	m(t)	μ(t)
10	4.87E-07	0.15	0.22	9.07E-07	0.28	0.22	2.07E-06	0.39	0.22
13	5.13E-07	0.16	0.22	9.92E-07	0.29	0.22	2.25E-06	0.40	0.22
16	5.20E-07	0.16	0.22	1.04E-06	0.29	0.22	2.51E-06	0.40	0.22
20	5.39E-07	0.17	0.22	1.12E-06	0.30	0.22	2.74E-06	0.41	0.22
25	5.64E-07	0.18	0.22	1.18E-06	0.30	0.22	3.01E-06	0.41	0.22
32	5.90E-07	0.18	0.22	1.28E-06	0.31	0.22	3.31E-06	0.42	0.22
40	6.20E-07	0.19	0.22	1.37E-06	0.32	0.22	3.61E-06	0.42	0.22
50	6.45E-07	0.20	0.22	1.45E-06	0.32	0.22	4.02E-06	0.43	0.22
63	6.79E-07	0.20	0.22	1.57E-06	0.33	0.22	4.45E-06	0.43	0.22
79	7.05E-07	0.21	0.22	1.71E-06	0.34	0.22	4.86E-06	0.44	0.22
100	7.10E-07	0.22	0.22	1.81E-06	0.34	0.22	5.29E-06	0.44	0.22



Appendix C Tutorial for MEPDG Thermal Cracking Analysis

Mechanistic-Empirical Pavement Design Guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is the product of National Cooperative Highway Research Program (NCHRP) Project 1-37A (*1*). The MEPDG is substantially different than most pavement design procedures used in the past by highway agencies. The MEPDG is based on mechanistic-empirical pavement design principles. Critical stresses and strains from vehicle and environmental loading are computed using mechanistic theory. These critical stresses and strains are then empirically related to the occurrence of distresses such as rutting and cracking in the pavement. Most agencies have used the 1993 AASHTO Pavement Design Guide, which is based on limited empirical pavement performance equations from the AASHO Road Test conducted in the late 1950's and early 1960's. The distress prediction models in the MEPDG have been calibrated using a large number of pavement sections from the Long-Term Pavement Performance database. Pavement sections used in the calibration were located throughout the United States. The MEPDG is an analysis tool. The output from the MEPDG is the predicted performance of a trial pavement section, not pavement thicknesses.

The MEPDG requires a large amount of information about the pavement being analyzed. This includes data concerning traffic, climate, subgrade soils, the condition of existing pavements for rehabilitation design, and the thicknesses and material properties for each layer of the pavement, including existing pavement layers for rehabilitation design. To provide flexibility for users with different capabilities, the MEPDG uses a hierarchical scheme for inputting the required data. Three levels are provided:

- **Level 1.** The input parameter is measured directly. This level provides the most accurate information about the input parameter.
- **Level 2.** The input parameter is estimated from correlations or regression equations that are embedded in the MEPDG.

- **Level 3.** The input parameter is based on default values provided by the MEPDG software.

Testing or data collection costs decrease as the hierarchical level increases from Level 1 to Level 3, but the accuracy of the input data also decreases.

The MEPDG has the capability to analyze flexible, semi-rigid, rigid, and composite pavements. For pavements with asphalt concrete surfaces, the MEPDG includes performance models to predict the following distresses:

- Rut depth for asphalt concrete layers, unbound aggregate layers, and the subgrade,
- Transverse thermal cracking,
- Alligator cracking due to bottom initiated fatigue,
- Longitudinal wheel path cracking due to surface initiated fatigue,
- Reflection cracking, and
- Roughness

Thermal Cracking Analysis in the MEPDG

Of particular interest to the Wisconsin Department of Transportation (WisDOT) is the thermal cracking model included in the MEPDG. This model is quite complex. It was originally developed during the Strategic Highway Research Program (SHRP) by researchers from The Pennsylvania State University (*2*). In this model, a thermo-viscoelastic analysis of a constrained asphalt layer is performed to compute stresses within the layer as a function of depth. Pavement temperatures as a function of depth and time for the thermal stress analysis are obtained from the environmental effects model. The computed thermal stresses are used in a linear fracture mechanics model to compute the propagation of a vertical surface crack through the asphalt layer. Finally, the crack spacing at the surface of the pavement is determined from an empirical model that relates the crack spacing observed in the pavement to the average crack depth calculate by the analysis. The thermal fracture model in the MEPDG is considered to be a valuable tool for evaluating the potential for thermal cracking in flexible pavements.

MEPDG Thermal Cracking Analysis Input Data

The asphalt concrete material property inputs needed to perform thermal cracking analyses using the MEPDG are: (1) the linear coefficient of thermal contraction, (2) the tensile strength at 14 °F (-10°C), and (3) creep compliance master curve data. The same data are required for Level 1 and Level 3 analyses. For Level 1 measured data are input. For Level 3 compliance and strength values are estimated from the grade of the binder and the volumetric properties of the mixture. WHRP Project 0092-10-07 found these estimates to be significantly in error for Wisconsin mixtures. Therefore thermal cracking analyses should be conducted as Level 1 analyses with the input properties described below.

Linear Coefficient of Thermal Contraction

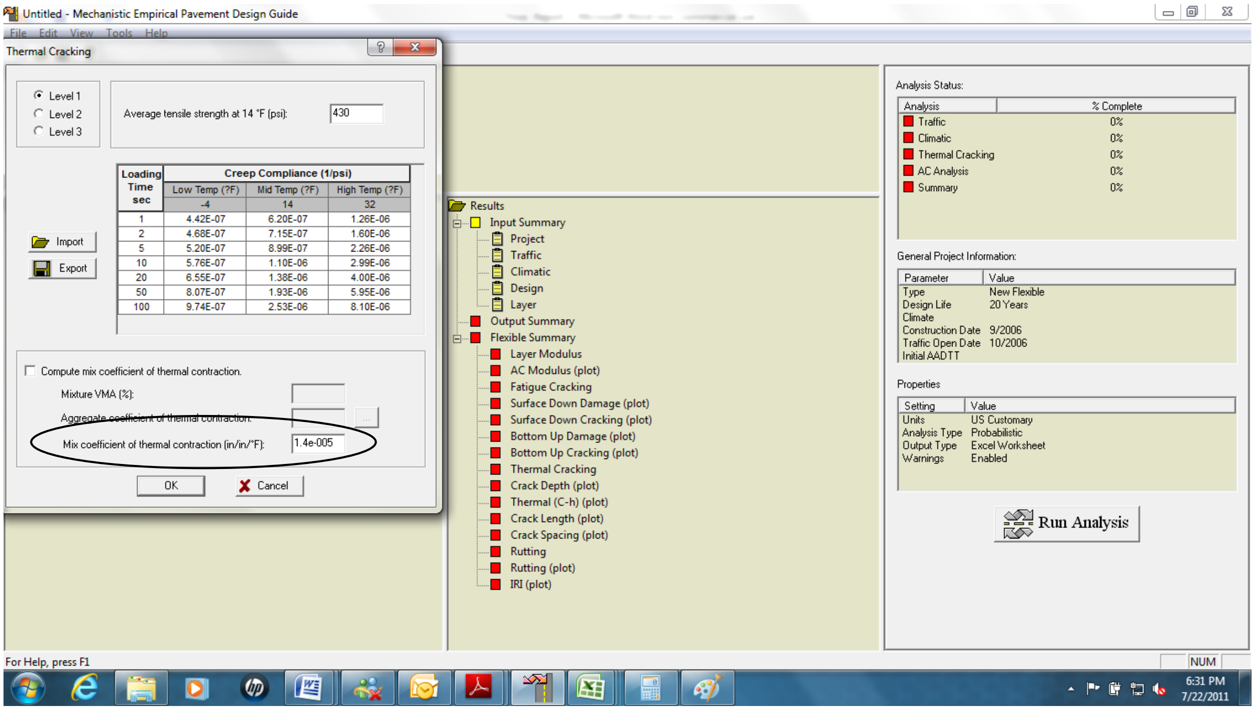
The MEPDG provides the option to estimate the thermal coefficient of contraction for the mixture from the thermal coefficient of contraction for the binder and aggregates, and the volumetric properties of the mixture using Equation C1.

$$\alpha_{mix} = \frac{VMA \times B_{ac} + (100 - VMA) \times B_{agg}}{300} \tag{C1}$$

Where:

α_{mix} = linear coefficient of thermal contraction of the asphalt concrete mixture, (1/°C)
B_{ac} = volumetric coefficient of thermal contraction of the asphalt cement in the solid state (1/°C)
B_{agg} = volumetric coefficient of thermal contraction of the aggregate (1/°C)
VMA = voids in mineral aggregate, %

Since the volumetric coefficient of thermal contraction for the asphalt binder and the aggregates are not usually known, they are estimated from published data, making the accuracy of the estimation suspect. Until measured values of the linear coefficient of thermal contraction are available for Wisconsin mixtures, it is recommended that a mid range value of 1.4×10^{-5}/°F (2.5×10^{-5}/°C) be used. This value can be directly input into the thermal cracking input screen as shown in Figure C1.



● Level 1
○ Level 2
○ Level 3

Average tensile strength at 14 °F (psi): 430

Loading Time sec	Creep Compliance (1/psi)		
	Low Temp (?F)	Mid Temp (?F)	High Temp (?F)
	-4	14	32
1	4.42E-07	6.20E-07	1.26E-06
2	4.68E-07	7.15E-07	1.60E-06
5	5.20E-07	8.99E-07	2.26E-06
10	5.76E-07	1.10E-06	2.99E-06
20	6.55E-07	1.38E-06	4.00E-06
50	8.07E-07	1.93E-06	5.95E-06
100	9.74E-07	2.53E-06	8.10E-06

☐ Compute mix coefficient of thermal contraction.
Mixture VMA (%):
Aggregate coefficient of thermal contraction:
Mix coefficient of thermal contraction (in/in/°F): 1.4e-005

Analysis Status:

Analysis	% Complete
🟥 Traffic	0%
🟥 Climatic	0%
🟥 Thermal Cracking	0%
🟥 AC Analysis	0%
🟥 Summary	0%

General Project Information:

Parameter	Value
Type	New Flexible
Design Life	20 Years
Climate	
Construction Date	9/2006
Traffic Open Date	10/2006
Initial AADTT	

Properties

Setting	Value
Units	US Customary
Analysis Type	Probabilistic
Output Type	Excel Worksheet
Warnings	Enabled

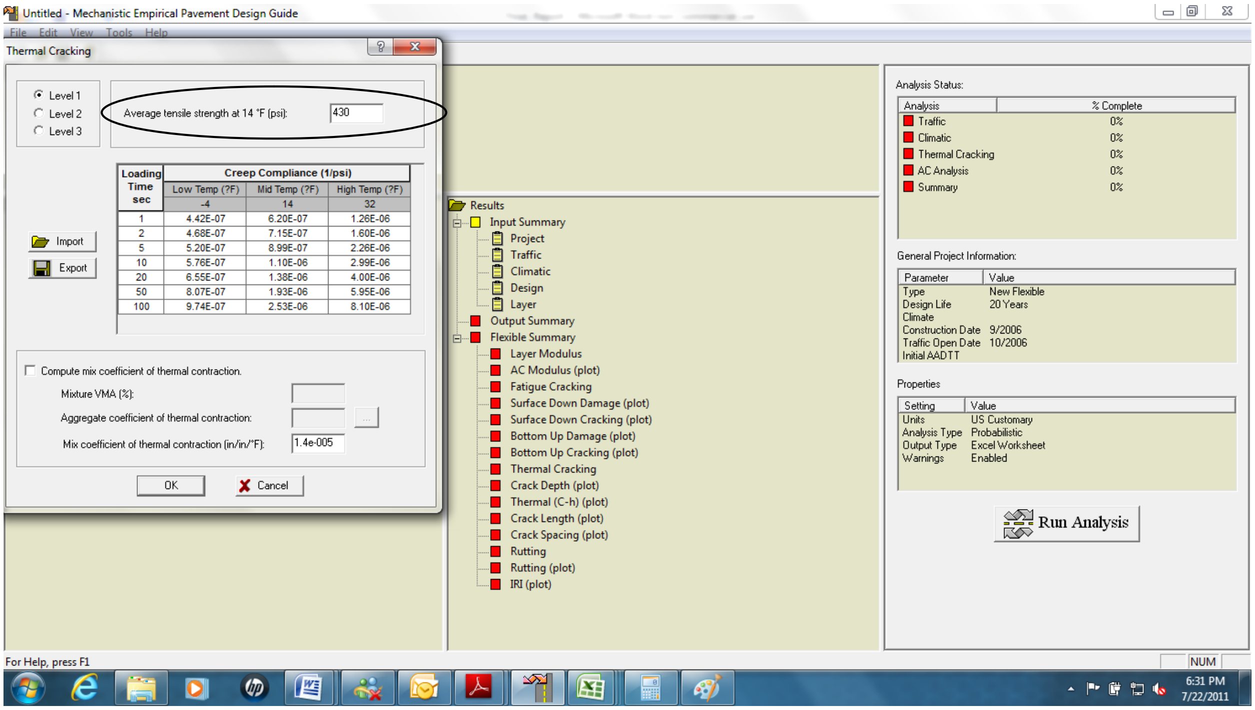
Figure C1. MEPDG Linear Coefficient of Thermal Contraction Input, Level 1 Analysis

Tensile Strength

Based on measured tensile strength data from WHRP Project 0092-10-07, the tensile strength of Wisconsin mixtures at 14 °F (-10 °C) was not a function of binder grade, aggregate source, or design traffic level. The average value for the mixtures tested was 430 psi with a standard deviation of 30 psi. For thermal cracking analyses using the MEPDG a tensile strength of 430 psi should be input into the thermal cracking input screen as shown in Figure C2.

Creep Compliance Data

Based on measured creep compliance data from WHRP Project 0092-10-07, the creep compliance master curve for Wisconsin mixtures was found to be a function of the low temperature grade of the binder in the mixture. Equation C2 was developed to estimate the compliance of Wisconsin mixtures as a function of the low temperature continuous grade of the binder. The reference temperature for Equation C2 is -4 °F (-20 °C). This equation can be used to estimate the compliance values required by the MEPDG for thermal cracking analyses. Equation C2 was developed for low temperature grades between -35.1 and -28.7 °C; therefore, it should be used with caution for binders with low temperature grades outside of this range.



● Level 1
○ Level 2
○ Level 3

Average tensile strength at 14 °F (psi): 430

Loading Time sec	Creep Compliance (1/psi)		
	Low Temp (?F)	Mid Temp (?F)	High Temp (?F)
	-4	14	32
1	4.42E-07	6.20E-07	1.26E-06
2	4.68E-07	7.15E-07	1.60E-06
5	5.20E-07	8.99E-07	2.26E-06
10	5.76E-07	1.10E-06	2.99E-06
20	6.55E-07	1.38E-06	4.00E-06
50	8.07E-07	1.93E-06	5.95E-06
100	9.74E-07	2.53E-06	8.10E-06

☐ Compute mix coefficient of thermal contraction.

Mixture VMA (%):

Aggregate coefficient of thermal contraction:

Mix coefficient of thermal contraction (in/in/°F): 1.4e-005

Analysis Status:

Analysis	% Complete
🟥 Traffic	0%
🟥 Climatic	0%
🟥 Thermal Cracking	0%
🟥 AC Analysis	0%
🟥 Summary	0%

General Project Information:

Parameter	Value
Type	New Flexible
Design Life	20 Years
Climate	
Construction Date	9/2006
Traffic Open Date	10/2006
Initial AADTT	

Properties

Setting	Value
Units	US Customary
Analysis Type	Probabilistic
Output Type	Excel Worksheet
Warnings	Enabled

Figure C2. MEPD Tensile Strength Input, Level 1 Analysis

$$D(t) = 3.729 \times 10^{-7} + 10^{-9.3552 - 0.0645 \times PG_{Low}} \left[\frac{t}{10^{0.0655(T+4)}} \right]^{0.4705} \qquad \text{(C2)}$$

where:

$D(t)$ = creep compliance, 1/psi

T = temperature, °F

PG_{Low} = low temperature continuous grade of the binder in the mixture, °C

t = time

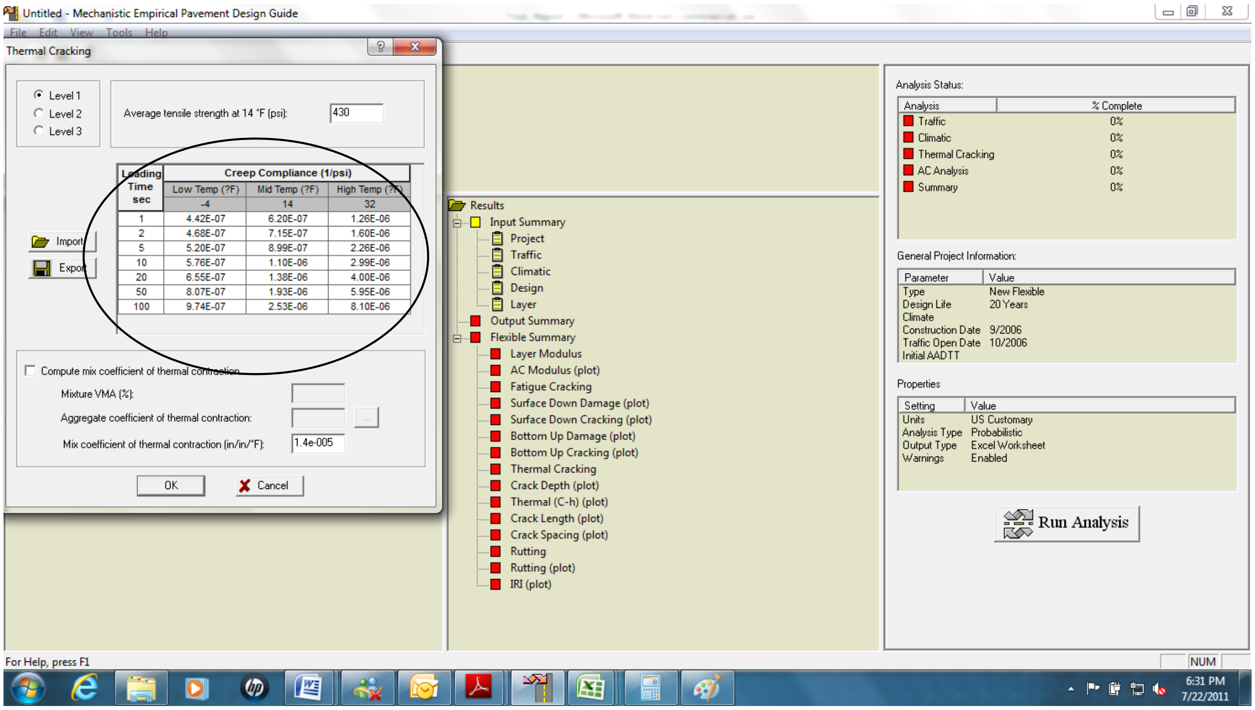
To facilitate the use of Equation C2, compliance values were calculated for low temperature binder grades ranging from -22 to -36 ºC in 1 ºC increments. The values are tabulated in Table C1. The appropriate compliance values can be entered into the thermal cracking input screen as shown in Figure C3.

Table C1. Low Temperature Creep Compliance Values for Wisconsin Mixtures for MEPDG thermal Cracking Analyses.

	Compliance, 1/psi			Compliance, 1/psi			Compliance, 1/psi			Compliance, 1/psi		
Low Temperature PG Grade	-36			-35			-34			-33		
Time, sec	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF
1	4.66E-07	7.05E-07	1.56E-06	4.53E-07	6.59E-07	1.40E-06	4.42E-07	6.20E-07	1.26E-06	4.32E-07	5.86E-07	1.14E-06
2	5.01E-07	8.33E-07	2.02E-06	4.84E-07	7.70E-07	1.80E-06	4.68E-07	7.15E-07	1.60E-06	4.55E-07	6.68E-07	1.43E-06
5	5.70E-07	1.08E-06	2.91E-06	5.43E-07	9.84E-07	2.56E-06	5.20E-07	8.99E-07	2.26E-06	4.99E-07	8.27E-07	2.00E-06
10	6.47E-07	1.35E-06	3.89E-06	6.09E-07	1.22E-06	3.41E-06	5.76E-07	1.10E-06	2.99E-06	5.48E-07	1.00E-06	2.63E-06
20	7.52E-07	1.73E-06	5.25E-06	7.00E-07	1.55E-06	4.58E-06	6.55E-07	1.38E-06	4.00E-06	6.16E-07	1.24E-06	3.50E-06
50	9.57E-07	2.47E-06	7.88E-06	8.76E-07	2.18E-06	6.85E-06	8.07E-07	1.93E-06	5.95E-06	7.47E-07	1.71E-06	5.18E-06
100	1.18E-06	3.27E-06	1.08E-05	1.07E-06	2.87E-06	9.34E-06	9.74E-07	2.53E-06	8.10E-06	8.91E-07	2.23E-06	7.04E-06
Low Temperature PG Grade	-32			-31			-30			-29		
Time, sec	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF
1	4.24E-07	5.56E-07	1.03E-06	4.17E-07	5.31E-07	9.40E-07	4.11E-07	5.09E-07	8.62E-07	4.06E-07	4.90E-07	7.94E-07
2	4.44E-07	6.27E-07	1.28E-06	4.34E-07	5.92E-07	1.16E-06	4.26E-07	5.62E-07	1.05E-06	4.18E-07	5.36E-07	9.57E-07
5	4.82E-07	7.64E-07	1.78E-06	4.67E-07	7.10E-07	1.58E-06	4.54E-07	6.64E-07	1.42E-06	4.43E-07	6.23E-07	1.27E-06
10	5.24E-07	9.15E-07	2.32E-06	5.03E-07	8.40E-07	2.05E-06	4.85E-07	7.76E-07	1.82E-06	4.70E-07	7.20E-07	1.62E-06
20	5.82E-07	1.12E-06	3.07E-06	5.53E-07	1.02E-06	2.69E-06	5.28E-07	9.31E-07	2.37E-06	5.07E-07	8.54E-07	2.10E-06
50	6.95E-07	1.53E-06	4.52E-06	6.51E-07	1.37E-06	3.95E-06	6.12E-07	1.23E-06	3.45E-06	5.79E-07	1.11E-06	3.03E-06
100	8.19E-07	1.97E-06	6.12E-06	7.58E-07	1.75E-06	5.32E-06	7.05E-07	1.56E-06	4.64E-06	6.59E-07	1.40E-06	4.05E-06

Table C1 (Continued). Low Temperature Creep Compliance Values for Wisconsin Mixtures for MEPDG thermal Cracking Analyses.

	Compliance, 1/psi			Compliance, 1/psi			Compliance, 1/psi			Compliance, 1/psi		
Low Temperature PG Grade	-28			-27			-26			-25		
Time, sec	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF
1	4.01E-07	4.74E-07	7.36E-07	3.97E-07	4.60E-07	6.86E-07	3.94E-07	4.48E-07	6.43E-07	3.91E-07	4.38E-07	6.06E-07
2	4.12E-07	5.13E-07	8.76E-07	4.07E-07	4.94E-07	8.07E-07	4.02E-07	4.77E-07	7.47E-07	3.98E-07	4.63E-07	6.95E-07
5	4.33E-07	5.89E-07	1.15E-06	4.25E-07	5.59E-07	1.04E-06	4.18E-07	5.33E-07	9.48E-07	4.11E-07	5.11E-07	8.69E-07
10	4.56E-07	6.72E-07	1.45E-06	4.45E-07	6.31E-07	1.30E-06	4.35E-07	5.95E-07	1.17E-06	4.26E-07	5.65E-07	1.06E-06
20	4.89E-07	7.88E-07	1.86E-06	4.73E-07	7.30E-07	1.65E-06	4.59E-07	6.81E-07	1.48E-06	4.47E-07	6.38E-07	1.33E-06
50	5.51E-07	1.01E-06	2.66E-06	5.26E-07	9.23E-07	2.35E-06	5.05E-07	8.47E-07	2.07E-06	4.87E-07	7.82E-07	1.84E-06
100	6.19E-07	1.26E-06	3.54E-06	5.85E-07	1.14E-06	3.11E-06	5.56E-07	1.03E-06	2.73E-06	5.31E-07	9.39E-07	2.40E-06
Low Temperature PG Grade	-24			-23			-22			-21		
Time, sec	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF	-4.0 ºF	14.0 ºF	32.0 ºF
1	3.88E-07	4.29E-07	5.73E-07	3.86E-07	4.21E-07	5.46E-07	3.84E-07	4.14E-07	5.22E-07	3.83E-07	4.09E-07	5.01E-07
2	3.95E-07	4.50E-07	6.51E-07	3.92E-07	4.40E-07	6.12E-07	3.89E-07	4.30E-07	5.79E-07	3.87E-07	4.23E-07	5.51E-07
5	4.06E-07	4.92E-07	8.01E-07	4.02E-07	4.76E-07	7.42E-07	3.98E-07	4.61E-07	6.91E-07	3.94E-07	4.49E-07	6.47E-07
10	4.19E-07	5.38E-07	9.65E-07	4.13E-07	5.15E-07	8.84E-07	4.07E-07	4.96E-07	8.13E-07	4.02E-07	4.79E-07	7.52E-07
20	4.37E-07	6.02E-07	1.19E-06	4.28E-07	5.70E-07	1.08E-06	4.20E-07	5.43E-07	9.83E-07	4.14E-07	5.20E-07	8.99E-07
50	4.71E-07	7.25E-07	1.64E-06	4.58E-07	6.77E-07	1.46E-06	4.46E-07	6.35E-07	1.31E-06	4.36E-07	5.99E-07	1.18E-06
100	5.09E-07	8.61E-07	2.12E-06	4.90E-07	7.94E-07	1.88E-06	4.74E-07	7.36E-07	1.67E-06	4.60E-07	6.86E-07	1.49E-06



● Level 1
○ Level 2
○ Level 3

Average tensile strength at 14 °F (psi): 430

Loading Time sec	Creep Compliance (1/psi)		
	Low Temp (?F)	Mid Temp (?F)	High Temp (?F)
	-4	14	32
1	4.42E-07	6.20E-07	1.26E-06
2	4.68E-07	7.15E-07	1.60E-06
5	5.20E-07	8.99E-07	2.26E-06
10	5.76E-07	1.10E-06	2.99E-06
20	6.55E-07	1.38E-06	4.00E-06
50	8.07E-07	1.93E-06	5.95E-06
100	9.74E-07	2.53E-06	8.10E-06

☐ Compute mix coefficient of thermal contraction.

Mixture VMA (%):

Aggregate coefficient of thermal contraction:

Mix coefficient of thermal contraction (in/in/°F): 1.4e-005

Analysis Status:

Analysis	% Complete
🟥 Traffic	0%
🟥 Climatic	0%
🟥 Thermal Cracking	0%
🟥 AC Analysis	0%
🟥 Summary	0%

General Project Information:

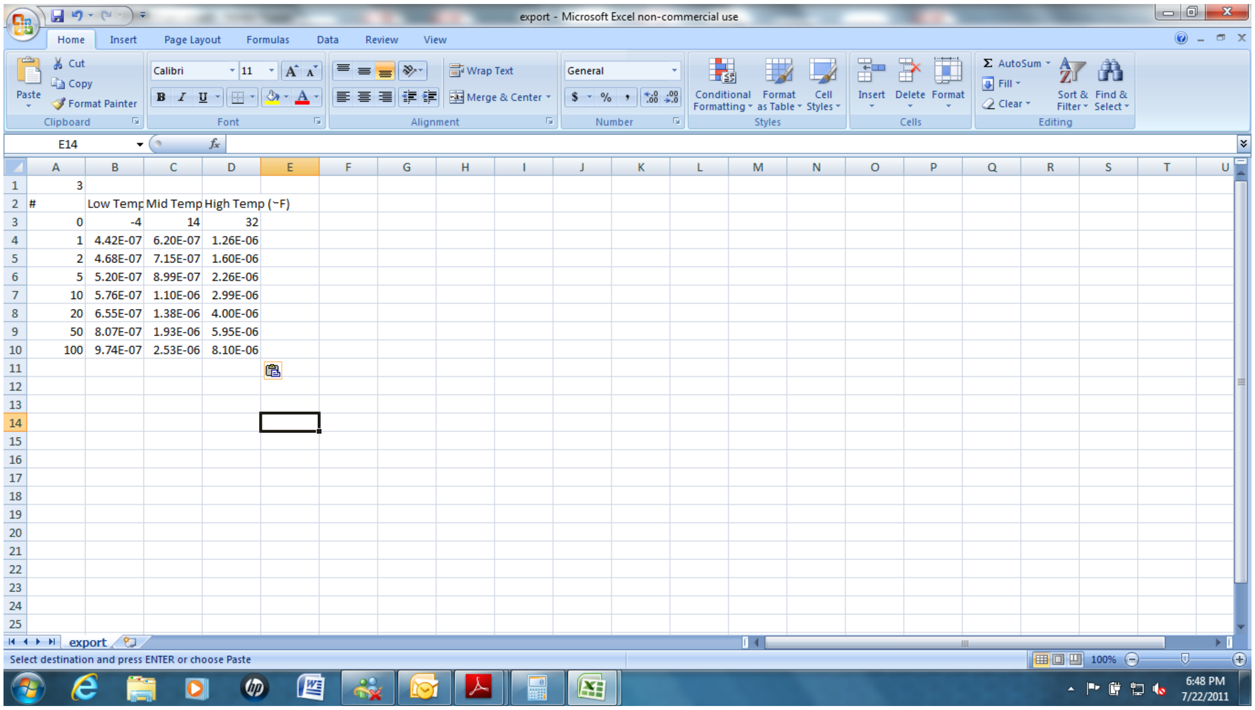
Parameter	Value
Type	New Flexible
Design Life	20 Years
Climate	
Construction Date	9/2006
Traffic Open Date	10/2006
Initial AADTT	

Properties

Setting	Value
Units	US Customary
Analysis Type	Probabilistic
Output Type	Excel Worksheet
Warnings	Enabled

Figure C3. MEPD Creep Compliance Input, Level 1 Analysis

Alternatively, comma separated files with the compliance values can be assembled and then imported into the MEPDG thermal cracking analysis. Figure C4 shows to format a comma separated file containing the creep compliance in Excel. After formatting the file in this manner, the file should be saved as a "CSV" file with the file extension ".thc". The ".thc" file can then be imported into the MEPDG.



	A	B	C	D
1	3			
2	#	Low Temp	Mid Temp	High Temp (~F)
3	0	-4	14	32
4	1	4.42E-07	6.20E-07	1.26E-06
5	2	4.68E-07	7.15E-07	1.60E-06
6	5	5.20E-07	8.99E-07	2.26E-06
7	10	5.76E-07	1.10E-06	2.99E-06
8	20	6.55E-07	1.38E-06	4.00E-06
9	50	8.07E-07	1.93E-06	5.95E-06
10	100	9.74E-07	2.53E-06	8.10E-06

Select destination and press ENTER or choose Paste

Figure C4. Format of Excel File for Creating MEPDG Compliance Files for Importing.

References

1. Applied Research Associates, Inc., ERES Consultants Division "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures," Final Report Prepared for the National Cooperative Highway Research Program, March, 2004.

2. Lytton, R.L., J. Uzan, E.G. Fernando, R. Roque, D. Hiltunen, S. Stoffels, "Development and Validation of Performance Prediction Models and Specification for Asphalt Binders and Paving Mixtures, "*Report SHRP-A-357*, Strategic Highway Research Program, Washington, D.C., 1993.

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