Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Asphalt Material Design Inputs for Use with the Mechanistic Empirical Pavement Design Guide

http://www.virginiadot.org/vtrc/main/online_reports/pdf/12-r6.pdf

ALEX K. APEAGYEI, Ph.D., P.E.
Research Scientist

STACEY D. DIEFENDERFER, Ph.D., P.E.
Research Scientist

Final Report VCTIR 12-R6

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VCTIR 12-R6	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Asphalt Material Design Inputs for Use with the Mechanistic-Empirical Pavement Design Guide in Virginia		5. Report Date: September 2011 6. Performing Organization Code:
7. Author(s): Alex K. Apeagyei, Ph.D., P.E., and Stacey D. Diefenderfer, Ph.D., P.E.		8. Performing Organization Report No.: VCTIR 12-R6
9. Performing Organization and Address: Virginia Center for Transportation Innovation and Research 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 94209
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final, 7-1-09 through 8-31-11 14. Sponsoring Agency Code:
15. Supplementary Notes:		

16. Abstract:

The *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures* (MEPDG), developed under NCHRP Project 1-37A and recently adopted by the American Association of State Highway and Transportation Officials (AASHTO), offers an improved methodology for pavement design and evaluation. To achieve this improved prediction capability, the MEPDG procedure requires fundamental material properties in addition to certain empirically determined binder and mixture properties as design inputs. One of the key tasks identified by the Virginia Department of Transportation's (VDOT) Asphalt Concrete MEPDG Committee was the laboratory characterization of asphalt mixtures commonly used in Virginia to generate a catalog of the MEPDG-required design inputs.

The purpose of this study was to evaluate, compile, and present asphalt material properties in a format that could be readily used in the MEPDG software and to develop a comprehensive catalog of MEPDG design input parameters for pavement design in Virginia. To achieve this objective, 18 asphalt concrete mixtures, sampled from seven of the nine VDOT districts, were tested using a battery of MEPDG- required tests including dynamic modulus (|E*|), flow number (FN), creep compliance, tensile strength, and beam fatigue tests. Testing involving binder and volumetric properties of the mixtures was also conducted. Finally, rut tests using the asphalt pavement analyzer (APA), a standard VDOT test protocol, were conducted to enable a direct comparison of the APA and FN test results. On the basis of these tests, suggestions for additional studies were made.

The results of the study were presented in a form matching the MEPDG input format, and a catalog of design input parameters was developed for the 18 asphalt concrete mixtures. Included in the catalog were binder stiffness, mixture |E*|, mixture gradation, and mixture volumetric properties that would enable a designer the flexibility to select the desired input level (1, 2, or 3) depending on the pavement type. An illustrative example of how the developed inputs could be implemented using the MEPDG software was also provided. The results showed that |E*| master curves of asphalt mixtures obtained using the five standard testing temperatures described in AASHTO TP 62 could be obtained by testing at only three temperatures, which could result in a substantial reduction of testing time. The results also showed that the FN test was a sensitive test for evaluating rutting susceptibility of asphalt mixtures in the laboratory. The FN test was found to be sensitive to binder stiffness, mixture stiffness, mixture volumetric properties, aggregate gradation, and amount of recycled asphalt pavement (RAP) for the mixtures considered in this study.

The study recommends that the catalog of input data for typical asphalt mixtures developed in this study be considered for pavement design in Virginia. The data followed expected trends and compared quite well with those reported in previous studies. Further studies should be conducted to evaluate the FN test as an additional tool for evaluating rutting in asphalt mixtures. Mixtures containing higher amounts of RAP (>20%) exhibited comparatively lower rutting resistance than those with 20% or less RAP. This phenomenon was unexpected since it is generally believed that adding more RAP should result in stiffer and hence more rut-resistant mixtures. Additional research should be conducted to investigate this phenomenon further.

17 Key Words: Full-depth reclamation, in-place pavement recycling, pavement rehabilitation	18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 82	22. Price:

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

ASPHALT MATERIAL DESIGN INPUTS FOR USE WITH THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE IN VIRGINIA

Alex K. Apeagyei, Ph.D., P.E.
Research Scientist

Stacey D. Diefenderfer, Ph.D., P.E.
Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

September 2011
VCTIR 12-R6

DISCLAIMER

ABSTRACT

The *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures* (MEPDG), developed under NCHRP Project 1-37A and recently adopted by the American Association of State Highway and Transportation Officials (AASHTO), offers an improved methodology for pavement design and evaluation. To achieve this improved prediction capability, the MEPDG procedure requires fundamental material properties in addition to certain empirically determined binder and mixture properties as design inputs. One of the key tasks identified by the Virginia Department of Transportation's (VDOT) Asphalt Concrete MEPDG Committee was the laboratory characterization of asphalt mixtures commonly used in Virginia to generate a catalog of the MEPDG-required design inputs.

The purpose of this study was to evaluate, compile, and present asphalt material properties in a format that could be readily used in the MEPDG software and to develop a comprehensive catalog of MEPDG design input parameters for pavement design in Virginia. To achieve this objective, 18 asphalt concrete mixtures, sampled from seven of the nine VDOT districts, were tested using a battery of MEPDG- required tests including dynamic modulus (|E*|), flow number (FN), creep compliance, tensile strength, and beam fatigue tests. Testing involving binder and volumetric properties of the mixtures was also conducted. Finally, rut tests using the asphalt pavement analyzer (APA), a standard VDOT test protocol, were conducted to enable a direct comparison of the APA and FN test results. On the basis of these tests, suggestions for additional studies were made.

The results of the study were presented in a form matching the MEPDG input format, and a catalog of design input parameters was developed for the 18 asphalt concrete mixtures. Included in the catalog were binder stiffness, mixture |E*|, mixture gradation, and mixture volumetric properties that would enable a designer the flexibility to select the desired input level (1, 2, or 3) depending on the pavement type. An illustrative example of how the developed inputs could be implemented using the MEPDG software was also provided. The results showed that |E*| master curves of asphalt mixtures obtained using the five standard testing temperatures described in AASHTO TP 62 could be obtained by testing at only three temperatures, which could result in a substantial reduction of testing time. The results also showed that the FN test was a sensitive test for evaluating rutting susceptibility of asphalt mixtures in the laboratory. The FN test was found to be sensitive to binder stiffness, mixture stiffness, mixture volumetric properties, aggregate gradation, and amount of recycled asphalt pavement (RAP) for the mixtures considered in this study.

The study recommends that the catalog of input data for typical asphalt mixtures developed in this study be considered for pavement design in Virginia. The data followed expected trends and compared quite well with those reported in previous studies. Further studies should be conducted to evaluate the FN test as an additional tool for evaluating rutting in asphalt mixtures. Mixtures containing higher amounts of RAP (>20%) exhibited comparatively lower rutting resistance than those with 20% or less RAP. This phenomenon was unexpected since it is generally believed that adding more RAP should result in stiffer and hence more rut-resistant mixtures. Additional research should be conducted to investigate this phenomenon further.

FINAL REPORT

ASPHALT MATERIAL DESIGN INPUTS FOR USE WITH THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE IN VIRGINIA

Alex K. Apeagyei, Ph.D., P.E.
Research Scientist

Stacey D. Diefenderfer, Ph.D., P.E.
Research Scientist

INTRODUCTION

The *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures* (MEPDG) (ARA, Inc., 2004), developed under NCHRP Project 1-37A, was adopted in 2008 by the American Association of State Highway and Transportation Officials (AASHTO) for implementation by various state departments of transportation. Implementation of the MEPDG is estimated to begin by 2013 in Virginia.

The MEPDG approach is an improved methodology for pavement design and the evaluation of paving materials. This is because the MEPDG procedure provides better capability for predicting pavement performance using mechanistic analyses to determine stresses and strains and empirical models to predict performance. To accomplish this improved prediction capability, the MEPDG procedure requires fundamental material properties in addition to certain empirically determined binder and mixture properties as design inputs. The required properties for asphalt mixtures include indirect tensile strength, creep compliance, and dynamic modulus ($|E^*|$). Required asphalt binder properties include the complex shear modulus and associated phase angle (G^* and δ). General asphalt mixture properties include asphalt binder content, aggregate gradation, and volumetric properties. Knowledge of these characteristics will improve the efficiency and reliability of future flexible pavement designs. Thus, one of the key tasks identified by the Virginia Department of Transportation's (VDOT) Asphalt Concrete MEPDG Committee was the laboratory characterization of asphalt mixtures commonly used in Virginia to generate a catalog of suitable design input parameters.

The MEPDG software uses the aforementioned material properties to calculate incremental and accumulated pavement damage based on the expected variation in environmental and traffic loading. This process, as defined by the user-selected reliability, allows the designer to judge whether or not the input design thickness and/or materials meet the expected performance during the design period. In the current version (1.100) of the MEPDG procedure, three input levels can be used based on the availability of materials characterization data. The site-specific laboratory-measured values of the material properties are used as Level 1 input parameters. Predicted values determined from basic volumetric properties of as-constructed mixtures are considered Level 2 input parameters. Level 3 input parameters are provided as default values in the software based on mixture gradation and the performance grade (PG) of the binder.

A previous study (Flintsch et al., 2007) tested a limited number of VDOT mixture types to develop input parameters for use in the MEPDG. Eleven separate hot-mix asphalt (HMA) mixtures were tested including three surface mixtures (SM) (SM-9.5A), three intermediate mixtures (IM) (IM-19.0A), and four base mixtures (BM) (BM-25.0); all used similar binder types (PG 64-22). Because of the limited number of mixtures and binders tested and the large differences observed in some of the mixtures, the authors identified the need for further evaluation of additional mixtures incorporating different binder and aggregate types. The authors noted that aggregates, asphalt grade, and percentage of recycled asphalt pavement (RAP) had a large effect on the |E*|, creep compliance, and indirect tensile strength of the mixtures.

PURPOSE AND SCOPE

The purpose of this study was to evaluate, compile, and present asphalt material properties in a format that could be readily used in the MEPDG software and to develop a comprehensive catalog of MEPDG design input parameters for pavement design in Virginia. To achieve this objective, 18 asphalt concrete mixtures, sampled from seven of the nine VDOT districts, were tested using a battery of MEPDG- required tests including dynamic modulus (|E*|), flow number (FN), creep compliance, tensile strength, and beam fatigue tests. Mixture tests to measure the volumetric properties of the mixtures were conducted. Rheological testing involving asphalt binders recovered from the plant-mixed materials was also conducted. Finally, rut tests using the asphalt pavement analyzer (APA), a standard VDOT test protocol, were conducted to enable a direct comparison of the APA and FN test results. On the basis of these tests, suggestions for additional studies were made.

The study conducted tests on 18 mixtures to complement those tests reported by Flintsch et al. (2007). As most asphalt mixtures produced in Virginia today contain between 0% and 30% RAP, the study also permitted the quantification of the effect of RAP on asphalt mixture performance to be quantified. A catalog of MEPDG-input parameters was developed for pavement design in Virginia.

METHODS

Materials Sampling and Collection

Samples of the most commonly used types of asphalt mixtures were collected from around Virginia. Records from VDOT's Maintenance Division for the period April 25, 2007, to March 26, 2008 were used to identify the top three most common mixture types as (1) BMs (BM-25.0, having a nominal maximum aggregate size [NMAS] of 25.0 mm); (2) dense-graded SMs (SM-9.5 and SM-12.5, having an NMAS of 9.5 and 12.5 mm, respectively); and (3) gap-graded SMs or stone-matrix asphalt (SMA) (SMA-12.5, having an NMAS of 12.5 mm). Of the

18 mixtures sampled, 15 were dense-graded SMs and 3 were SMA mixtures. Additional details regarding the mixtures sampled and tested in this study including the design asphalt binder PG grade and amount, amount of RAP used, and mixture source are shown in Table 1. Overall, mixtures were collected from seven of the nine VDOT districts for testing.

All samples were plant-mixed as previously noted and were sampled loose at the plant and sent to the Virginia Center for Transportation Innovation and Research (VCTIR) laboratory for further processing and testing. Samples were stored in a temperature-controlled environment in sealed containers before testing. Additional details about the mixtures including key gradation parameters and mixture volumetrics are provided in Table 2 and Table 3, respectively. Further details of the gradation used are presented in Appendix A. The gradation parameters in Table 2 and asphalt binder contents in Table 3 were obtained following ignition oven testing of loose sample mixtures, and the design mixture volumetrics were obtained on loose specimens compacted to 65 gyrations in a Superpave gyratory compactor. These tests were conducted to verify that the plant-produced mixtures sampled conformed to VDOT specifications in terms of gradation and volumetrics (VDOT, 2007). Subsequently, the loose mixtures were processed into compacted specimens for mechanical testing as detailed later.

The testing necessary to conduct this study was done by technical and professional staff at VCTIR. Laboratory tests included (1) binder grading, (2) |E*|, (3) FN, (4) creep compliance, (5) indirect tensile strength, (6) four-point beam fatigue, and (7) APA rut tests. Asphalt binder extraction and recovery testing were conducted by VDOT Materials Division technical staff at Elko, Virginia.

Table 1. Plant-mixed Loose Asphalt Mixtures Sampled for Testing

Mix Designation	Mix ID	VDOT District	Mix Type	RAP (%)	Design Binder Grade
SM	08-1019D	Culpeper	SM-9.5D	15	PG 70-22
	08-1036D	Staunton	SM-12.5D	10	PG 70-22
	08-1043A	NOVA	SM-9.5A	0	PG 64-22
	08-1045D	NOVA	SM-9.5D	20	PG 70-22
	08-1047D	Hampton Roads	SM-9.5D	10	PG 70-22
	08-1052E	Bristol	SM-12.5E	12	PG 76-22
	08-1055D	Lynchburg	SM-12.5D	25	PG 70-22
	09-1001E	NOVA	SM-12.5E	15	PG 76-22
BM	08-1044A	NOVA	BM-25.0A	20	PG 64-22
	09-1049A	Bristol	BM-25.0A	15	PG 64-22
	09-1051D	Bristol	BM-25.0D	15	PG 70-22
	09-1053D	Bristol	BM-25.0D	15	PG 70-22
	09-1070D	Fredericksburg	BM-25.0D	25	PG 70-22
	09-1071D	Fredericksburg	BM-25.0D	25	PG 70-22
	09-1072D	Fredericksburg	BM-25.0D	25	PG 70-22
SMA	08-1012E	Fredericksburg	SMA-12.5E	0	PG 76-22
	08-1025E	Fredericksburg	SMA-12.5E	10	PG 76-22
	08-1046D	Hampton Roads	SMA-12.5D	0	PG 70-22

RAP = recycled asphalt pavement; SM = surface mixture; NOVA = Northern Virginia; BM = base mixture; SMA = stone-matrix asphalt.

Table 2. Mixture Gradation Parameters

Mix Designation	Mix ID	NMAS (mm)	Percent Passing Sieve Size		
			No. 4	No. 16	No. 200
SM	08-1019D	9.5	60.5	29.0	5.8
	08-1036D	12.5	51.6	25.4	5.6
	08-1043A	9.5	58.3	30.1	5.8
	08-1045D	9.5	40.5	18.3	4.2
	08-1047D	9.5	66.6	37.8	6.6
	08-1052E	12.5	61.1	23.2	6.8
	08-1055D	12.5	50.2	35.0	5.2
	09-1001E	12.5	57.6	29.2	4.6
BM	08-1044A	25.0	28.7	19.0	4.4
	09-1049A	25.0	39.8	16.8	7.0
	09-1051D	25.0	37.0	16.8	6.8
	09-1053D	25.0	37.9	16.8	6.8
	09-1070D	25.0	47.4	24.9	6.4
	09-1071D	25.0	43.8	23.4	5.9
	09-1072D	25.0	38.8	20.3	5.0
SMA	08-1012E	12.5	26.2	17.8	11.3
	08-1025E	12.5	25.6	17.4	11.4
	08-1046D	12.5	23.8	11.8	5.8

NMAS = nominal maximum aggregate size; SM = surface mixture; BM = base mixture; SMA = stone-matrix asphalt.

Table 3. Design Mixture Volumetrics

Mix Designation	Mix ID	V_b	V_a	VMA	VFA
SM	08-1019D	5.44	4.23	16.6	74.5
	08-1036D	5.68	3.15	15.5	79.7
	08-1043A	5.60	3.90	16.9	76.9
	08-1045D	4.43	9.65	20.3	52.5
	08-1047D	5.42	3.71	15.8	76.4
	08-1052E	5.92	4.31	17.2	74.9
	08-1055D	5.60	4.16	16.3	74.5
	09-1001E	5.22	5.00	17.0	70.6
BM	08-1044A	4.48	3.89	15.0	74.1
	09-1049A	4.90	4.30	14.9	71.3
	09-1051D	4.73	3.80	14.1	77.8
	09-1053D	5.00	3.10	14.1	77.8
	09-1070D	4.60	2.40	12.6	80.8
	09-1071D	5.00	2.20	12.5	82.7
	09-1072D	5.40	1.80	12.9	85.8
SMA	08-1012E	6.45	2.10	18.2	88.5
	08-1025E	6.48	3.06	18.2	83.2
	08-1046D	7.05	8.61	23.3	63.0

V_b = binder content (%); V_a = air voids (%); VMA = voids in mineral aggregates; VFA = voids filled with asphalt; SM = surface mixture; BM = base mixture; SMA = stone-matrix asphalt.

Specimen Preparation

Gyratory Compaction

A Pine Superpave gyratory compactor was used to fabricate the specimens used for the following tests: (1) |E*|, (2) FN, (3) creep compliance, and (4) indirect tensile strength. All mixtures were compacted to a target air void level of 7 ± 0.5%.

For the |E*| and FN tests, 180 mm tall by 150 mm diameter gyratory specimens were fabricated. A coring rig and wet-saw were then used to obtain the standard 150 mm tall by 100 mm diameter specimen from the 180 mm by 150 mm gyratory specimens. The same specimens were used for the |E*| and the FN tests since the former is considered a non-destructive test. At least three replicate specimens of each mixture type were fabricated.

The standard 50 mm thick by 150 mm diameter specimens required for the creep compliance and tensile strength tests were obtained by saw-cutting from gyratory-compacted specimens measuring 150 mm in diameter by 150 mm in height. Similar to the |E*| and FN tests, for each mixture, the same specimens were used for creep compliance and indirect tensile strength tests since the former test is considered a non-destructive test. At least three replicate specimens were fabricated for each mixture type.

Vibratory Beam Compactor

A Pavement Technology Inc. (PTI) Asphalt Vibratory Compactor was used to fabricate specimens for the beam fatigue and APA rut tests. For the fatigue tests, compacted beams measuring approximately 75 mm thick by 125 mm wide by 381 mm long were fabricated. From these compacted beams, the 50.8 mm by 63.5 mm by 381 mm specimens required for the fatigue testing were saw-cut. At least nine replicate fatigue beam specimens were fabricated for each mixture type. For the APA rut tests, three replicate beams each measuring 75 mm thick by 125 mm wide by 300 mm long were fabricated. The target air void level for the fatigue and APA beams was 7 ± 0.5%.

Test Methods

Table 4 is a summary of the testing conditions used. Additional details of the testing program are discussed later.

Table 4. Test Details

Test	Testing Conditions				Test Specification and Reference
	Temperature (°F)	Loading frequency (Hz)	Applied strain (μm/m)	Applied stress (psi)	
|E*|	14, 40, 70, 100, 130	25, 10, 5, 1, 0.5, 0.1	75-120	Varies	AASHTO TP 62 (AASHTO, 2009)
FN	130	1	-	30	AASHTO TP 79 (AASHTO, 2010c)
Creep compliance	-4, 14, 32	-	-	Varies	AASHTO T 322 (AASHTO, 2008)
Indirect tensile strength	14	-	12.5mm/min	-	AASHTO T 322 (AASHTO, 2008)
APA rut	120	-	-	120	VTM 110 (VDOT 2007)
Four-point beam fatigue	68	10	300-1000	-	AASHTO T 321 (AASHTO, 2007b)
Binder extraction	-	-	-	-	AASHTO T 164 (AASHTO, 2010b)
Binder recovery	-	-	-	-	AASHTO T 170 (AASHTO, 2000)
Binder grading	-	-	-	-	AASHTO M 320 (AASHTO, 2010a)

|E*| Tests Using Standard AASHTO Protocols

|E*| tests were performed with the IPC Global (IPC) 100-UTM universal testing machine in accordance with AASHTO TP 62 (AASHTO, 2007a). Tests were performed on 150 mm tall by 100 mm diameter specimens as previously mentioned. Five testing temperatures ranging from 14°F to 130°F were used.

Six testing frequencies ranging from 0.1 Hz to 25 Hz as shown in Table 4 were used. To ensure against damage to the test samples, the tests were conducted starting from the coldest temperatures to the warmest temperatures. In addition, at each test temperature, the tests were performed starting from the highest to the lowest frequency. Each sample was conditioned at the testing temperature for a minimum period of 3 hr before the |E*| test was started.

Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75 to 125 microstrain. This was done to ensure that testing was conducted in the linear viscoelastic range of asphalt concrete, a necessary requirement for a valid |E*| test. All tests were conducted in the uniaxial mode without confinement in line with current standard AASHTO specifications. It should be noted, however, that previous studies (e.g., Sotil et al., 2007) have shown that when tested without confinement, certain gap- and open-graded mixtures such as SMA mixtures may have lower |E*| values than dense-graded mixtures. SMA mixtures may, therefore, show lower rutting resistance when modeled in the current MEPDG software, contrary to the observed superior rutting resistance of SMAs (Michael et al., 2003) in the field. Future studies should therefore include confinement to characterize SMA rutting better in the MEPDG when such procedures become standardized.

Stress versus strain values were captured continuously and used to calculate |E*|. |E*| was computed automatically using IPC |E*| software (Test Version 2.14). Results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

|E*| Master Curves

|E*| master curves were constructed in accordance with AASHTO PP 62 (AASHTO, 2009). There are several reasons for constructing |E*| master curves for asphalt mixtures. First, a master curve of |E*| provides the ability to predict |E*| at temperatures and/or frequencies that would be difficult or impossible to determine in the laboratory because of equipment limitations or time constraints. Second, a master curve relates to the ability to model pavements across all possible pavement climatic and loading conditions. The |E*| master curve is one of the key inputs required for mechanistic-empirical pavement design and evaluation. Third, a master curve is useful for ranking mixture performance in terms of fatigue and rutting resistance. For instance, for most mixtures, a higher |E*| is often associated with higher rutting resistance.

|E*| Tests Using Abbreviated Testing Temperatures

As previously noted, determination of |E*| in accordance with AASHTO TP 62 requires testing two or three replicate asphalt concrete specimens at five temperatures (14°F, 40°F, 70°F, 100°F, and 130°F) and six loading frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). Given that a substantial amount of time is required for conditioning mixtures for |E*| testing at the specified temperatures, reducing the testing time required for |E*| has been the focus of several studies (Bonaquist, 2008; Bonaquist and Christensen, 2005; Dougan et al., 2003). One focus of this study was, therefore, to evaluate time-saving procedures for conducting the |E*| tests for routine use.

Two such procedures were evaluated: (1) the Hirsch model (Bonaquist and Christensen 2005), and (2) the ABBREV model (Apeagyei et al., 2011a). Both require only three (40°F, 70°F, 100°F) instead of the five standard temperatures required for |E*| to develop a complete |E*| master curve for input into the MEPDG software. There are differences in the methods used by the two approaches to estimate |E*| at the lowest and highest temperatures. The Hirsch model uses two mixture volumetric properties (voids in mineral aggregate [VMA] and voids filled with asphalt [VFA]) and binder stiffness to estimate the limiting maximum modulus of asphalt concrete. The ABBREV model uses |E*| data at 40°F and 100° to estimate the corresponding |E*| values at 14°F and 130°F, respectively. Thus mixture volumetric properties and binder stiffness data are not required using the ABBREV model as shown in Eqs. 1 and 2.

$$|E^*|_{-10C} = -5987.2344 + 1.00539*|E^*|_{4C} + 6537.1562*\log f + 3.3966*\frac{|E^*|_{4C,25} - |E^*|_{4C,0.1}}{1+e^{\log f}}$$ (Eq. 1)

($R^2 = 0.81$)

where

$|E^*|_{-10C}$ = |E*| at -10°C at a given frequency, MPa

$|E^*|_{4C}$ = |E*| at 4°C at same frequency as $|E^*|_{-10C}$, MPa

f = testing frequency, Hz

$|E^*|_{4C,\ 25}$ = |E*| at 4°C and frequency of 25 Hz, MPa

$|E^*|_{4C,\ 0.1}$ = |E*| at 4°C and frequency of 0.1 Hz, MPa.

$$|E^*|_{54C} = 242.0873 + 0.2334*|E^*|_{38C} - 22.6443*\log f - 25.0850*\sqrt{(25-f)}$$ (Eq. 2)

($R^2 = 0.97$)

where

$|E^*|_{54C}$ = |E*| at 54°C at a given frequency, MPa

$|E^*|_{38C}$ = |E*| at 38°C at same frequency as $|E^*|_{54C}$, MPa

f = testing frequency, Hz.

FN Tests

The FN test is designed to characterize rutting resistance of asphalt mixtures as recommended in NCHRP Project 9-19 (Witczak et al., 2002). For this study, FN tests were performed in accordance with AASHTO TP 79 (AASHTO, 2010) and the NCHRP Project 9-19 recommendations. Tests were performed on 100 mm diameter by 150 mm tall specimens that had previously been used for the |E*| tests. The test involves subjecting a specimen of asphalt concrete to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test is conducted at a temperature that represents the expected pavement temperature at the site and layer of the pavement section. In this study, the FN test was conducted at 130°F, which represents the 50% reliability maximum high pavement temperature in the southeastern portion of the United States, based on LTPPBind software. Each sample was, therefore, conditioned at 130°C for a minimum period of 3 hr before the FN test was started. As discussed previously, an IPC UTM-100 was used for the FN tests. The FN tests were performed in the unconfined mode using a deviator stress of 30 psi. The tests were continued to 10,000 cycles or a permanent strain of 5%, whichever came first.

FN was computed automatically by the IPC software (Test Version 1.42) by fitting the accumulated strain (ε_p) versus number of loading cycles (N) to the Francken model shown in Eq. 3. Three stages, i.e., primary, secondary, and tertiary, are typically identified from the plots of ε_p versus N (Witczak, 2007). The primary stage is characterized by a decrease in the strain rate with time. The secondary stage is typified by a relatively constant strain rate. The tertiary stage begins when the strain rate begins to increase. At the tertiary stage, the specimen undergoes significant deformation with individual aggregates within the aggregate skeleton moving past each other (Kanitpong and Bahia, 2005). *FN* is defined as the cycle number at the initiation of tertiary flow (Witczak, 2007). Therefore, mathematically, FN is equivalent to the cycle number at which the strain rate (Eq. 4) is at a minimum. For each mixture, FN results were computed individually for each replicate tested.

It should be noted that the current rutting distress model (such as Eq. 5) used in the MEPDG software is based on earlier repeated load permanent deformation tests (Ayres and Witczak, 1998; Leahy, 1989) that are similar to the current FN tests. The FN test is, therefore, a key component of the MEPDG distress predictions.

$$\varepsilon_p(N) = AN^B + C\left(e^{DN} - 1\right) \qquad \text{(Eq. 3)}$$

$$\frac{\partial^2 \varepsilon_p}{\partial N^2} = A * B * (B-1) * N^{B-2} + C * D^2 * e^{DN} \qquad \text{(Eq. 4)}$$

where

ε_p = permanent strain from the FN test
N = number of loading cycles
A, B, C, and D = regression constants
$\frac{\partial^2 \varepsilon_p}{\partial N^2}$ = second derivative of permanent strain versus N.

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z * 10^{-3.35412} * T^{1.5606} N^{0.4791} \qquad \text{(Eq. 5)}$$

where

ε_p = accumulated plastic strain at N repetitions of load, in/in
ε_r = resilient strain of the asphalt material as a function of mixture properties, temperature, and time rate of loading, in/in
T = temperature, °F
N = number of load repetitions
k_z = function of total asphalt layers thickness and depth to computational point, to correct for the confining pressure at different depths.

Creep Compliance Tests

Creep compliance testing was performed in accordance with AASHTO T 322 (AASHTO, 2008). The test was conducted using the IPC UTM-100 with a servo-hydraulic loading frame capable of providing a constant load of up to 25 kN. Tests were conducted using three replicates of each mixture type at three temperatures (-4°F, 14°F, and 32°F) using disk-shaped specimens measuring 150 mm in diameter by 50 mm in thickness. Because of a lack of materials, only eight mixtures were tested. Each sample was conditioned at the testing temperature for a minimum period of 3 hr before the creep compliance test was started. Creep loads in the range of 3 kN to 10 kN were used to ensure that horizontal strains were kept in the viscoelastic range (about 500 microstrain) throughout the test and also that the horizontal tensile strain during the first 30 sec of the test was within 40 and 120 microstrain (Buttlar and Roque, 1994). A seating load of about 0.1 kN was used during each test.

All creep compliance tests were conducted for a period of up to 1,000 sec. To avoid damage to the test specimens, the tests were conducted starting from the coldest temperature, followed by the next warmer temperature. The tests at the relatively warm temperature of 32°F were always conducted last.

The test was remotely controlled using the IPC software (Test Version 1.11), and load and deformation data were sampled and stored automatically by the testing software. Creep compliance for each mixture was then estimated using standard procedures (AASHTO T 322 [AASHTO, 2008]); Buttlar and Roque, 1994). Creep compliance master curves were constructed for the mixtures so that the m-value, a key thermal cracking parameter, could be determined.

A catalog of creep compliance test results was developed for input into the MEPDG. Creep compliance master curves using the power law model were developed to generate thermal cracking parameters. Creep compliance master curves were constructed in a fashion similar to that for |E*| master curves using the time-temperature superposition principle.

Indirect Tensile Strength Tests

The indirect tensile strength tests were performed with the IPC UTM-100 in accordance with AASHTO T 322 (AASHTO, 2008) on the same specimens previously used for creep compliance testing. This was possible because the creep compliance test is not considered a destructive test and AASHTO T 322 requires that the creep compliance and indirect tensile strength tests be conducted on the same specimen. The setup for the tensile strength test was the same as for the creep compliance test. The major difference between the tests are that the indirect tensile strength test is a destructive test requiring a loading rate of 12.5 mm/min (0.5 in/min) and a 100-kN load cell. To obtain this loading rate, a ramp load of amplitude 4.167 mm at a 20-sec duration was used. Thus, test data consisting of load and deformation were captured for a maximum period of 20 sec during each test. All tensile strength tests were performed at a single temperature of 14°F as specified in AASHTO T 322. Each sample was conditioned at the testing temperature for a minimum period of 3 hr before the tensile strength test was conducted.

At least three replicates of each mixture were tested. Tensile strength (σ) for each specimen was calculated using Eq. 6. Because of a lack of materials, only 11 of the 18 mixtures were tested.

$$\sigma = \frac{2 * P_{f,n}}{\pi * b_n * D_n} \qquad \text{(Eq. 6)}$$

where

σ = indirect tensile strength of specimen, psi
$P_{f,n}$ = maximum load observed for specimen, lb
b_n = thickness of specimen, in
D_n = diameter of specimen, in.

APA Rut Tests

The PTI APA was used to conduct the rut tests in accordance with Virginia Test Method 110 (VDOT, 2007). Three replicate beams 75 mm thick by 125 mm wide by 300 mm long were tested in the APA at a test temperature of 49°C (120°F). All three beams were tested simultaneously. A vertical load of 120 lbf was applied through a rubber hose filled with compressed air at a pressure of 120 psi. The loading wheel speed was 2 ft/sec, and a total of about 135 min was required to complete 8,000 cycles of load applications. Total deformation after 8,000 cycles of load applications which is considered the total rut depth, was measured manually with a specially designed ruler. The reported test result is the average rut depth for the three replicate beams of each mixture type tested simultaneously.

Beam Fatigue Tests

Four-point flexural beam fatigue tests were performed in accordance with AASHTO T321 (AASHTO, 2007b) using three replicate specimens at three strain levels (total of nine beams) for each mixture type. IPC beam fatigue test equipment was used. All tests were conducted at a single temperature of 68°F. The tests were conducted in the strain-controlled mode. Applied tensile strain levels ranging from 300 to 800 microstrain were used so that fatigue curves of strain versus number of cycles to failure could be developed. During the test, repeated application of the specified strain was continued until failure occurred in the test specimen. *Specimen failure* was defined as the number of cycles at which beam stiffness degraded to 50% of the initial flexural stiffness.

Two model forms were used to analyze the fatigue results. The first involved the traditional k-n fatigue model shown in Eq. 7 that relates fatigue life, N_f, to applied strain (ε). This model is the most commonly used for characterizing asphalt mixtures, and an extensive database already exists for some Virginia mixtures (Flintsch et al., 2007). Inclusion of the k-n model would enable comparisons between mixtures tested in this study and mixtures tested in earlier studies.

The second model form involved a model similar to those implemented in the MEPDG that takes into account both the applied strain and mixture stiffness, as shown in Eq. 8. Eq. 8 could be considered an improvement on Eq. 7 as it considers not only mixture stiffness but also certain mixture properties such as air voids and effective binder content (P_{be}). With the selection of an appropriate shift factor (relating laboratory performance to field performance), Eq. 8 could be used directly in the MEPDG software for Virginia mixtures.

The regression model in Eq. 7 was used to estimate the fatigue endurance limit for each mixture. *Endurance limit* is defined as the strain level, at a given temperature, below which no fatigue damage occurs in an asphalt concrete pavement (Prowell et al., 2010). Theoretically, a pavement designed to carry strain levels similar to the endurance limit of its mixtures should have an indefinite fatigue life. In practice, the strain level to achieve an N_f of 50 million cycles in the laboratory fatigue test is considered the endurance limit of a mixture.

$$N_f = k\left(\frac{1}{\varepsilon}\right)^n \quad \text{or} \quad \log N_f = \log k + n \log \varepsilon \qquad \text{(Eq. 7)}$$

where

N_f = cycles to failure
k = constant
n = constant
ε = tensile strain, microstrain.

$$N_f = k_1\left(\frac{1}{\varepsilon}\right)^{k_2}\left(\frac{1}{E}\right)^{k_3} \qquad \text{(Eq. 8)}$$

where

N_f = cycles to failure
k_1 = constant
k_2 = constant
k_3 = constant
ε = tensile strain, microstrain
E = stiffness of mixture.

Binder Extraction and Recovery Tests

Asphalt binder extraction (AASHTO T 164, Method A) (AASHTO, 2010b) and Abson recovery (AASHTO T 170) (AASHTO, 2000) were conducted on samples of the loose mixtures to separate the asphalt binder from the aggregate so that an estimate of binder content and aggregate gradation could be made. This was important because most of the mixtures contained up to 25% RAP. Both Abson recovery tests and ignition oven tests were performed on separate samples of each mixture. For the extraction and recovery (ER) tests, a normal propyl bromide solvent (Lenium) was used. The ER tests yielded binder samples for determining the rheological properties of the binders (AASHTO M 320) (AASHTO, 2010a), and the ignition oven tests enabled the binder content to be confirmed. These tests enabled the actual binder PG grade and the binder stiffness in each mixture to be determined accurately and enabled the effects of RAP to be evaluated.

A TA Instruments AR 2000ex dynamic shear rheometer (DSR) was used to measure the rheological response of the recovered binders at multiple temperatures using a 10 rad/sec loading rate to provide the dynamic shear modulus (G*) and phase angle (δ) data required for Level 1 and Level 2 asphalt inputs in the MEPDG. The DSR tests were conducted in accordance with AASHTO M 320 (AASHTO, 2010a).

RESULTS AND DISCUSSION

|E*| Tests

MEPDG |E*| Inputs

As previously stated, |E*| is one of the key design inputs for the MEPDG software. The |E*| test results were compiled and presented in a form matching the MEPDG input format for use by VDOT pavement designers. For pavements in Virginia, |E*| may be one of the most important MEPDG design input parameters as it could be used to predict some pavement distresses common in Virginia such as fatigue cracking and rutting.

Table 5 shows sample |E*| data formatted as MEPDG inputs at five testing temperatures and six loading frequencies. This measured |E*| is described as the MEPDG Level 1 input data. Results of Level 1 inputs for all 18 mixtures evaluated in this study are presented in Appendix B. Each |E*| data point reported represents the average of at least three replicate specimens for each mixture. The variability in |E*| data was estimated using the coefficient of variation (COV). For the mixtures considered in this study, the COV averaged about 11.0% and ranged from 0.5% to 32.2%. This range of COV values compares favorably with those from previous studies. For instance, Flintsch et al. (2007) reported a COV range of 0.9% to 32.3% for 11 Virginia mixtures.

Electronic copies of the |E*| data created as .DWN files for direct input into the MEPDG software are available from the authors upon request. This is expected to expedite the design procedure by reducing the amount of data entry involved with the |E*| input data.

Table 5. Sample |E*| in MEPDG Format for Mixture 08-1055D

	Mixture |E*| (psi)					
Temperature (°F)	**0.1 Hz**	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	1990691	2290870	2420244	2696686	2816149	2959543
40	1245825	1580766	1730928	2054169	2195049	2372188
70	431294	612252	725043	983066	1112439	1290642
100	136621	198557	244872	377968	454838	559169
130	50280	65804	83044	139198	166842	217847

Binder Complex Shear Modulus and Phase Angle

For the required Level 1 and 2 asphalt binder inputs, the binder data in terms of complex shear modulus measured with a DSR at multiple temperatures are required. As previously stated, extracted and recovered binders were tested since most of the mixtures contained RAP and so that the effect of RAP binder on the mixture could be adequately reflected.

The use of ER methods for obtaining binder could be a major problem in the future since ER procedures are known to affect properties of recovered binders, and some ER procedures involve hazardous materials. In addition, ER methods could be time prohibitive. Further studies might be required regarding ER procedures, especially since RAP is in the majority of VDOT asphalt mixtures. Finally, it is unclear if binder recovered from mixtures containing RAP actually represents the as-produced binder in the mixture, as there is still debate as to how the RAP binder interacts with virgin binder in a mixture. Microscopic studies may be required to answer this question.

Table 6 shows sample binder properties required for Level 1 and 2 inputs. Appendix B shows the complete catalog of binder data for the mixtures tested. Similar to the |E*| data, electronic copies of the binder stiffness data created as .BIF files for direct input into the MEPDG software are available from the authors upon request.

Table 6. Sample Binder Inputs in MEPDG Format for Mixture 08-1055D

	Angular Frequency = 10 rad/sec	
Temperature (°F)	**G* (Pa)**	**Delta (degree)**
147	6883	80.8
158	2324	84.3
169	1127	86.0

|E*| Master Curve Construction

From Appendix B it can be seen that |E*| is very sensitive to both temperature and frequency (or time) of loading. As expected, |E*| decreased as testing temperature increased from 14°F to 130°F. It can also be noticed that at each testing temperature, |E*| increased with increasing loading frequency from 0.1 to 25 Hz, which was to be expected. The effects of temperature and loading frequency (or time of loading) on the asphalt mixtures tested are typical of viscoelastic materials and are best illustrated by constructing |E*| master curves.

Construction of |E*| master curves is based on time-temperature superposition principles, which suppose that for viscoelastic materials tested in the linear range, time of loading and temperature of loading are interchangeable. That is to say, |E*| obtained at short loading times, for instance, could be equivalent to that obtained at colder temperatures. Conversely, |E*| at longer loading times are considered equivalent to those obtained at higher testing temperatures.

To construct the master curve, a standard reference temperature is selected (70°F with the MEPDG) and then data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. Eqs. 9, 9a, and 10 comprise the model used to describe |E*| master curves in the MEPDG. As can be seen, both the mixture |E*| and binder complex modulus data are required for constructing MEPDG master curves. Figure 1 shows a sample |E*| master curve constructed using the MEPDG software for Mixture 08-1055D input data. Also shown in Figure 1 are the master curve model parameters and the temperature shift factor parameters, which together completely describe the viscoelastic behavior of the mixtures. It should be noted that the parameter δ in Eq. 9 is not the same as the phase angle, δ, in Equation 10.

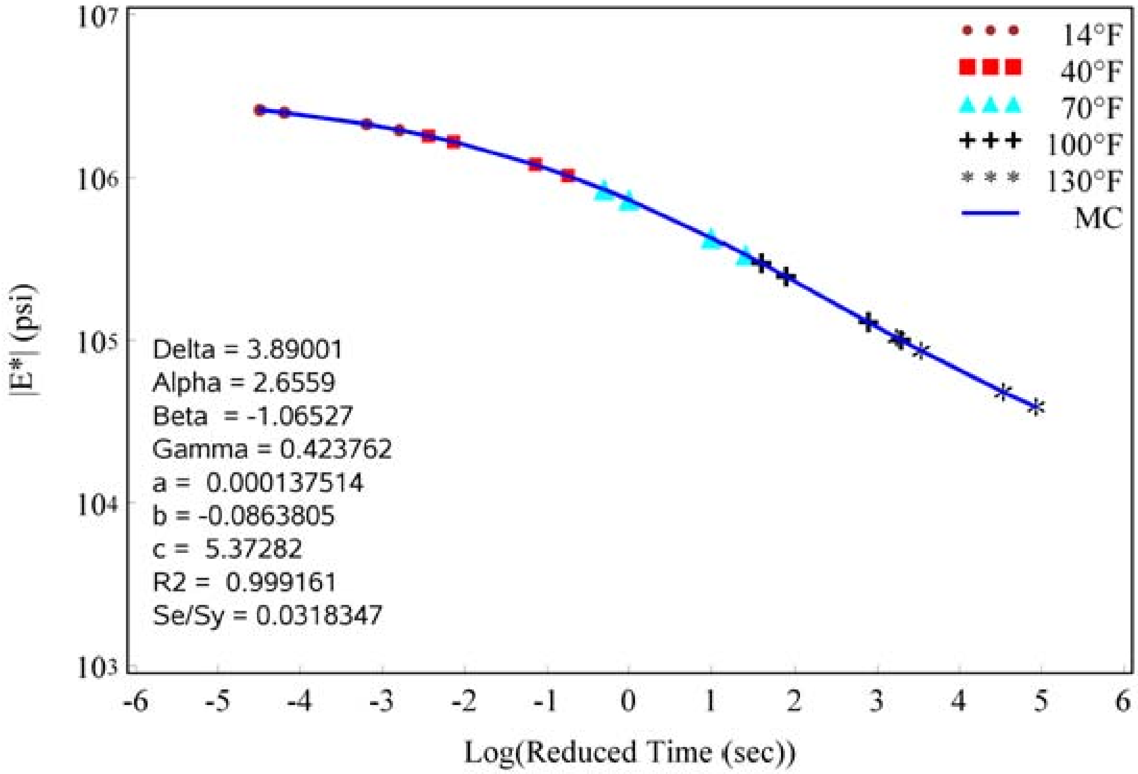

Figure 1. Sample |E*| Master Curve Constructed Using MEPDG Software for Mixture 08-1055D

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma(\log t_r))}} \quad \text{(Eq. 9)}$$

$$\log(t_r) = \log(t) - c\left(\log(\eta) - \log(\eta_{T_r})\right) \quad \text{(Eq. 9a)}$$

where

t_r = loading time at the reference temperature, sec
η = viscosity at temperature of interest, cP
η_{Tr} = viscosity at reference temperature, cP
α, β, δ, γ, c = mixture specific fitting parameters parameter.

$$\eta = \left(\frac{G^*}{10}\right)\left(\frac{1}{\sin\delta}\right) \quad \text{(Eq. 10)}$$

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

where

G^* = binder complex shear modulus, Pa
δ = binder phase angle, º
η = viscosity, cP
T_R = mixture temperature in degrees Rankine (ºR) at which the viscosity was estimated
A, VTS = regression parameters.

|E*| Master Curve Prediction with MEPDG

The foregoing discussion on |E*| master curves illustrates the most accurate procedure for obtaining |E*| for pavement design with the MEPDG. As stated previously, this is called Level 1 input and could be difficult or even impossible to obtain for certain projects. To address this, two empirical approaches with comparatively lower levels of accuracy are provided at Level 2 and Level 3 inputs. Level 3 is considered the least accurate and requires the least amount of information, limited to certain gradation parameters, volumetric properties, and the PG of the binder. As expected, Level 2 is considered more accurate than Level 3, as it also requires complex shear modulus binder data in the same form as required for Level 1 input. Table 7 shows some of the mixture details required for the |E*| empirical prediction models in the MEPDG.

Table 7. MEPDG Volumetric and Gradation Inputs for Asphalt Concrete Mixtures

Mix Designation	Mix ID	V_{be} (%)	VTM (%)	Unit Weight (lb/ft^3)	Cumulative % Retained 3/4 in Sieve	Cumulative % Retained 3/8 in Sieve	Cumulative % Retained No. 4 Sieve	% Passing No. 200 Sieve	VMA	VFA
SM	08-1019D	11.9	6.8	148.64	0.0	2.8	39.5	5.8	18.9	63.7
	08-1036D	11.9	7.0	144.67	0.0	15.8	48.4	5.6	18.8	63.0
	08-1043A	13.0	7.1	149.67	0.0	8.1	41.7	5.8	19.5	64.7
	08-1045D	11.6	7.8	161.43	0.0	8.2	59.5	4.2	18.3	59.7
	08-1047D	11.8	6.9	142.71	0.0	4.7	33.4	6.6	18.5	63.0
	08-1052E	12.5	7.1	144.87	0.0	13.9	38.9	6.8	19.6	63.8
	08-1055D	11.7	7.0	146.13	0.0	15.3	49.8	5.2	18.8	62.5
	09-1001E	11.7	6.8	155.59	0.0	16.8	42.4	4.6	18.6	63.2
BM	08-1044A	10.7	6.9	155.93	8.8	58.0	71.3	4.4	17.6	61.1
	09-1049A	10.3	7.6	151.32	8.2	35.9	60.2	7.0	17.8	57.5
	09-1051D	9.9	7.6	150.95	9.9	41.9	63.0	6.8	17.5	56.5
	09-1053D	10.7	6.0	153.27	10.9	41.9	62.1	6.9	16.7	64.0
	09-1070D	9.7	7.0	144.62	18.0	40.0	53.0	6.4	16.7	58.1
	09-1071D	9.7	7.0	146.22	22.0	44.0	56.0	5.9	16.7	58.1
	09-1072D	10.4	7.0	144.33	24.0	50.0	61.0	5.0	17.4	59.8
SMA	08-1012E	15.3	7.0	154.31	0.0	33.0	73.8	11.3	22.3	68.6
	08-1025E	14.2	7.5	153.42	0.0	37.0	74.4	11.4	21.7	66.8
	08-1046D	14.9	7.8	139.98	0.2	38.3	76.2	5.8	22.7	65.0

SM = surface mixture; V_{be} = volumetric effective binder content (calculated as voids in mineral aggregate minus voids in total mix); VTM = voids in total mix; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; BM = base mixture; SMA = stone-matrix asphalt.

Using the data required for the Level 1, 2, and 3 inputs, |E*| master curves were constructed for Levels 2 and 3 using Mixture 08-1055D as an example. Figure 2 shows how the measured |E*| using Level 1 inputs compares with the predicted |E*| using Level 2 and Level 3 inputs. Also shown in Figure 2 are the |E*| master curve parameters obtained from the MEPDG software at each input level. Differences in the predicted and measured |E*| can be seen. For instance, at a reduced time of zero (equivalent to a 1 Hz testing frequency), the predicted Level 3 |E*| was 2.23 and 1.52 times less than that of Level 2 and Level 1, respectively. For many mixtures tested, most of the differences between measured and predicted |E*| were seen at long loading times or high testing temperatures; for some others, differences were seen at both temperature extremes.

In general, for most of the mixtures studied, differences between the measured Level 1 |E*| master curves and the predicted |E*| master curves at Level 2 and 3 inputs were seen. Figures 3 and 4 show examples of how Level 1 |E*| master curves compared with those for Level 2 and 3, respectively, for eight mixtures. In some cases, differences in predicted |E*| using Level 2 inputs were up to 190% those of Level 1 inputs at high testing temperatures. For other mixtures, the Level 2 |E*| values were under predicted by as much as 85%. Similar, albeit smaller, differences were seen when Level 1 |E*| and Level 3 values were compared (maximum and minimum differences were 70% and -82%, respectively) for the eight mixtures. In Figures 3 and 4, data points plotted above the equality line indicate the predicted values were higher than the measured values. It should be noted that in Figures 3 and 4, even though logarithmic scales were used in the plots because |E*| decreases by orders of magnitude as the temperature increases from the coldest to the warmest, the differences between measured |E*| and predicted |E*| at a given temperature/frequency is still significant in terms of asphalt mixture performance.

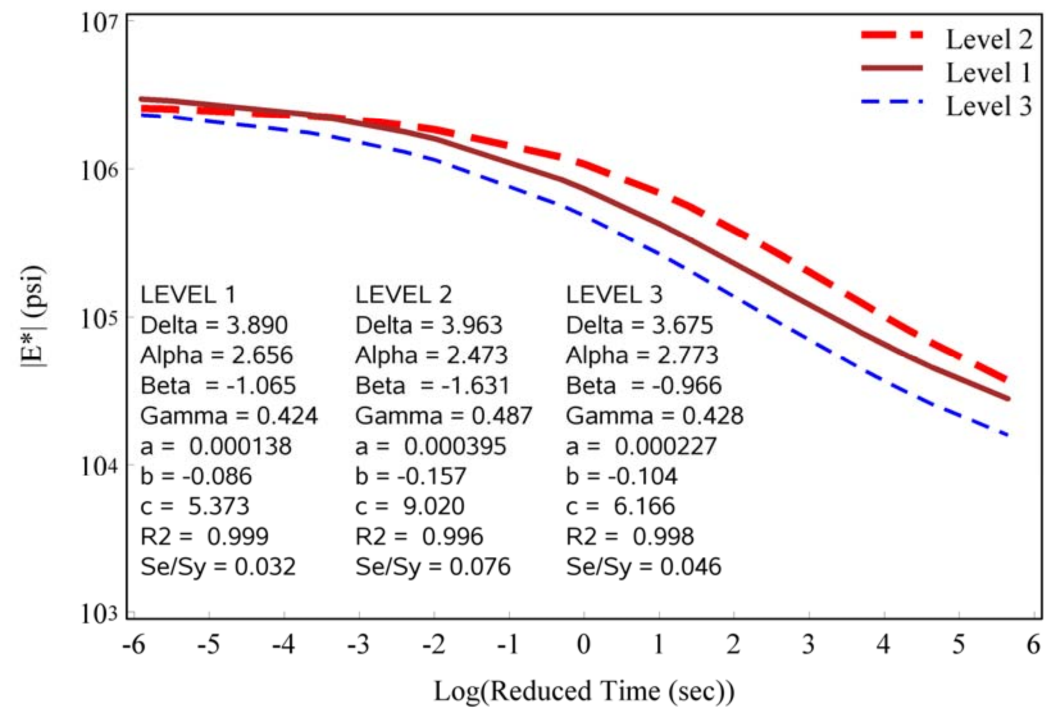

Figure 2. Comparison of Measured |E*| (Level 1) with Predicted |E*| at Level 2 and 3 for Mixture 08-1055D. ***Middle:*** **|E*| from Level 1 inputs;** ***top:*** **|E*| from Level 2 inputs;** ***bottom:*** **|E*| from Level 3 inputs.**

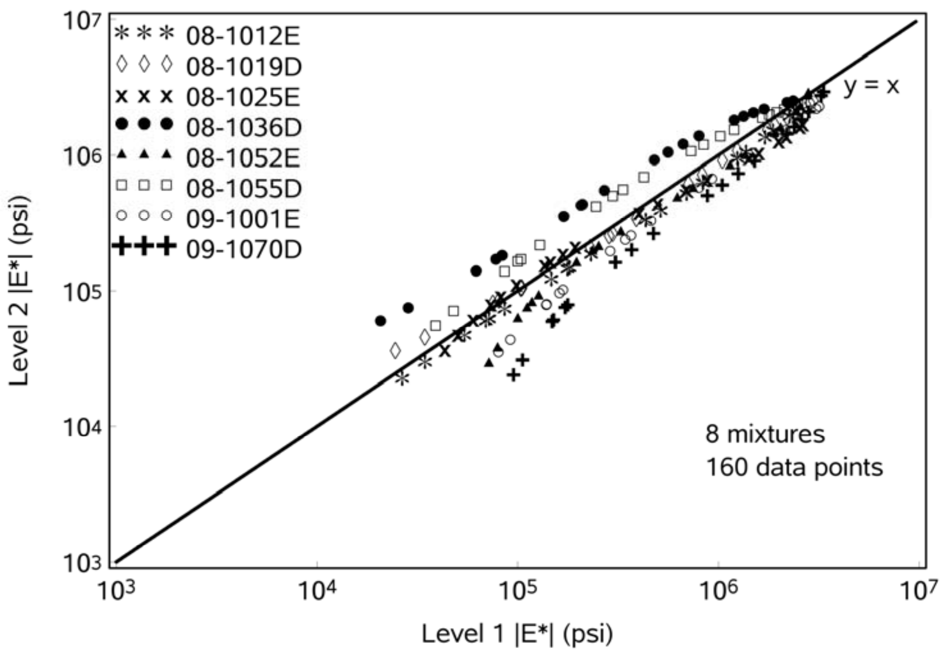

Figure 3. Comparison of Level 1 and Level 2 |E*| Master Curves for Eight Selected Mixtures

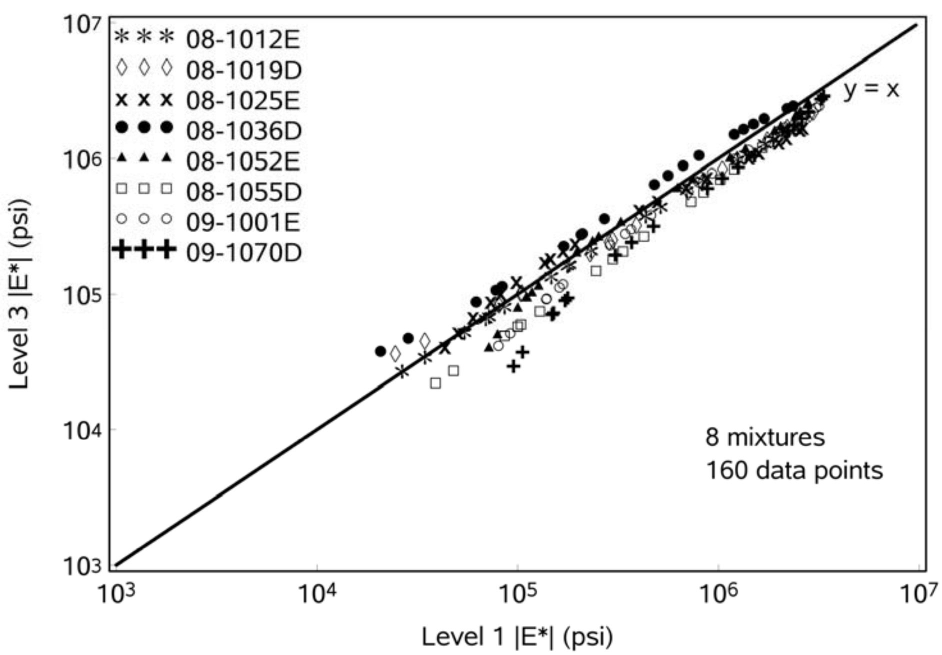

Figure 4. Comparison of Level 1 and Level 3 |E*| Master Curves for Eight Selected Mixtures

There appears to be no consistent way of determining, prior to testing, if a mixture |E*| master curve will be over-predicted or under-predicted using the Level 2 or Level 3 inputs. Similar observations (shown in Appendix C) concerning measured |E*| and predicted |E*| could be made based on data from previous studies (e.g., Flintsch et al., 2007; Diefenderfer, 2010) concerning measured |E*| and Level 2 and Level 3 predicted |E*|. These differences in measured versus predicted |E*| and their effects on predicted performance need to be studied further. Such a study should ideally be conducted using locally calibrated MEPDG distress models so that the effect of |E*| can be accurately quantified.

Comparison of |E*| Master Curves

As previously noted, |E*| master curves offer a means to rank mixtures in terms of their expected performance. For instance, in Figure 5, |E*| master curves for the six mixtures are compared. In most cases, it is generally assumed that mixtures with higher |E*| at long loading times (equivalent to high temperatures) would be more resistant to rutting than mixtures with lower |E*|. It is also generally assumed that mixtures with low |E*| at intermediate temperatures tend to be more resistant to fatigue cracking. Even though the preceding is a gross generalization and therefore may not be true for all mixtures, |E*| master curves are a powerful tool for ranking asphalt concrete performance and could help pavement designers using the database developed in this study to make some educated guesses with regard to what input values to use. In the future, as the performance data for pavement sections that incorporated the mixtures tested in this study become available, it is anticipated that pavement designers would be more informed about the choice of input parameters to use for new paving projects.

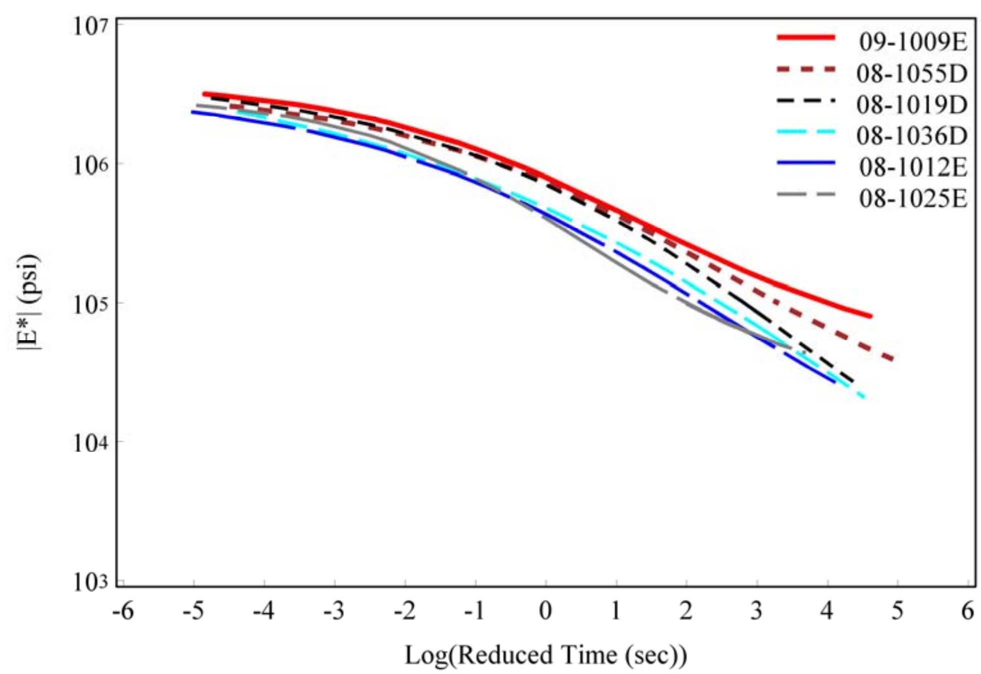

Figure 5. Comparison of Measured |E*| (Level 1) for Six Different Surface Mixtures. Notice the large differences among the mixtures.

|E*| Master Curves Using Abbreviated Testing Temperatures

Figure 6 shows plots of predicted |E*| using the ABBREV models of Eq. 1 and Eq. 2 for eight selected mixtures. It can be seen from the plots that on average, the ABBREV model predictions differed by about 15% and 4% at 130°F and 14°F, respectively. The plots also show that the ABBREV models' predictions were quite good, with R^2 values 0.82 and 0.87 at 130°F and 14°F, respectively. The results suggest the ABBREV models developed in this study could be used to predict |E*| at the lowest and highest testing temperatures with reasonable accuracy.

Figure 7 compares |E*| master curves for four mixtures using the two abbreviated testing temperatures methods (ABBREV and Hirsch) based on the three temperatures (40°F, 70°F, 100°F) compared with the standard AASHTO TP 62 procedures based on the five standard temperatures. It can be seen from the figure that that the abbreviated methods' predictions were quite good. Thus |E*| master curves of asphalt mixtures obtained using the standard five testing temperatures could be obtained by testing at only three temperatures (40°F, 70°F, 100°F) and using the prediction models to estimate |E*| at the warmest and coldest temperatures. Therefore, abbreviated testing temperatures approaches should be considered for developing |E*| master curves in Virginia. Substantial reduction in testing time could be achieved if the approach is adopted for routine use.

FN Tests

Figure 8 shows typical ε_p-N results obtained from two mixtures during the FN tests. The mixtures are VDOT Type D mixtures designed for similar traffic levels of 3 to 10 million equivalent single-axle loads. The two mixtures differ only in the type of binder used, the amount of RAP, mixture gradation, and volumetric properties. Similar plots were made for each mixture tested, and FN was determined automatically using the Francken model, as previously discussed.

Table 8 shows FN test results and information on the RAP content, rutting parameter G*/sinδ, and binder grade of each mixture. Each mean FN value in Table 8 represents the average of at least three replicate specimens of each mixture tested. Also shown in Table 8 is the variability in FN test results represented by the COV, which ranged from 1.9% to 38.2% and averaged about 16.4%. These levels of variability are comparable to those reported by other investigators (Mohammad et al., 2006).

The results show that the FN test is a very sensitive test capable of showing differences in performance even among different mixtures of the same type. For the mixtures considered, FN ranged from about 700 cycles to about 7,500 cycles. Statistical analyses using Tukey's least significant difference method showed significant differences between the mixtures in terms of FN as shown in Table 8 where the FNs for mixtures with the same letters are not significantly different. Several factors account for the significant differences in FN among the mixtures. Results of statistical analysis using the stepwise regression method (Eq. 11) showed that binder stiffness was the most significant factor affecting FN for the mixtures tested. The results showed binder stiffness accounted for over 70% ($R^2 = 0.73$, $p < 0.001$) of the variance in FN, with mixture volumetrics (P_{be}, VFA, dust to effective binder ratio [DB]), and mixture gradation (percent passing sieve sizes 25 mm, 19 mm, 0.075 mm) accounting for the rest.

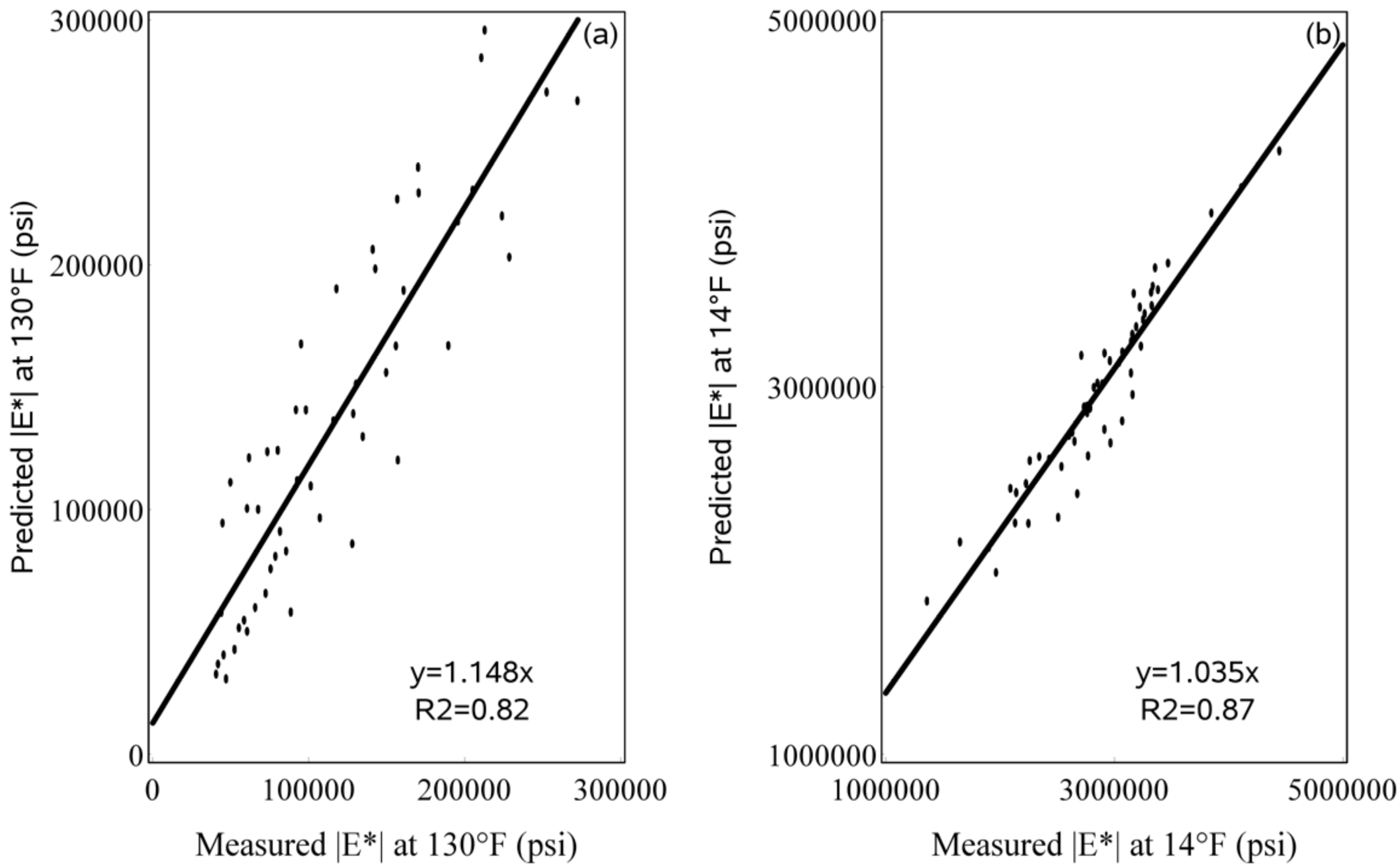

Figure 6. Comparison of Measured |E*| with Predicted |E*| Using ABBREV Models for 8 Different Asphalt Mixtures

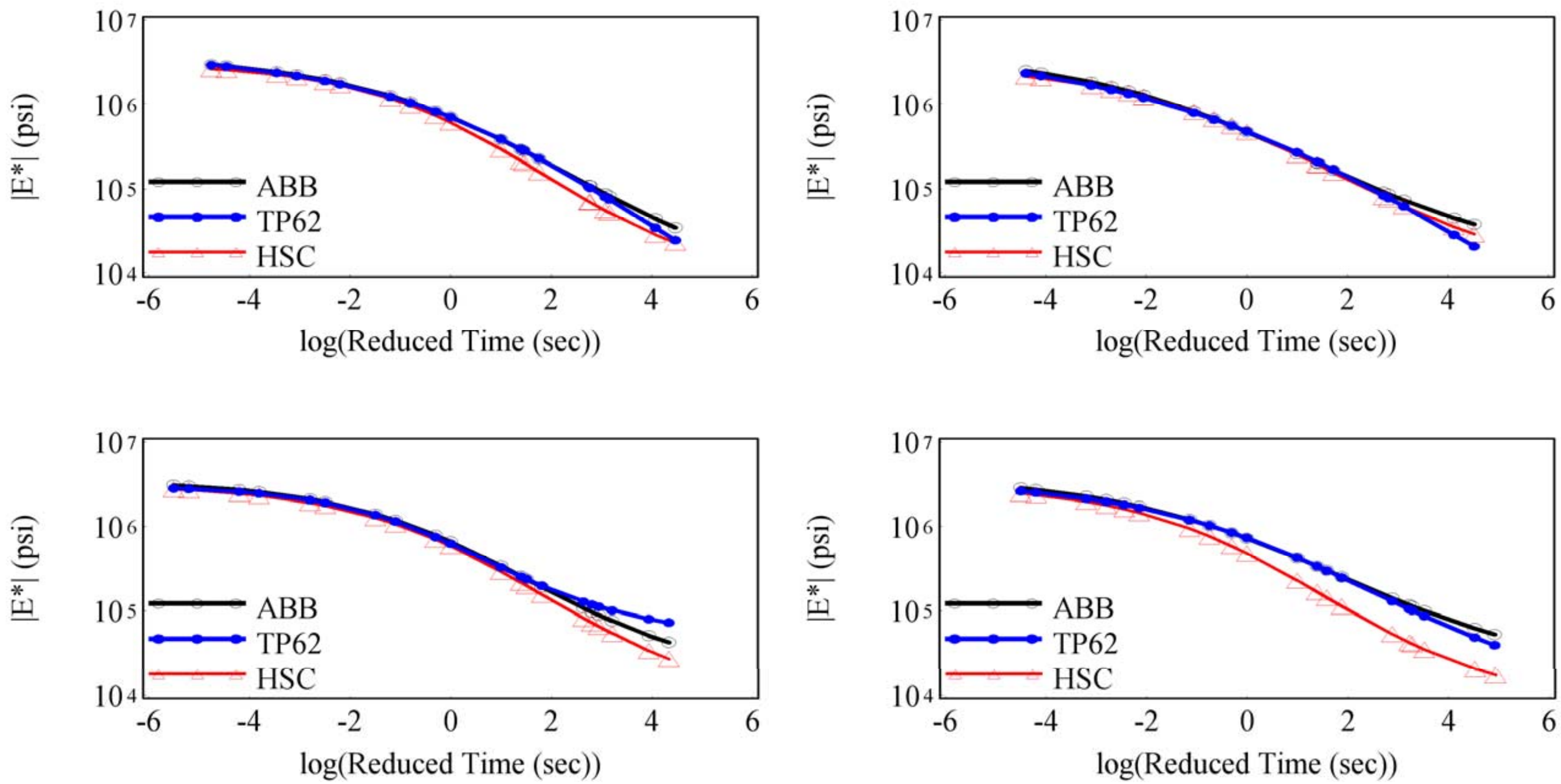

Figure 7. Comparison of ABBREV-Based Master Curve (ABB) with AASHTO TP 62 (TP62) and Hirsch (HSC) Model for Four Selected Mixtures

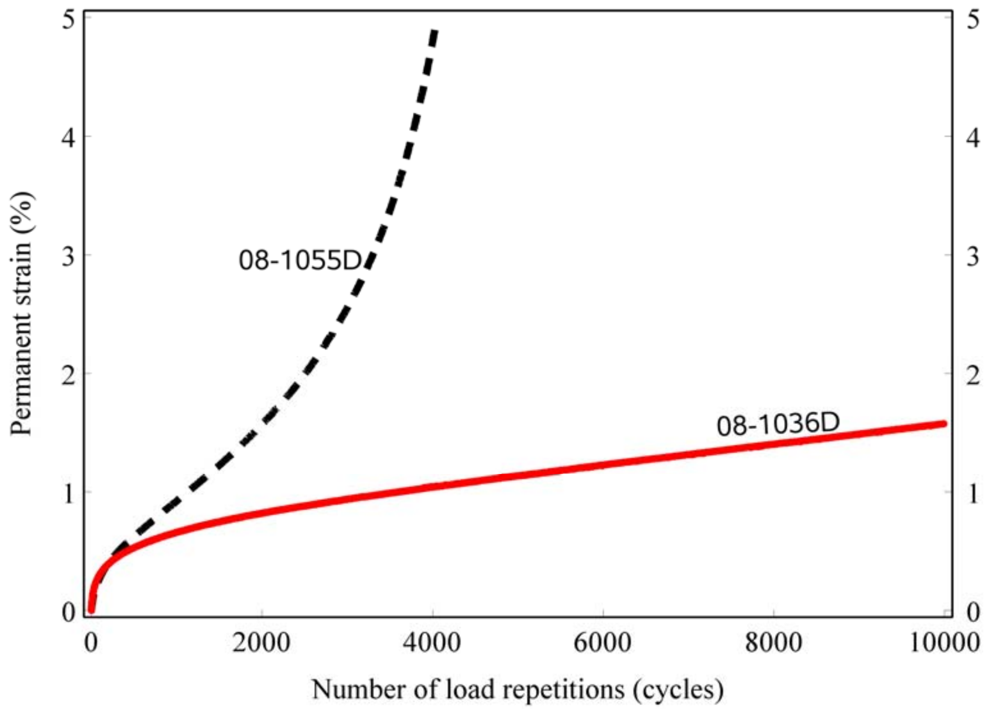

Figure 8. Typical ε_p-N Results: Two asphalt mixtures with different rutting resistance.

Table 8. FN of Asphalt Mixtures at 130ºF and 30 psi Deviator Stress

Mix Designation	Mix ID	FN (cycles) Mean	FN (cycles) COV (%)	RAP Amount (%)	G*/sinδ at 70°C (kPa)	Binder Grade[a]	Tukey Grouping[b]				
SM	08-1019D	3373	13.2	15	4.441	76-22			C	D	
	08-1043A	702	23.6	0	-	-					E
	08-1045D	4385	10.5	20	-	-		B	C		
	08-1047D	7438	25.5	10	-	-	A				
	08-1036D	6910	1.9	10	8.498	76-22	A				
	08-1052E	5753	24.6	12	6.362	76-22	A	B			
	08-1055D	1133	4.6	25	2.324	70-22					
	09-1001E	7514	30.6	15	8.410	82-22	A				
BM	08-1044A	2623	38.2	20	-	-			C	D	E
	09-1049A	1624	7.9	15	2.546	70-22				D	E
	09-1051D	6454	4.1	15	4.113	70-22	A	B			
	09-1053D	6781	9.8	15	4.113	70-22	A				
	09-1070D	1465	20.0	25	1.737	64-22				D	E
	09-1071D	1164	12.5	25	1.637	64-22				D	E
	09-1072D	779	23.7	25	1.796	64-22					E
SMA	08-1012E	2810	6.0	0	3.811	70-22			C	D	E
	08-1025E	4330	26.8	10	5.690	76-22		B	C		
	08-1046D	1631	27.0	0	-	-				D	E

Mix ID = mixture identification (last letter denotes specified binder grade); COV = coefficient of variation; RAP = recycled asphalt pavement; SM = surface mixture; BM = base mixture; SMA = stone- matrix asphalt; - = no data available.

[a] Obtained from recovered binder.

[b] The FNs for mixtures with the same letters are not significantly different.

$$FN = 4698.1734 P_{be} + 423.6569 VFA + 924.1876 G^*/\sin\delta - 1001.435 P_{25} + 148.0361 P_{19} - 4395.186 P_{200} + 24751 DB + 31393;$$

$R^2 = 0.94$ (Eq. 11)

where

FN = FN at 54°C, cycles
P_{be} = effective binder content (%)
VFA = voids in mineral aggregate (%)
$G^*/\sin\delta$ = rutting parameter at 70°C, kPa
P_{25} = passing 25 mm sieve (%)
P_{19} = passing 19 mm sieve (%)
P_{200} = passing 0.075 mm sieve (%)
DB = P_{200} to P_{be} ratio.

Regarding Eq. 11, regression analysis showed that binder stiffness was the most dominant factor affecting FN. Binder stiffness accounted for about 65% of the variation in FN for the mixtures. Thus, statistical analysis of the results of extracted binder tests (indicated by the rutting parameter G*/sinδ in Table 8) suggests the significant differences in FN found in this study were due mainly to differences in binder stiffness. For instance, comparing Mixtures 08-1036D and 08-1055D, it could be noticed that the stiffness of the former is almost 4 times greater than that of the latter at the testing temperature of 70°C, which clearly agrees with the FN results of 6910 and 1133 cycles, respectively, for Mixtures 08-1036D and 08-1055D. For the other mixtures, it appears that the FN test results are in good agreement with the extracted binder DSR G*/sinδ test results. It should be noted that DSR G*/sinδ testing is a Superpave (and VDOT's) specification requirements for controlling rutting in asphalt mixtures.

RAP amount also appeared to influence FN for the mixtures tested. However, the effect was unexpected in some of the mixtures. For instance, it can be noted in Table 8 that mixtures with the three lowest FNs, Mixtures 08-1043A, 08-1055D, and 09-1072D, contained either 0% RAP or 25% RAP. This was unexpected, as it is generally assumed that adding RAP to a mixture should increase its rutting resistance. Several reasons could account for these unexpected findings where mixtures containing 25% RAP appear to have an FN similar to those of certain VDOT Type A mixtures without RAP. One likely reason could be the fact that Mixture 08-1034A, being a VDOT Type A mixture, was fabricated with a PG 64-22 asphalt binder whereas Mixtures 08-1055D and 09-1072D even though designed as Type D mixtures, by virtue of the addition of 25% RAP, were also fabricated with PG 64-22 binders as permitted under current VDOT specifications. Thus, in this limited case, the effect of the stiffness of the base PG 64-22 binder appears to be more influential than the amount of RAP used. The results suggest that adding 25% RAP to certain PG 64-22 binders might not always lead to the expected stiffness increase or a grade bump. Additional studies are required to investigate whether allowing more than 25% RAP to VDOT mixtures may be warranted as the limited results in this study suggest that the expected stiffness increases with added RAP might not always be achieved. Mixtures 08-1055D, 09-1070D, 09-1071D, and 09-1072D are examples of mixtures that contained 25% RAP and a PG 64-22 binder but had stiffness at 70°C that barely graded (in the case of Mixture 08-1055D) or even failed to grade as the expected PG 70-22 binder.

Additional detailed discussion of other possible factors considered in this study that impacted the rutting resistance of the mixtures is provided elsewhere (Apeagyei, 2011; Apeagyei and Diefenderfer, 2011; Apeagyei et al., 2011b) and quantified in Eq. 12. These factors include air voids or VTM, percent aggregate passing the 0.6 mm sieve, percent aggregate passing the 0.075 mm sieve, and mixture stiffness obtained as the |E*| at 38°C and 0.1 Hz.

$$FN = -25.70RAP^2 + 592.21RAP + K \; ; \; R^2 = 0.77 \qquad \text{(Eq. 12)}$$

where

RAP = RAP amount, %
$K = -891.21VTM + 91.05P_{30} + 277.83P_{200} + 2.03|E^*| + 3512.34$
VTM = voids in total mix, %
P_{30} = % passing No. 30 or 0.600 mm sieve, %
P_{200} = % passing No. 200 or 0.075 mm sieve, %
|E*| = dynamic modulus at 38°C, 0.1 Hz, MPa.

The preceding discussion suggests that FN appears to be a sensitive test for evaluating mixture rutting performance in the laboratory. The FN test appears to be particularly sensitive to mixture volumetrics, binder stiffness, mixture stiffness, aggregate gradation, and RAP amount for the mixtures considered in this study.

Since there are currently no standard VDOT specifications for rutting based on FN, the observed sensitivity of FN to RAP amount would need to be verified in additional studies involving field measurements. Such studies would confirm whether the lower FN for certain mixtures in this study correlated to field rutting. Such studies might also answer the question of whether the observed effect of RAP amount on FN was limited to the mixtures tested in this study.

Further studies on using the FN for evaluating the rutting resistance of Virginia mixtures, especially those containing RAP, are also recommended. Such a study should consider the potential of using the FN test for evaluating RAP mixtures without binder extraction and recovery tests, as is currently done by VDOT.

Creep Compliance Tests

Table 9 shows a catalog of the creep compliance test results for five SM and three SMA mixtures. The results are provided for three testing temperatures and presented in a format for direct input into the MEPDG software at input Level 1 (-4°F, 14°F, and 32°F) and input Level 2 (14°F).

Table 9. Creep Compliance Test Results (1/psi) at Three Temperatures

Time (sec)	Mixture ID							
	08-1019D	08-1036D	08-1052E	08-1055D	09-1001E	08-1012E	08-1025E	08-1046D
Test Temperature, -4°F								

1	1.586E-07	1.655E-07	1.517E-07	1.172E-07	1.379E-07	2.275E-07	2.413E-07	2.206E-07
2	3.172E-07	3.309E-07	2.482E-07	2.344E-07	2.482E-07	3.861E-07	2.758E-07	3.723E-07
5	3.654E-07	3.999E-07	3.103E-07	2.689E-07	2.482E-07	3.861E-07	3.516E-07	3.723E-07
10	3.654E-07	3.999E-07	2.758E-07	2.965E-07	2.758E-07	3.861E-07	3.516E-07	5.240E-07
20	4.206E-07	3.999E-07	2.758E-07	3.516E-07	3.034E-07	3.861E-07	4.137E-07	4.826E-07
50	4.206E-07	4.688E-07	3.999E-07	3.516E-07	3.309E-07	4.619E-07	4.551E-07	5.585E-07
100	4.206E-07	5.654E-07	4.895E-07	4.413E-07	3.861E-07	6.136E-07	5.585E-07	6.688E-07
Test Temperature, 14°F								
1	1.172E-07	2.758E-07	2.551E-07	1.172E-07	1.586E-07	2.344E-07	3.034E-07	4.068E-07
2	2.758E-07	4.137E-07	3.516E-07	3.585E-07	2.344E-07	3.930E-07	4.137E-07	6.136E-07
5	3.034E-07	4.137E-07	4.551E-07	4.206E-07	3.930E-07	4.688E-07	6.136E-07	8.136E-07
10	3.034E-07	6.205E-07	5.033E-07	4.206E-07	3.930E-07	6.274E-07	6.136E-07	9.170E-07
20	3.378E-07	6.205E-07	5.033E-07	5.309E-07	4.757E-07	6.274E-07	6.205E-07	1.020E-06
50	4.275E-07	7.653E-07	7.102E-07	5.929E-07	5.516E-07	7.860E-07	8.274E-07	1.227E-06
100	4.895E-07	9.722E-07	7.584E-07	8.343E-07	5.516E-07	1.096E-06	1.034E-06	1.531E-06
Test Temperature, 32°F								
1	3.447E-07	6.274E-07	4.206E-07	1.862E-07	2.896E-07	4.826E-07	4.275E-07	1.999E-07
2	6.067E-07	4.688E-07	6.343E-07	5.585E-07	3.585E-07	8.687E-07	7.722E-07	1.069E-06
5	6.895E-07	7.860E-07	6.343E-07	8.136E-07	5.102E-07	1.069E-06	1.034E-06	1.296E-06
10	6.895E-07	9.446E-07	8.412E-07	8.136E-07	6.481E-07	1.262E-06	1.207E-06	1.717E-06
20	8.067E-07	1.413E-06	1.055E-06	8.756E-07	8.687E-07	1.648E-06	1.462E-06	2.144E-06
50	1.158E-06	1.572E-06	1.158E-06	1.186E-06	9.377E-07	2.337E-06	2.062E-06	2.985E-06
100	1.282E-06	2.048E-06	1.793E-06	1.496E-06	1.158E-06	2.930E-06	2.579E-06	3.833E-06

As expected, creep compliance of the mixtures increased with increasing temperature from -4°F to 32°F. Similarly, at each testing temperature, the creep compliance of each mixture increased with time, which is also to be expected. It should be noted that the higher the creep compliance of a mixture, the greater its resistance to thermal cracking. This suggests the three SMA mixtures (Mixtures 08-1012E, 08-1025E, and 08-1046D) with a higher creep compliance would be expected to be more resistant to thermal cracking than the SM mixtures. Another observation was that the three SMA mixtures also had comparatively higher binder contents and higher volumetric properties (VMA and VFA), which may account for the observed relatively high creep compliance values. Therefore, binder type, binder content, and mixture volumetrics all appear to influence creep compliance in the mixtures tested.

Creep Compliance Master Curve

As previously noted, creep compliance master curve parameters are useful inputs for computing thermal cracking in the MEPDG. Table 10 shows the creep compliance master curve parameters, including the m-value, D_0, and D_1, that are useful in conducting low-temperature cracking analysis. A graphical representation of the creep compliance master curve is also shown in Figure 9, which compares the performance of the eight mixtures tested. The large differences in creep compliance can be clearly seen. The plot may be useful for ranking mixtures in terms of low-temperature cracking susceptibility. In Figure 9, the SMA mixtures showed the highest creep compliance master curves, which are consistent with the previous observations on the individual creep compliance data at different temperatures. This is to be expected, since SMA

Table 10. Creep Compliance Master Curve Parameters

Parameter	Mixture ID							
	08-1019D	**08-1036D**	**08-1052E**	**08-1055D**	**09-1001E**	**08-1012E**	**08-1025E**	**08-1046D**
D_0 (1/psi)	1.029E-07	1.093E-07	5.202E-08	1.092E-07	1.256E-07	2.294E-07	1.626E-07	1.655E-07

D_1 (1/psi)	1.116E-07	1.249E-07	1.328E-07	5.700E-08	5.340E-08	4.943E-08	9.121E-08	1.165E-07
m-value	0.3063	0.3036	0.2487	0.4345	0.3870	0.4823	0.3257	0.3294
$1/a_{T1}$	0.6310	5.6230	10.0000	3.9810	3.9810	3.5480	10.0000	19.9530
$1/a_{T2}$	25.1190	50.1190	100.0000	19.9530	25.1190	50.1190	100.0000	63.0960

a_{T1} = shift factor at 14°F; a_{T2} = shift factor at 32°F.

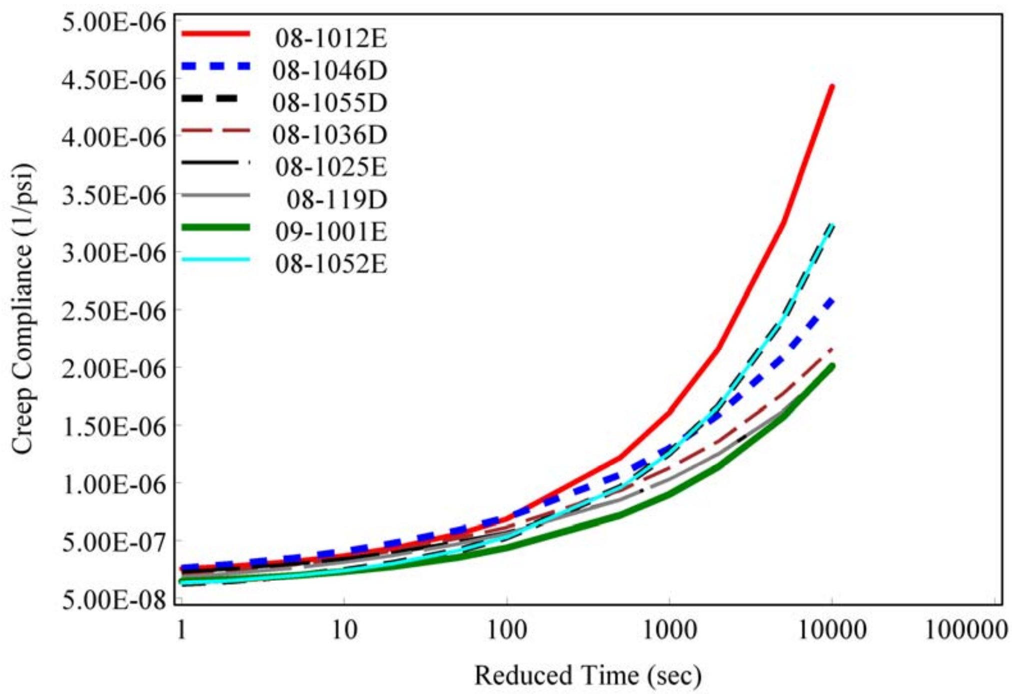

Figure 9. Creep Compliance Master Curves. Dashed lines = stone-matrix asphalt mixtures, solid lines = surface mixtures.

Mixtures 08-1012E and 08-1025E contain the same polymer-modified asphalt. It is interesting to note the effect of RAP on creep compliance and the m-value for Mixtures 08-1012E and 08-1025E, which were similar except that the latter contains 10% added RAP. This suggests that Mixture 08-1012E, under a given thermal loading, would crack at a relatively colder temperature than Mixture 08-1025E because of the added RAP.

Indirect Tensile Strength Tests

In addition to creep compliance, indirect tensile strength is a required input in the MEPDG software for estimating thermal cracking. Table 11 lists the results of the indirect tensile strength tests performed at 14°F. Each data point represents the average of at least three specimens tested. The catalog of mean tensile strengths shown in Table 11 is all that is required for MEPDG input Levels 1, 2, and 3. The data are also provided in Appendix B, which contains the complete catalogue of MEPDG inputs for all mixtures tested.

Table 11. Indirect Tensile Strength at 14°F

Specimen ID	Tensile Strength (psi)	
	Mean	COV (%)
08-1012E	462	8.5

08-1019D	688	2.7
08-1025E	523	7.2
08-1036D	513	5.2
08-1044A	452	20.0
08-1045D	593	18.8
08-1046D	359	3.1
08-1047D	600	2.9
08-1052E	507	26.5
08-1055D	515	12.2
09-1001E	573	19.2

Tensile strength, as with other asphalt material properties, could also be used to evaluate mixtures and rank them in terms of expected performance. Therefore, it was important during this study to identify key factors that might affect the tensile strength of asphalt mixtures tested. To investigate some of these factors, a statistical analysis was performed using Tukey's least significance difference method; the results are shown in Table 12. The results indicate that for majority of the mixtures (8 of the 11 mixtures tested), the differences in tensile strength among the mixtures was not statistically significant. Compared with the FN test, the indirect tensile strength test appears to be less sensitive to binder stiffness, mixture stiffness, mixture volumetrics, and gradation. This lack of sensitivity has been reported in previous studies (Al-Khateeb, 2001; Apeagyei, 2006; Wagoner et al., 2005).

Table 12. Statistical Analysis of Indirect Tensile Strength Results

Tukey Grouping[a]			Mean (psi)	N	Mix ID
	A		688	3	081019D
B	A		600	3	081047D
B	A		593	3	081045D
B	A		573	6	091001E
B	A	C	523	6	081025E
B		C	515	6	081055D
B		C	513	6	081036D
B		C	507	3	081052E
B		C	462	6	081012E
B		C	452	4	081044A
		C	359	3	081046D

[a]Means with the same letter are not significantly different; minimum significant difference = 169 psi; N = number of specimens tested. Mix ID = Mixture Identification.

APA Rut Test Results

Table 13 shows the APA rut test results. Each data point represents the average rut depth after 8,000 cycles of loading of three beams tested simultaneously. The manual method of rut depth measurement was used (Virginia Test Method 110 [VDOT, 2007]). Statistical analysis showed little differences between the mixtures in terms of measured rut depth even though binder grades, for instance, varied from PG 64-22 to PG 76-22, as was indicated in Table 8. The effect of binder type, binder stiffness, mixture stiffness, gradation, and mixture volumetric properties was not as apparent as was seen with the FN test.

Table 13. APA Rut Test Results[a]

Mix ID	Rut Depth (mm)				
	Left	Middle	Right	Mean	COV (%)
08-1012E	1.59	1.61	1.68	1.63	2.9

08-1019D	1.39	0.96	1.14	1.16	18.6
08-1025E	2.13	1.57	1.55	1.75	18.8
08-1036D	1.24	1.53	1.30	1.36	11.3
08-1043A	1.47	1.82	1.58	1.62	10.9
08-1047D	1.28	1.28	1.16	1.24	5.7
08-1052E	1.27	1.32	1.26	1.28	2.4
08-1055D	1.24	1.43	1.40	1.36	7.3
09-1001E	1.11	1.17	1.14	1.14	2.5
09-1049A	1.67	0.83	0.62	1.04	53.4
09-1051D	1.41	0.89	0.51	0.94	48.2
09-1053D	0.71	0.71	0.91	0.78	14.9
09-1070D	1.16	1.11	0.87	1.05	14.8
09-1071D	1.12	1.49	1.34	1.32	14.1
09-1072D	1.27	1.74	1.75	1.59	17.3

Left = left beam; Middle = middle beam; Right = right beam; COV = coefficient of variation.
[a]Test temperature = 120°F; loading level = 120 psi; No. of cycles = 8,000.

With regard to VDOT's APA rut specification criteria (Table 14), the APA results obtained in this study suggest all mixtures performed similarly in terms of rutting. One possible reason for the apparent lack of sensitivity of the APA test might be the testing conditions used; a single testing temperature of 120°F is specified in Virginia whereas some states use testing temperatures corresponding to the high temperature binder grade. If this assertion is true, it would suggest the APA rut testing conditions as currently used (120°F, 120 psi) might need to be investigated further in future studies. Such studies should include the use of the FN test, which appeared in this study to be more sensitive (in terms of binder stiffness ($G^*/\sin\delta$), mixture stiffness ($|E^*|$), mixture volumetrics, and mixture gradation) than the APA test (see Figure 10). In addition, with the adoption of the MEPDG, it may be necessary to develop a VDOT FN rutting criterion similar to that used for the APA rut test.

Table 14. VDOT's APA Rut Criteria (VDOT, 2007)

Mixture Type	Maximum Rut Depth (mm)
SM-1	8.5
SM-2A/12.5A/9.5A	7.0
SM-2D/12.5D/9.5D	5.5
SM-2E/12.5E	3.5
SMA	4.0

SM = surface mixture; SMA = stone-matrix asphalt.

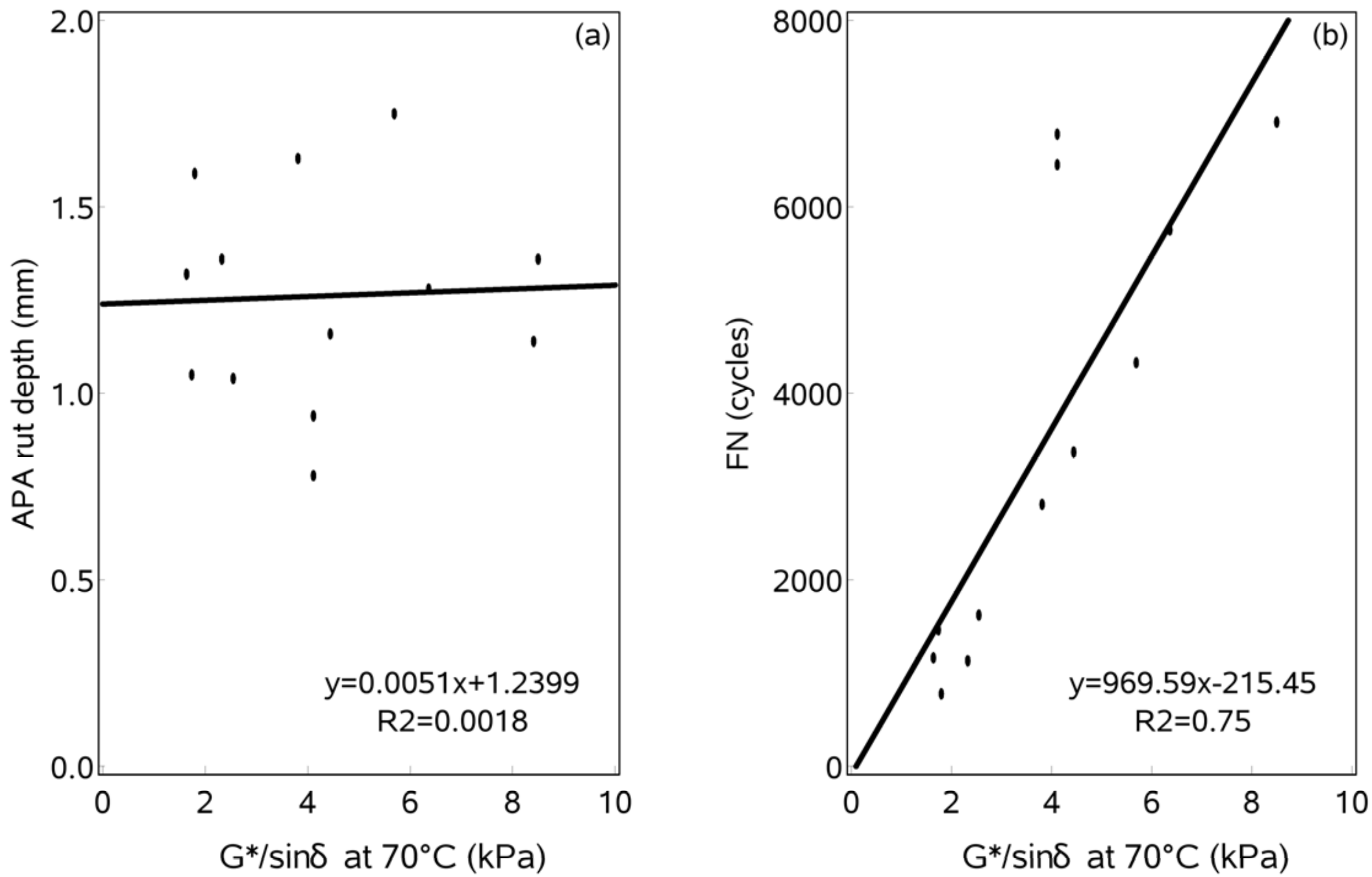

Figure 10. Relationship Between G*/sinδ and Rutting. APA rut depth appears to be insensitive to binder stiffness. Note that G*/sinδ data were obtained from recovered binders.

Four-point Beam Fatigue Test Results

Fatigue Regression Models

The fatigue data in terms of number of cycles to failure (N_f) and applied strain levels were used to estimate the fatigue curve parameters shown in Tables 15 and 16. The results in Table 15 were used to generate fatigue curves relating number of load cycles N_f to applied strain. The fatigue curve parameters in Table 15 were used to generate strain versus N_f curves that could be used to rank mixtures in terms of their susceptibility to fatigue cracking.

Figure 11 shows the fatigue curves of the mixtures using the traditional k-n fatigue models. Some differences in fatigue performances can be seen. Four of the top-performing mixtures in terms of fatigue resistance contain polymer-modified asphalt. It is interesting to note the effect of RAP on these mixtures. For instance, Mixture 08-1012E with the highest fatigue life at any of the strain levels considered contained no RAP. Compared with Mixture 08-1025E, which was identical to Mixture 08-1012E except for the 10% RAP, the differences in fatigue

Table 15. Beam Fatigue Test Results Using the Traditional k-n Model

Mix ID	VTM	V_{be}	n	k	R^2
08-1019D	7.1	7.1	-4.94788	18.22850	0.98
08-1036D	6.7	6.7	-5.38570	19.81540	0.98
08-1052E	7.2	12.5	-5.16776	19.56686	0.99
08-1055D	6.9	11.7	-5.91987	21.08523	0.98
09-1001E	6.6	11.7	-5.40460	19.74800	0.98
08-1043A	7.3	13.0	-5.36071	19.76532	0.99
08-1047D	6.7	11.8	-4.99183	18.32898	0.98
08-1012E	6.7	6.7	-5.57947	20.88280	0.93
08-1025E	7.2	7.2	-6.18818	22.18055	0.98
08-1046D	9.2	14.9	-4.48789	17.04615	0.97

VTM = voids in total mix.

Table 16. Fatigue Model Parameters Using the k_1-k_2-k_3 MEPDG Approach

Mix ID	VTM	V_{be}	C	k_1	k_2	k_3	R^2
08-1019D	7.1	7.1	220.09	0.1690	5.1842	2.2851	0.98
08-1036D	6.7	6.7	253.47	0.0002	5.8733	2.1822	0.98
08-1052E	7.2	12.5	237.27	0.2497	5.6963	2.5306	0.99
08-1055D	6.9	11.7	229.94	0.9718	6.4752	3.1099	0.98
09-1001E	6.6	11.7	252.13	0.2159	6.1037	2.7878	0.97
08-1043A	7.3	13.0	281.25	0.0000	5.1327	1.3969	0.97
08-1047D	6.7	11.8	252.87	0.1082	5.3283	2.3487	0.98
08-1012E	6.7	6.7	474.97	0.0583	6.8152	3.1209	0.93
08-1025E	7.2	7.2	334.39	0.0583	6.8152	3.1209	0.99
08-1046D	9.2	14.9	200.97	0.0000058	5.60031	1.8280	0.96

VTM = voids in total mix.

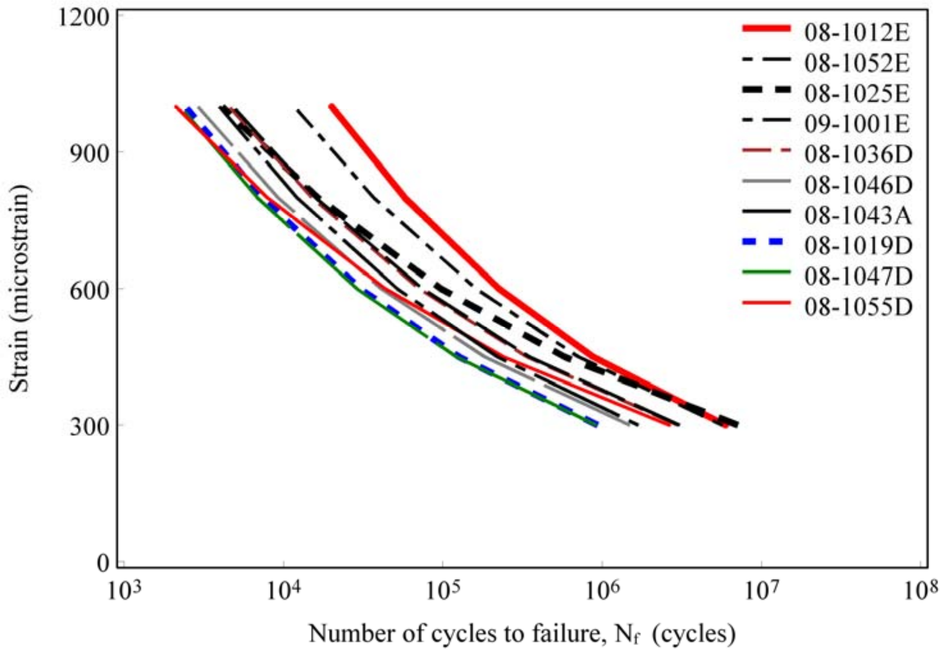

Figure 11. Fatigues Curves for Virginia Mixtures. Four of the top-performing mixtures in terms of fatigue resistance contained polymer-modified asphalt binders.

resistance between these two mixtures appeared to be quite large. The mixture with the highest susceptibility to strain levels appeared to be Mixture 08-1055D that contained 25% RAP and PG 64-22 binder. The effect of RAP seen in this limited study may need to be investigated further in future studies.

Fatigue Endurance Limit

Table 17 shows the endurance limit for the mixtures tested in increasing order of magnitude. Endurance limits for the mixtures ranged from 126 to 232 microstrain. Prowell et al. (2010) reported an endurance limit range of 70 to 200 microstrain for asphalt concrete mixtures. Therefore, the fatigue test results obtained in this study appear to be in agreement with those of previous studies. Overall, mixtures with the three largest endurance limits also contained polymer-modified binders, which suggests the endurance limit may be sensitive to binder type.

Table 17. Fatigue Endurance Limit

Mix ID	Endurance Limit
08-1046D	126
08-1019D	137
08-1047D	139
09-1001E	174
08-1043A	179
08-1036D	181
08-1055D	185
08-1052E	200
08-1025E	221
08-1012E	232

Implementation of Design Inputs in MEPDG: Illustrative Design Example

To illustrate how the design input catalog developed in this study (see Appendix B) could be used in the MEPDG software (Version 1.1), an example involving the design of a hypothetical section of I-81 in Staunton, Virginia, was analyzed. Even though MEPDG software (Version 1.1) was used, it is expected that the approach would be similar with future versions of the MEPDG software. Details of the design approach, including a discussion of the results, are presented in Appendix D.

CONCLUSIONS

- *A catalog of MEPDG design input parameters was developed for 18 asphalt concrete mixtures sampled from seven of the nine VDOT districts and is included in Appendix B. Included in the catalog were binder stiffness, mixture |E*|, mixture gradation, and mixture volumetric properties. These properties should enable a designer the flexibility to select the desired input level (1, 2, or 3) depending on the project type for pavement design in Virginia.*

- *|E*| master curves of asphalt mixtures obtained using the five standard testing temperatures (i.e., 14°F, 40°F, 70°F, 100°F, 130°F) specified in AASHTO TP 62 can be obtained by testing at only three temperatures (i.e., 40°F, 70°F, 100°F) and using the prediction models to estimate |E*| at the warmest and coldest temperatures.* A substantial reduction in testing time by the elimination of time spent conditioning mixtures for testing could be achieved if the approach were adopted for routine use. In addition, the need to buy expensive conditioning chambers required for low-temperature testing could be minimized or eliminated.

- *The FN test is a very sensitive test for evaluating the rutting susceptibility of asphalt mixtures in the laboratory*. It appears to be particularly sensitive to binder stiffness, mixture stiffness, mixture volumetrics, aggregate gradation, and RAP amount for the mixtures considered in this study. The effect of RAP on FN was unexpected for the high-RAP mixtures as these mixtures showed comparatively lower rutting resistance.

- *Compared to the FN test, the APA rut test appears to be less sensitive to mixture properties such as binder grade, binder stiffness, mixture stiffness, mixture volumetrics, mixture gradation, and RAP amount.* Results from the APA rut test showed no significant differences among the majority of the mixtures tested.

- *The fatigue resistance of the mixtures tested is sensitive to binder type, binder content, and RAP content, as expected.* Four of the top-performing mixtures in terms of fatigue resistance all contained polymer-modified asphalt at comparatively higher binder contents.

- *Both creep compliance and indirect tensile strength appear to be sensitive to the temperature, binder type, and binder content of the mixtures tested.*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider the catalog of input data for typical Virginia mixtures developed in this study (see Appendix B) for pavement design in Virginia.* The data followed expected trends and compared quite well with those reported in previous studies. The catalog of design inputs developed in this study together with that developed in a previous VCTIR study (Flintsch et al., 2007) should provide enough data to enable the initiation of MEPDG implementation in Virginia to proceed.

2. *VDOT's Materials Division and VCTIR should continue to support routine testing of asphalt mixtures with the aim of expanding the catalog of design inputs for asphalt concrete produced in Virginia.* Even though the 18 mixtures tested in this study and the 11 tested in the previous VCTIR study should be enough for implementation of the MEPDG in Virginia, the catalog should be continually updated and expanded by VCTIR to include additional materials such as SMAs, stabilized bases, warm mixtures, fiber-modified mixtures, etc.

3. *VCTIR, with the support of VDOT's Materials Division, should conduct further studies to evaluate the FN test as a tool in addition to the APA test for evaluating rutting in mixtures.* This is because the APA test, which is currently a VDOT rut specification criterion, was found to be less sensitive in terms of gradation, binder grade, or mixture volumetrics than the FN test. Such future studies should also include field evaluation of the FN test to ensure FN predictions in the laboratory agree with field observations.

4. *VCTIR should conduct additional research to investigate the unexpected effects of RAP on the laboratory-measured rutting found in this study.* Such effects were unexpected in certain mixtures containing PG 64-22 binder with a high amount of RAP (20% or more) since it is generally believed that adding more RAP should result in stiffer and hence more rut-resistant mixtures. FN for these high-RAP mixtures with PG 64-22 was lower than for mixtures with PG 70-22 binder.

5. *VCTIR should compile a stand-alone catalog of the MEPDG design inputs developed in this and previous VCTIR studies.* This catalog should be capable of being updated with new asphalt materials design inputs as they become available.

BENEFITS AND IMPLEMENTATION PROSPECTS

This study developed a catalog of MEPDG design input parameters for pavement design in Virginia (see Appendix B). It is expected that this catalog will enable a designer the flexibility to select the desired MEDPG input level (1, 2, or 3) depending on the pavement type needed by the MEPDG software for pavement design / pavement evaluation in Virginia.

The study directly supports VDOT's MEPDG implementation efforts currently underway to initiate statewide use of the MEPDG in asphalt materials characterization. The results of this study will provide necessary inputs for the MEPDG software; help improve the efficiency of flexible pavement designs in Virginia; and enable more accurate predictions of maintenance and rehabilitation needs over the life of a pavement.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of Troy Deeds, Donnie Dodds, and Aaron Dupont for materials testing and Linda Evans for editorial support (all of VCTIR) and Todd Rorrer for binder extraction and recovery testing (VDOT Materials Division). Trenton Clark (Virginia Asphalt Association, formerly of VDOT's Materials Division); Mohamed Elfino and Affan Habib (VDOT Materials Division); Brian Diefenderfer and Kevin McGhee (VCTIR); and Lorenzo Casanova (FHWA) served as the technical review panel for this study. The panel's helpful discussion and comments are very much appreciated.

REFERENCES

Al-Khateeb, G.G. Development of a Hollow-Cylinder Tensile Tester to Obtain Fundamental Mechanical Properties of Asphalt Paving Mixtures. Doctoral Dissertation. University of Illinois, Urbana, 2001.

American Association of State Highway and Transportation Officials. AASHTO T 170, Standard Method of Test for Recovery of Asphalt Binder from Solution by Abson Method. Washington, DC, 2000.

American Association of State Highway and Transportation Officials. AASHTO TP 62, Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA). Washington, DC, 2007a.

American Association of State Highway and Transportation Officials. AASHTO T 321, Standard Method of Test for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending. Washington, DC, 2007b.

American Association of State Highway and Transportation Officials. AASHTO T 322, Standard Method of Test for Determining Creep Compliance and Strength of Hot Mix Asphalt (HMA). Washington, DC, 2008.

American Association of State Highway and Transportation Officials. AASHTO PP 62, Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA). Washington, DC, 2009.

American Association of State Highway and Transportation Officials. AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder. Washington, DC, 2010a.

American Association of State Highway and Transportation Officials. AASHTO T 164, Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA). Washington, DC, 2010b.

American Association of State Highway and Transportation Officials. AASHTO TP 79, Standard Method of Test for Determining Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). Washington, DC, 2010c.

Apeagyei, A.K. Development of Antioxidant Treatments for Asphalt Binders and Mixtures. Doctoral dissertation. University of Illinois, Urbana, 2006.

Apeagyei, A.K. Rutting as a Function of Dynamic Modulus and Gradation. *Journal of Materials in Civil Engineering,* Vol. 23, No. 9, 2001, pp. 1302-1310.

Apeagyei, A.K., and Diefenderfer, B.K. Asphalt Concrete Rutting Resistance Assessment by the Flow Number Test. In *Proceedings of the First T&DI Congress 2011: Integrated Transportation and Development for a Better Tomorrow,* Chicago, 2011, pp. 406-417.

Apeagyei, A.K., Diefenderfer, B.K., and Diefenderfer, S.D. Development of Dynamic Modulus Master Curves for Hot-mix Asphalt with Abbreviated Testing Temperatures. *International Journal of Pavement Engineering.* In press, 2011a. http://www.tandfonline.com/doi/full/10.1080/10298436.2011.566612. Accessed September 26, 2011.

Apeagyei, A.K., Diefenderfer, B.K., and Diefenderfer, S.D. Rutting Resistance of Asphalt Concrete Mixtures Containing Recycled Asphalt Pavement. In *Transportation Research Record: Journal of the Transportation Research Board.* Transportation Research Board of the National Academies, Washington, DC. In press, 2011b.

ARA, Inc., ERES Consultants Division. *Guide for the Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures.* NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, DC, 2004.

Ayres, M., and Witczak, M.W. AYMA: Mechanistic Probabilistic System to Evaluate Flexible Pavement Performance. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1629. Transportation Research Board of the National Academies, Washington, DC, 1998, pp. 137-148.

Bonaquist, R. *Refining the Simple Performance Tester for Use in Routine Practice.* NCHRP Report 614. Transportation Research Board of the National Academies, Washington, DC, 2008.

Bonaquist, R., and Christensen, D.W. Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design. In *Transportation Research Record:*

Journal of the Transportation Research Board, No. 1929. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 208–217.

Diefenderfer, S.D. *Analysis of the Mechanistic-Empirical Pavement Design Guide Performance Predictions: Influence of Asphalt Material Input Properties.* VTRC 11-R3. Virginia Transportation Research Council, Charlottesville, 2010.

Dougan, C., Stephens, J.E., Mahoney, J., and Hansen, G. *E*-Dynamic Modulus: Test Protocol: Problems and Solutions.* CT-SPR-0003084-F03-3. Connecticut Department of Transportation, Newington, 2003.

Buttlar, W.G., and Roque, R. Development and Evaluation of the New SHRP Measurement and Analysis System for Indirect Tensile Testing of Asphalt Mixtures at Low Temperatures. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1454. Transportation Research Board of the National Academies, Washington, DC, 1994, pp. 163-171.

Flintsch, G.W., Loulizi, A., Diefenderfer, S.D., Galal, K.A., and Diefenderfer, B. *Asphalt Materials Characterization in Support of Implementation of the Proposed Mechanistic-Empirical Pavement Design Guide.* VTRC 07-CR10. Virginia Transportation Research Council, Charlottesville, 2007.

Kanitpong, K., and Bahia, H. Relating Adhesion and Cohesion of Asphalts to the Effect of Moisture on Laboratory Performance of Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1901. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 33-43.

Kim, Y.R., Seo, Y., King, M., and Momen, M. Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1891. Transportation Research Board of the National Academies, Washington, DC, 2004, pp. 163-173.

Leahy, R.B. *Permanent Deformation Characteristics of Asphalt Concrete.* Doctoral dissertation. University of Maryland, College Park, 1989.

Michael, L., Burke, G., and Schwartz, C.W. Performance of Stone Matrix Asphalt Pavements in Maryland. *Journal of the Association of Asphalt Paving Technologies,* Vol. 72, 2003, pp. 287-314.

Mohammad, L.N., Wu, Z., Obularreddy, S., Cooper, S., and Abadie, C. Permanent Deformation Analysis of Hot-Mix Asphalt Mixtures with Simple Performance Tests and 2002 Mechanistic-Empirical Pavement Design Software. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1970. Transportation Research Board of the National Academies, Washington, DC, 2006, pp. 133-142.

Prowell, B.D., Brown, E.R., Anderson, M.R., Daniel, J.S., Swamy, A.K., Von Quintus, H., Shen, S., Carpenter, S.H., Bhattacharjee, S., and Maghsoodloo, S. *Validating the Fatigue Endurance Limit for Hot Mix Asphalt.* NCHRP Report 646. Transportation Research Board of the National Academies, Washington, DC, 2010.

Sotil A., Kaloush, K.E., and Witczak M.W. Reduced Confined Dynamic Modulus Testing Protocol for Asphalt Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board,* No. 1891. Transportation Research Board of the National Academies, Washington, DC, 2007, pp. 153-162.

Virginia Department of Transportation, Materials Division. *Virginia Test Methods.* Richmond, 2007.

Wagoner, M.P., Buttlar, W.G. Paulino, G.H., and Blankenship, P. Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1929. Transportation Research Board of the National Academies, Washington, DC, 2005, pp. 183-192.

Witczak, M.W. *Specification Criteria for Simple Performance Tests for Rutting.* NCHRP Report 580. Transportation Research Board of the National Academies, Washington, DC, 2007.

Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Quintus, H.V. *Simple Performance Test for SUPERPAVE Mix Design.* NCHRP Report 465. Transportation Research Board of the National Academies, Washington, DC, 2002.

APPENDIX A

GRADATION

Table A1. Gradation

Mix Type	Mix ID	Sieve Size 1 in	3/4 in	1/2 in	3/8 in	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
SM	08-1019D	100	100	99.9	97.2	60.5	40.6	29	19.6	12.1	8.4	5.8
	08-1036D	100	100	96.8	84.2	51.6	33.2	25.4	20.8	13.5	7.9	5.6
	08-1043A	100	100	98.8	91.9	58.3	41.9	30.1	20.4	13	8.7	5.8
	08-1045D	100	100	99.8	91.8	40.5	24.4	18.3	14	9.8	6.4	4.2
	08-1047D	100	100	100	95.3	66.6	47.9	37.8	27.5	16	9.6	6.6
	08-1052E	100	100	96.6	86.1	61.1	37.7	23.1	15.1	10.6	8.2	6.8
	08-1055D	100	100	96.5	84.7	50.2	42.5	35	24.1	12.3	7.7	5.2
	09-1001E	100	100	94.6	83.2	57.6	39.8	29.2	20	11.4	6.9	4.6
BM	08-1044A	99	91.2	56.3	42	28.7	22.9	19	14.6	9.7	6.4	4.4
	09-1049A	98.5	91.8	74.2	64.1	39.8	24.6	16.8	12.9	10.5	8.7	7
	09-1051D	95.8	90.1	68.7	58.1	37	24.5	16.8	12.6	10.1	8.3	6.8
	09-1053D	97.4	89.1	70.1	58.1	37.9	24.9	17	12.9	10.4	8.4	6.9
	09-1070D	97	81.5	66.4	60.1	47.4	35.5	24.9	17.7	12.2	8.7	6.4
	09-1071D	96.1	77.9	62.5	56.2	43.8	32.8	23.4	16.7	11.6	8.1	5.9
	09-1072D	94.9	76.4	58.6	50.1	38.8	28.9	20.3	14.3	9.8	6.8	5
SMA	08-1012E	100	100	89.3	67	26.2	19.6	17.8	16.8	16	14.5	11.3
	08-1025E	100	100	90	63	25.6	19.3	17.4	16	14.8	13.7	11.4
	08-1046D	100	99.8	83.9	61.7	23.8	14.2	11.8	10.2	8.7	7.6	5.8

SM = surface mixture; BM = base mixture; SMA = stone-matrix asphalt.

APPENDIX B

CATALOG OF MEPDG DESIGN INPUTS FOR ASPHALT MIXTURES

Table B1. Mixture ID: 08-1019D

Mixture Type: SM-9.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2448430	2737345	2861110	3134797	3248990	3366857
40	1258637	1591595	1744900	2091975	2243733	2436198
70	403156	584744	701451	982872	1125928	1320085
100	104456	173658	237378	389620	474225	592382
130	36917	54810	80921	151255	189564	230465

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	4369	79.7
168.8	2208	82.0
179.6	1144	84.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.9
Air voids (%)	6.8
Total unit weight (pcf)	148.64

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	2.8
Cumulative % Retained #4 sieve	39.5
% Passing #200 sieve	5.8

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	4369	79.7
168.8	2208	82.0
179.6	1144	84.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.9
Air voids (%)	6.8
Total unit weight (pcf)	148.64

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	2.8
Cumulative % Retained #4 sieve	39.5
% Passing #200 sieve	5.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.9
Air voids (%)	6.8
Total unit weight (pcf)	148.64

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	688	Tensile Strength	688	Tensile Strength	688

Table B2. Mixture ID: 08-1036D

Mixture Type: SM-12.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	1835694	2128138	2260703	2567216	2705630	2891713
40	788473.3	1034651	1166490	1475855	1612384	1820126
70	278472.4	386429	466055	682402	785573	926549
100	86051	128726	177526	275137	341806	425033
130	30874	42897	60012	111814	136234	156041

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
158.0	8152	73.6
168.8	4163	76.7
179.6	2152	79.6

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.9
Air voids (%)	7.0
Total unit weight (pcf)	144.67

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	15.8
Cumulative % Retained #4 sieve	48.8
% Passing #200 sieve	5.6

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular frequency = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
158.0	8152	73.6
168.8	4163	76.7
179.6	2152	79.6

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.9
Air voids (%)	7.0
Total unit weight (pcf)	144.67

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	15.8
Cumulative % Retained #4 sieve	48.8
% Passing #200 sieve	5.6

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.9
Air voids (%)	7.0
Total unit weight (pcf)	144.67

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	513	Tensile Strength	513	Tensile Strength	513

Table B3. Mixture ID: 08-1043A

Mixture Type: SM-9.5A

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	2599946	2890601	3017461	3288682	3400506	3530701
40	1265647	1613206	1781353	2155164	2316300	2516114
70	466296	680904	809600	1125734	1284164	1495967
100	165440	264114	349928	581069	709669	887486
130	58005	75811	96614	166987	203149	266966

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	Delta (degree)
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	13
Air voids (%)	7.1
Total unit weight (pcf)	149.76

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	8.1
Cumulative % Retained #4 sieve	41.7
% Passing #200 sieve	5.8

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	Delta (degree)
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	13
Air voids (%)	7.1
Total unit weight (pcf)	149.76

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	8.1
Cumulative % Retained #4 sieve	41.7
% Passing #200 sieve	5.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	13
Air voids (%)	7.1
Total unit weight (pcf)	149.76

Asphalt Binder: Superpave Binder Grading:	PG 64-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B4. Mixture ID: 08-1045D

Mixture Type: SM-9.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	**Mixture |E*|, psi**					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	3173183	3510347	3650309	3948748	4085664	4287073
40	1825783	2215499	2387369	2762920	2922655	3115603
70	735631	966483	1106493	1443899	1608710	1832503
100	276925	394696	477319	690089	805056	967305
130	58102	86051	120236	219925	270495	349783

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.6
Air voids (%)	7.8
Total unit weight (pcf)	161.43

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	8.2
Cumulative % Retained #4 sieve	59.5
% Passing #200 sieve	4.2

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.6
Air voids (%)	7.8
Total unit weight (pcf)	161.43

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	8.2
Cumulative % Retained #4 sieve	59.5
% Passing #200 sieve	4.2

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.6
Air voids (%)	7.8
Total unit weight (pcf)	161.43

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	593	Tensile Strength	593	Tensile Strength	593

Table B5. Mixture ID: 08-1047D

Mixture Type: SM-9.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	2426068	2755720	2885400	3191699	3328819	3516545
40	1329985	1649412	1802038	2140745	2302694	2504114
70	449134	604652	708967	959983	1092634	1271660
100	161279	223817	281954	417535	496998	606387
130	100108	124198	140742	198319	229384	284560

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	Delta (degree)
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.8
Air voids (%)	6.9
Total unit weight (pcf)	142.71

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	4.7
Cumulative % Retained #4 sieve	33.4
% Passing #200 sieve	6.6

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	Delta (degree)
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.8
Air voids (%)	6.9
Total unit weight (pcf)	142.71

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	4.7
Cumulative % Retained #4 sieve	33.4
% Passing #200 sieve	6.6

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.8
Air voids (%)	6.9
Total unit weight (pcf)	142.71

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	600	Tensile Strength	600	Tensile Strength	600

Table B6. Mixture ID: 08-1052E

Mixture Type: SM-12.5E

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2258285	2625617	2770268	3077410	3223511	3444452
40	1154065	1539333	1708012	2075489	2235176	2443257
70	426024	624291	742303	1032282	1175724	1377230
100	85364	125704	170323	284129	348816	445362
130	94516	111133	121145	167664	190144	226791

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	5873	67.4
168.8	3358	69.4
179.6	1936	71.8

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	12.5
Air voids (%)	7.1
Total unit weight (pcf)	144.87

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	13.9
Cumulative % Retained #4 sieve	38.9
% Passing #200 sieve	6.8

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	5873	67.4
168.8	3358	69.4
179.6	1936	71.8

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	12.5
Air voids (%)	7.1
Total unit weight (pcf)	144.87

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	13.9
Cumulative % Retained #4 sieve	38.9
% Passing #200 sieve	6.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	12.5
Air voids (%)	7.1
Total unit weight (pcf)	144.87

Asphalt Binder: Superpave Binder Grading:	PG 76-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	507	Tensile Strength	507	Tensile Strength	507

Table B7. Mixture ID: 08-1055D

Mixture Type: SM-12.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	1990691	2290870	2420244	2696686	2816149	2959543
40	1245825	1580766	1730928	2054169	2195049	2372188
70	431294	612252	725043	983066	1112439	1290642
100	136621	198557	244872	377968	454838	559169
130	50280	65804	83044	139198	166842	217847

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	6883	80.8
158.0	2324	84.3
168.8	1127	86.0

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.7
Air voids (%)	7
Total unit weight (pcf)	146.13

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	15.3
Cumulative % Retained #4 sieve	49.8
% Passing #200 sieve	5.2

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	6883	80.8
158.0	2324	84.3
168.8	1127	86.0

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.7
Air voids (%)	7.0
Total unit weight (pcf)	146.13

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	15.3
Cumulative % Retained #4 sieve	49.8
% Passing #200 sieve	5.2

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.7
Air voids (%)	7.0
Total unit weight (pcf)	146.13

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	515	Tensile Strength	515	Tensile Strength	515

Table B8. Mixture ID: 09-1001E

Mixture Type: SM-12.5E

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	2621992	2998558	3143257	3435991	3549894	3675642
40	1309159	1678280	1846958	2217095	2376733	2580511
70	547517	762125	891692	1198156	1347980	1547697
100	147489	210256	268852	415581	498011	615008
130	100434	123664	140749	206244	239796	295829

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	G* (Pa)	Delta (degree)
158.0	7844	68.9
168.8	4241	70.9
179.6	2318	73.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.7
Air voids (%)	6.8
Total unit weight (pcf)	155.59

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	16.8
Cumulative % Retained #4 sieve	42.4
% Passing #200 sieve	4.6

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	G* (Pa)	Delta (degree)
158.0	7844	68.9
168.8	4241	70.9
179.6	2318	73.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	11.7
Air voids (%)	6.8
Total unit weight (pcf)	155.59

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	16.8
Cumulative % Retained #4 sieve	42.4
% Passing #200 sieve	4.6

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	11.7
Air voids (%)	6.8
Total unit weight (pcf)	155.59

Asphalt Binder: Superpave Binder Grading:	PG 76-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	573	Tensile Strength	573	Tensile Strength	573

Table B9. Mixture ID: 08-1044A

Mixture Type: BM-25.0A

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2599946	2890601	3017461	3288682	3400506	3530701
40	1265647	1613206	1781353	2155164	2316300	2516114
70	466296	680904	809600	1125734	1284164	1495967
100	165440	264114	349928	581069	709669	887486
130	58005	75811	96614	166987	203149	266966

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.7
Air voids (%)	6.9
Total unit weight (pcf)	155.93

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	8.8
Cumulative % Retained 3/8 inch sieve	58.0
Cumulative % Retained #4 sieve	71.3
% Passing #200 sieve	5.8

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
-	-	-
-	-	-
-	-	-

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.7
Air voids (%)	6.9
Total unit weight (pcf)	155.93

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	8.8
Cumulative % Retained 3/8 inch sieve	58.0
Cumulative % Retained #4 sieve	71.3
% Passing #200 sieve	5.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	10.7
Air voids (%)	6.9
Total unit weight (pcf)	155.93

Asphalt Binder: Superpave Binder Grading:	PG 64-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	452	Tensile Strength	452	Tensile Strength	452

Table B10. Mixture ID: 09-1049A

Mixture Type: BM-25.0A

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2937731	3259872	3401607	3701600	3818710	3990199
40	1320568	1700180	1885297	2314802	2496679	2777734
70	435113.1	659341.4	819076.2	1201154	1364805	1703806
100	98676.4	158722	256136.6	481380.1	564631.8	596467.5
130	44217.89	54767.65	75917.11	143933.2	175827	188986.9

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	5425	82.1
158.0	2533	84.3
168.8	1218	86.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.3
Air voids (%)	7.6
Total unit weight (pcf)	151.32

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	8.2
Cumulative % Retained 3/8 inch sieve	35.9
Cumulative % Retained #4 sieve	60.2
% Passing #200 sieve	7.0

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	5425	82.1
158.0	2533	84.3
168.8	1218	86.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.3
Air voids (%)	7.6
Total unit weight (pcf)	151.32

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	8.2
Cumulative % Retained 3/8 inch sieve	35.9
Cumulative % Retained #4 sieve	60.2
% Passing #200 sieve	7.0

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	10.3
Air voids (%)	7.6
Total unit weight (pcf)	151.32

Asphalt Binder: Superpave Binder Grading:	PG 64-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B11. Mixture ID: 09-1051D

Mixture Type: BM-25.0D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
14	2613386	2993708	3168595	3531323	3808435	4022180
40	1280925	1616639	1781788	2145349	2441782	2681239
70	448021	621293	753229	1063948	1204490	1390235
100	126893	190966	281421	441736	527309	632219
130	40556	66791	104108	171050	207202	251925

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	G* (Pa)	Delta (degree)
147.2	5994	76.3
158.0	4036	78.9
168.8	2076	81.5

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.9
Air voids (%)	7.6
Total unit weight (pcf)	150.95

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	9.9
Cumulative % Retained 3/8 inch sieve	41.9
Cumulative % Retained #4 sieve	63.0
% Passing #200 sieve	6.8

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	G* (Pa)	Delta (degree)
147.2	5994	76.3
158.0	4036	78.9
168.8	2076	81.5

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.9
Air voids (%)	7.6
Total unit weight (pcf)	150.95

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	9.9
Cumulative % Retained 3/8 inch sieve	41.9
Cumulative % Retained #4 sieve	63.0
% Passing #200 sieve	6.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	9.9
Air voids (%)	7.6
Total unit weight (pcf)	150.95

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B12. Mixture ID: 09-1053D

Mixture Type: BM25.0D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2089702	2398347	2542962	2854993	2991380	3155961
40	1235044	1569260	1737407	2124657	2304214	2529071
70	414179.3	578507	704544.8	1006852	1155032	1347013
100	156820	223068	284081	474128	555446	647980
130	79425	92833	105958	151611	173352	199701

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	5994	76.3
158.0	4036	78.9
168.8	2076	81.5

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.7
Air voids (%)	6.0
Total unit weight (pcf)	153.27

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	10.9
Cumulative % Retained 3/8 inch sieve	41.9
Cumulative % Retained #4 sieve	62.1
% Passing #200 sieve	6.9

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	5994	76.3
158.0	4036	78.9
168.8	2076	81.5

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.7
Air voids (%)	6.0
Total unit weight (pcf)	153.27

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	10.9
Cumulative % Retained 3/8 inch sieve	41.9
Cumulative % Retained #4 sieve	62.1
% Passing #200 sieve	6.9

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	10.7
Air voids (%)	6.0
Total unit weight (pcf)	153.27

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B13. Mixture ID: 09-1070D

Mixture Type: BM-25.0D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2714144	3056980	3194474	3485458	3586618	3651227
40	1660633	2084240	2255143	2664391	2827268	3048692
70	472194.4	701740.7	854368.7	1199994	1371283	1593433
100	171671.5	253187.5	314635.1	514207	630575.6	798964.3
130	116615.1	128706.5	142383.5	205518.4	242261.3	310090.6

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	144.62

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	18.0
Cumulative % Retained 3/8 inch sieve	40.0
Cumulative % Retained #4 sieve	53.0
% Passing #200 sieve	6.5

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	144.62

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	18.0
Cumulative % Retained 3/8 inch sieve	40.0
Cumulative % Retained #4 sieve	53.0
% Passing #200 sieve	6.5

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	144.62

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B14. Mixture ID: 09-1071D

Mixture Type: BM-25.0D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	3038588	3389338	3522434	3810092	3957064	4196327
40	1697280	2157146	2344583	2738263	2898917	3087321
70	642469	955460	1128393	1520575	1703855	1944956
100	142359	215284	276684	463299	574301	733407
130	102053	125211	139410	202811	239022	304482

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	146.22

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	22.0
Cumulative % Retained 3/8 inch sieve	44.0
Cumulative % Retained #4 sieve	56.0
% Passing #200 sieve	5.9

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	146.22

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	22.0
Cumulative % Retained 3/8 inch sieve	44.0
Cumulative % Retained #4 sieve	56.0
% Passing #200 sieve	5.9

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	9.7
Air voids (%)	7.0
Total unit weight (pcf)	146.22

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B15. Mixture ID: 09-1072D

Mixture Type:BM-25.0D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2718925	3102743	3263252	3752077	4004346	4276437
40	1489344	1960039	2158306	2579399	2750495	2958527
70	385462	619118	767781	1123849	1299344	1537158
100	98413	152652	199862	365495	469825	622744
130	82986	99583	115184	172740	202714	265999

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.4
Air voids (%)	7.0
Total unit weight (pcf)	144.33

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	24.0
Cumulative % Retained 3/8 inch sieve	50.0
Cumulative % Retained #4 sieve	61.0
% Passing #200 sieve	5.0

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
147.2	3495	83.9
158.0	1733	85.9
168.8	863	87.3

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	10.4
Air voids (%)	7.0
Total unit weight (pcf)	144.33

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	24.0
Cumulative % Retained 3/8 inch sieve	50.0
Cumulative % Retained #4 sieve	61.0
% Passing #200 sieve	5.0

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	10.4
Air voids (%)	7.0
Total unit weight (pcf)	144.33

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	-	Tensile Strength	-	Tensile Strength	-

Table B16. Mixture ID: 08-1012E

Mixture Type: SMA-12.5E

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	**Mixture |E*|, psi**					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	1786429	2082113	2213904	2516162	2646116	2808027
40	856544	1101513	1232869	1540590	1682776	1859528
70	250964	360854	438497	637102	742738	887872
100	73360	105597	142403	239602	296699	368057
130	37657	45552	75081	125869	150834	173862

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	3542	68.3
168.8	2028	70.8
179.6	1193	72.9

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	15.3
Air voids (%)	7.0
Total unit weight (pcf)	154.31

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	33.0
Cumulative % Retained #4 sieve	73.8
% Passing #200 sieve	5.6

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	3542	68.3
168.8	2028	70.8
179.6	1193	72.9

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	15.3
Air voids (%)	7.0
Total unit weight (pcf)	154.31

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	33.0
Cumulative % Retained #4 sieve	73.8
% Passing #200 sieve	5.6

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	15.3
Air voids (%)	7.0
Total unit weight (pcf)	154.31

Asphalt Binder: Superpave Binder Grading:	PG 76-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	462	Tensile Strength	462	Tensile Strength	462

Table B17. Mixture ID: 08-1025E

Mixture Type: SMA-12.5E

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	2062339	2390705	2535356	2851151	2986230	3146641
40	904697	1206617	1359245	1710720	1871760	2076988
70	217121	343304	444734	672008	791326	953623
100	50333	85374	139352	249368	309801	385800
130	62221	77668	96450	124863	147598	184488

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	5334	69.6
168.8	2883	71.7
179.6	1589	74.0

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	14.2
Air voids (%)	7.5
Total unit weight (pcf)	153.42

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	37.0
Cumulative % Retained #4 sieve	74.4
% Passing #200 sieve	5.8

Asphalt Binder: Superpave Binder Test Data

	Angular freq. = 10 rad/sec	
Temp. (°F)	**G* (Pa)**	**Delta (degree)**
158.0	5334	69.6
168.8	2883	71.7
179.6	1589	74.0

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	14.2
Air voids (%)	7.5
Total unit weight (pcf)	153.42

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.0
Cumulative % Retained 3/8 inch sieve	37.0
Cumulative % Retained #4 sieve	74.4
% Passing #200 sieve	5.8

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	14.2
Air voids (%)	7.5
Total unit weight (pcf)	153.42

Asphalt Binder: Superpave Binder Grading:	PG 76-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	523	Tensile Strength	523	Tensile Strength	523

Table B18. Mixture ID: 08-1046D

Mixture Type: SMA-12.5D

Level 1

Asphalt Mix: Dynamic Modulus Table

Temperature (°F)	Mixture |E*|, psi					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
14	1787630	2015321	2117030	2329203	2432737	2552687
40	1007260	1274592	1405181	1687083	1824364	1954403
70	344444	488808	595399	824905	944685	1085181
100	136547	186489	241357	368489	445403	554382
130	74142	92320	109361	160651	188869	240539

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
158.0	4369	79.7
168.8	2208	82.0
179.6	1144	84.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	14.9
Air voids (%)	7.8
Total unit weight (pcf)	139.98

Level 2

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.2
Cumulative % Retained 3/8 inch sieve	38.3
Cumulative % Retained #4 sieve	76.2
% Passing #200 sieve	4.2

Asphalt Binder: Superpave Binder Test Data

Temp. (°F)	Angular freq. = 10 rad/sec	
	G* (Pa)	**Delta (degree)**
158.0	4369	79.7
168.8	2208	82.0
179.6	1144	84.1

Asphalt General: Volumetric Properties as Built

Effective Binder content (%)	14.9
Air voids (%)	7.8
Total unit weight (pcf)	139.98

Level 3

Asphalt Mix: Aggregate Gradation

Cumulative % Retained 3/4 inch sieve	0.2
Cumulative % Retained 3/8 inch sieve	38.3
Cumulative % Retained #4 sieve	76.2
% Passing #200 sieve	4.2

Asphalt General: Vol. Properties as Built

Volumetric Properties as Built	
Effective Binder content (%)	14.9
Air voids (%)	7.8
Total unit weight (pcf)	139.98

Asphalt Binder: Superpave Binder Grading:	PG 70-22

Low-Temperature Cracking

Level 1		Level 2		Level 3	
Creep compliance:	Table 9	Creep compliance:	Table 9	Creep compliance:	-
Tensile Strength	359	Tensile Strength	359	Tensile Strength	359

APPENDIX C

COMPARISON OF MEASURED |E*| WITH THAT PREDICTED FROM PREVIOUS STUDIES

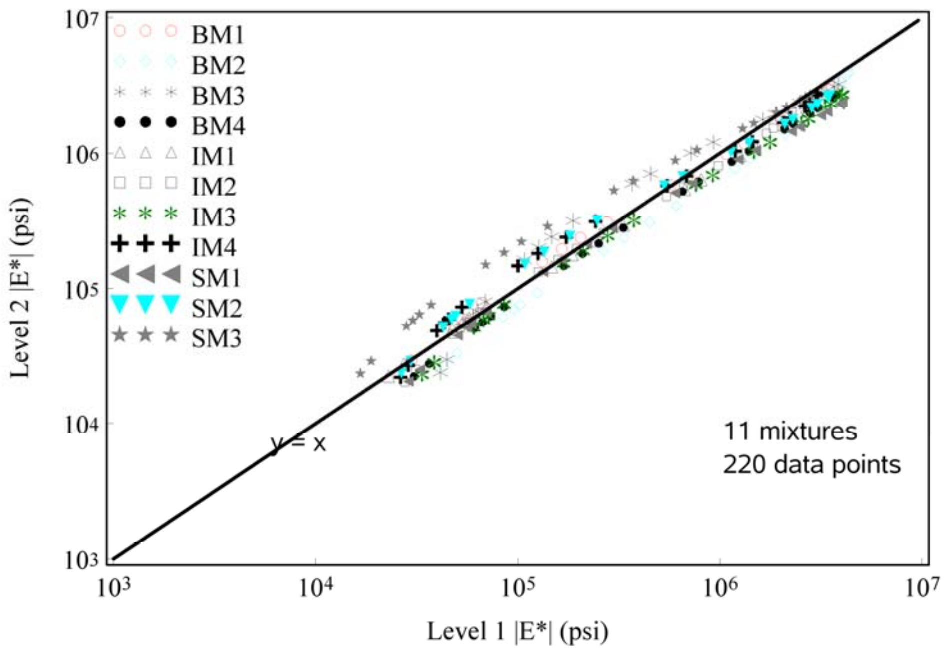

Figure C1. Comparison of Level 1 and Level 2 |E*| Master Curves. After Flintsch et al. (2007) and Diefenderfer (2010).

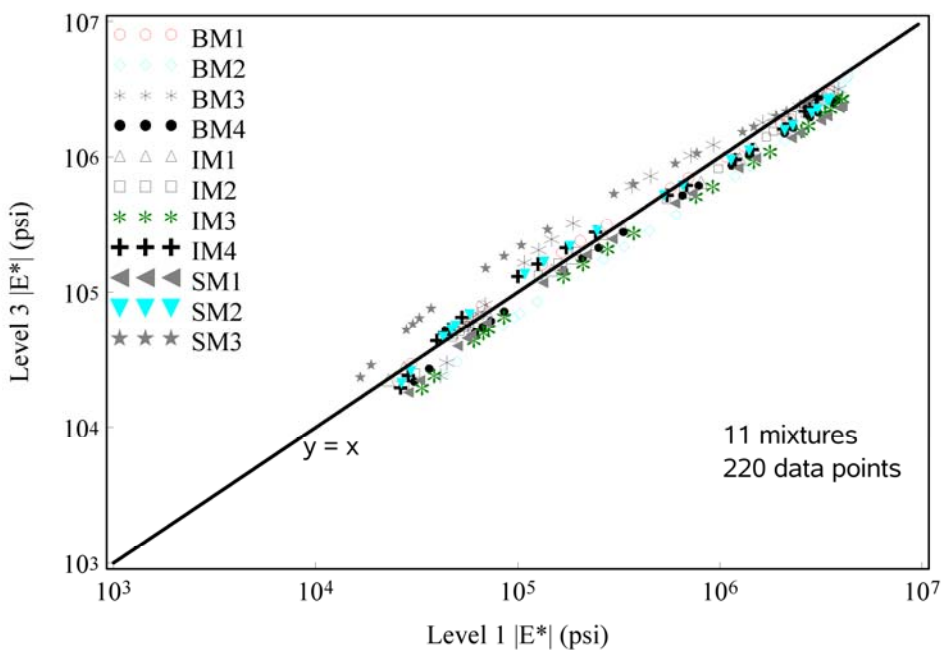

Figure C2. Comparison of Level 1 and Level 3 |E*| Master Curves. After Flintsch et al. (2007) and Diefenderfer (2010).

APPENDIX D

NEW FLEXIBLE PAVEMENT DESIGN EXAMPLE

Flexible Pavement Reconstruction Project Design

A 4-mile section of I-81 in VDOT's Staunton District is being reconstructed. The existing heavily deteriorated pavement will be removed and a new asphalt concrete structure constructed.

Design Life

The new pavement will have a 20-year design life. The base will be constructed in May 2011, the hot-mix asphalt (HMA) will be constructed in July 2011, and the completed pavement will be opened to traffic in August 2011.

Construction Requirements

The new pavement is expected to have an initial International Roughness Index (IRI) of approximately 60 in/mile.

Performance Criteria

The performance criteria were selected in accordance with current MEPDG (Version 1.1, 2009) national defaults for an interstate highway at a 90% reliability level. At the end of the 20-year design life, the pavement will have less than 25% alligator cracking; no more than 0.75 in total rutting (maximum 0.25 in in asphalt layer); longitudinal cracking of less than 2,000 ft/mile; transverse cracking spacing greater than 70 ft; a transverse crack length of 1,000 ft/mile; and an IRI of less than 172 in/mile.

Traffic Inputs

Table D1 lists the traffic input parameters used.

Climate Inputs

The project is located a few miles from Staunton, Virginia. Therefore, climatic data from the Staunton Treatment Plant Weather Station, the closest weather station to the project, was used to generate the climatic file. A depth to groundwater table of 10 ft was assumed.

HMA Design Properties

The nationally calibrated NCHRP 1-37A viscosity-based |E*| predicted model was used.

HMA Design Properties

The nationally calibrated NCHRP 1-37A viscosity-based |E*| predicted model and HMA rutting model coefficients were selected.

Table D1. Traffic Inputs

Traffic Input Parameter	
Initial two-way average annual daily truck traffic (AADTT)	5,980
Lanes in design direction	2
Trucks in design direction, %	50
Trucks in design lane, %	95
Operational speed, mph	65
Monthly adjustment factors	Default
Hourly truck traffic distribution	Default
Traffic growth factor	2% compound
Axle load distribution factors	Default
Axles per truck	Default
Mean wheel location, inches from the lane marking	18
Traffic wander standard deviation, in	10
Design lane width, ft	12
Average axle width, ft	8.5
Dual tire spacing, in	12
Tire pressure, psi	120
Average tandem axle spacing, in	51.6
Average tridem axle spacing, in	49.2
Average quad axle spacing, in	49.2

Structure and Layer Materials Definition

Structure Definition

A total pavement thickness of 24 in was assumed (Figure D1) including 12 in of aggregate base and 12 in of asphalt concrete. The 12-in asphalt concrete layer comprised 4 in SM-12.5D, 4 in IM-19.0A, and 4 in BM-25.0A. A VDOT 21-B crushed aggregate base layer 12 in thick and a subgrade with an A-7-6 AASHTO classification were used. A full friction interface (=1) was assumed between the different pavement layers. The default short-wave absorptivity of 0.85 was used.

Layer Materials Properties

Asphalt Concrete. Inputs required for the asphalt concrete layers were obtained from Table B2 (surface layer), and Table B10 (base layers) using input Level 1 values. For the intermediate layer, input Level 3 values was assumed. Sample inputs at Level 1 are shown in Figures D2 through D4 for the surface layer. Figures D5 through D7 show the corresponding Level 3 inputs for the intermediate layer.

Thermal Cracking. Since thermal cracking is not a major problem for most parts of Virginia, Level 3 inputs from Table B2 were used.

Calibration Factors. The current MEPDG software (Version 1.1) has not been calibrated for Virginia climatic and material conditions. Therefore, the MEPDG national calibration factors were used for all the distress models.

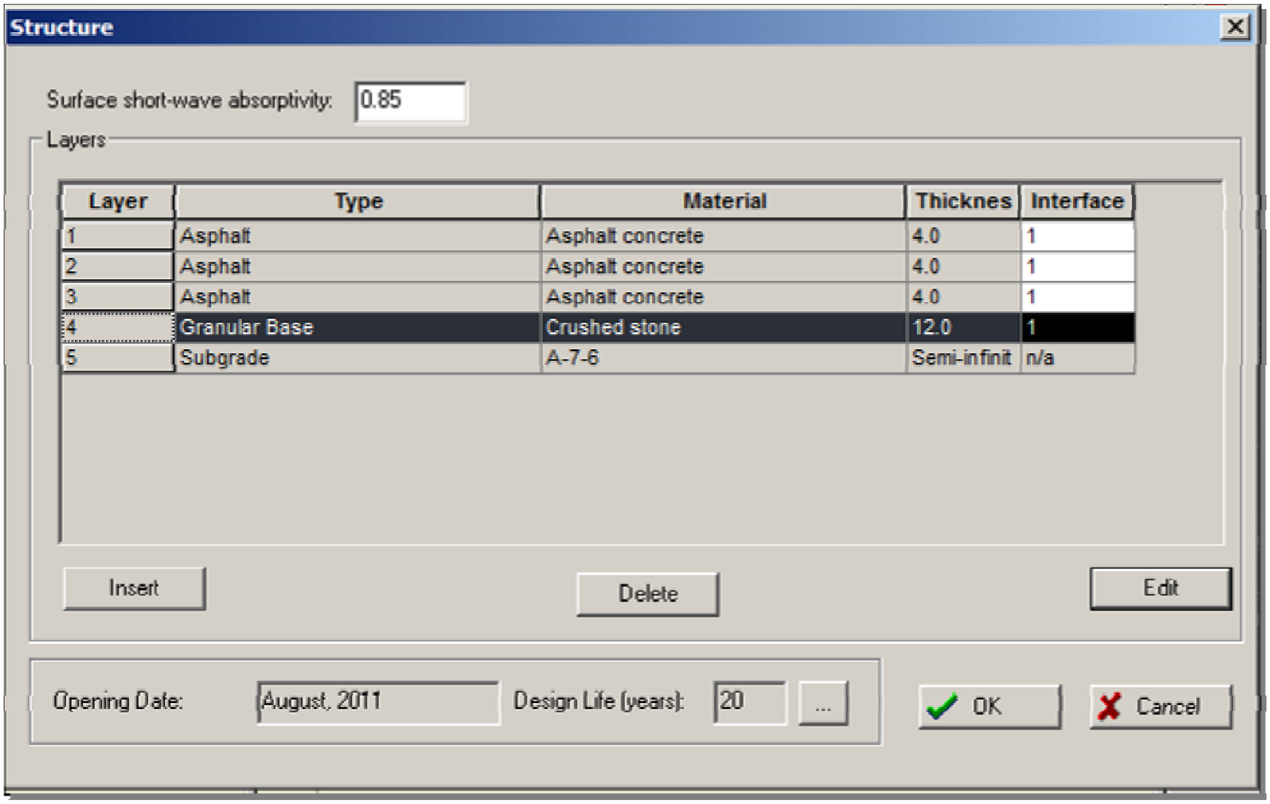

Figure D1. Design Structure Definition for New Flexible Pavement Design Example

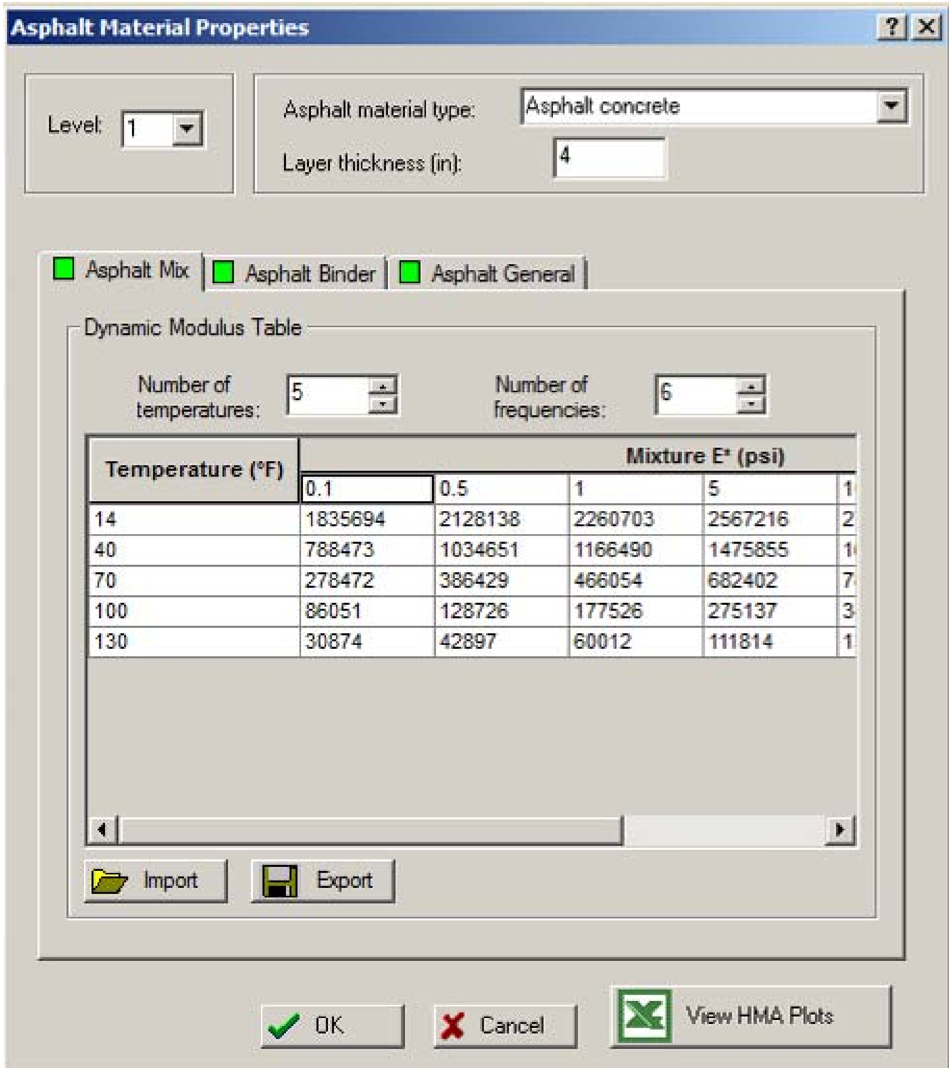

Figure D2. Illustration of Input Level 1 Asphalt Mixture Properties for SM-12.5D From Table B2

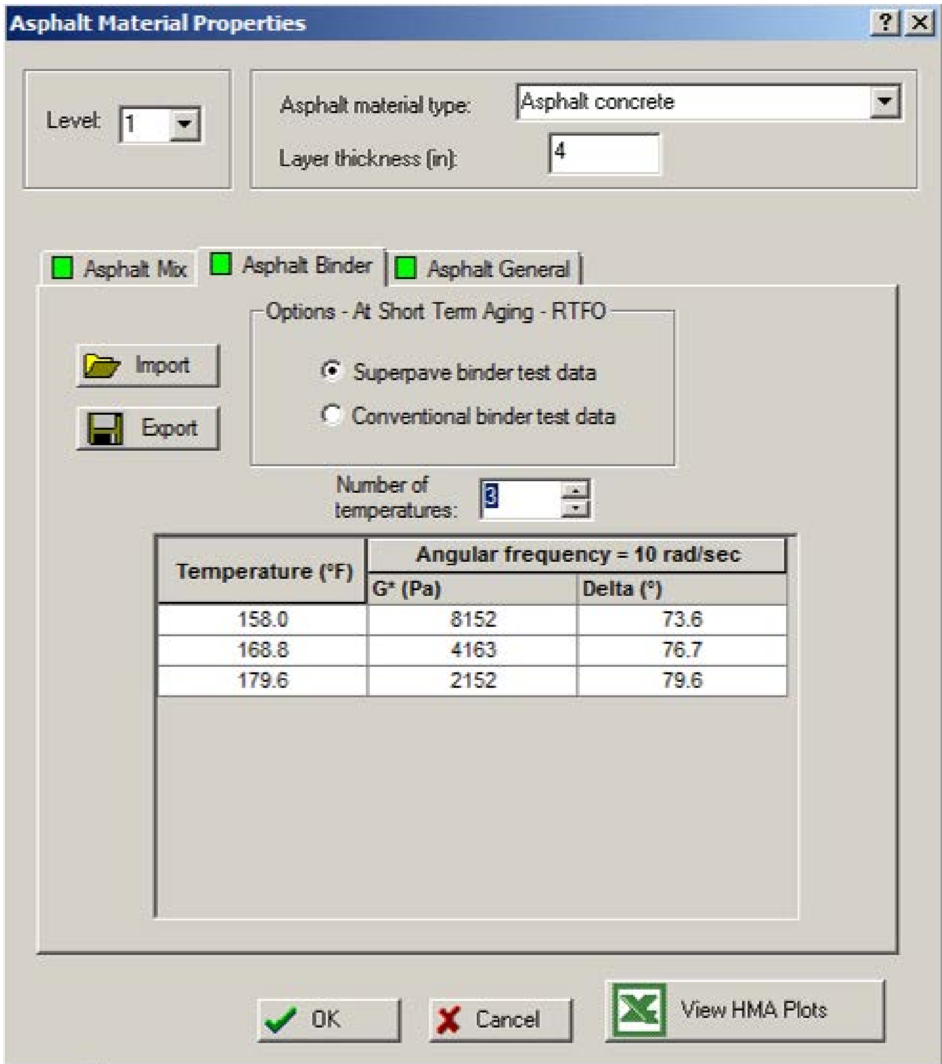

Figure D3. Illustration of Input Level 1 Asphalt Binder Properties for SM-12.5D from Table B2

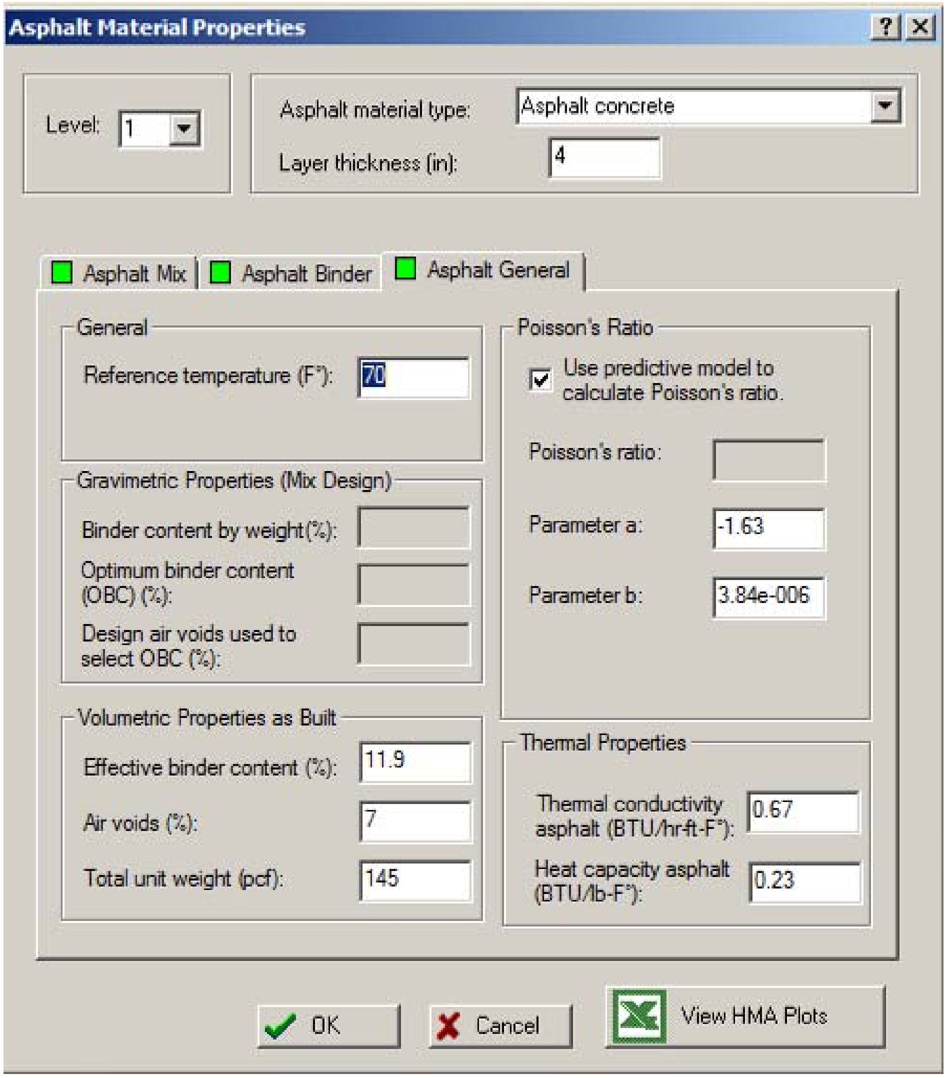

Figure D4. Illustration of Input Level 1 Asphalt Volumetric Properties for SM-12.5D from Table B2

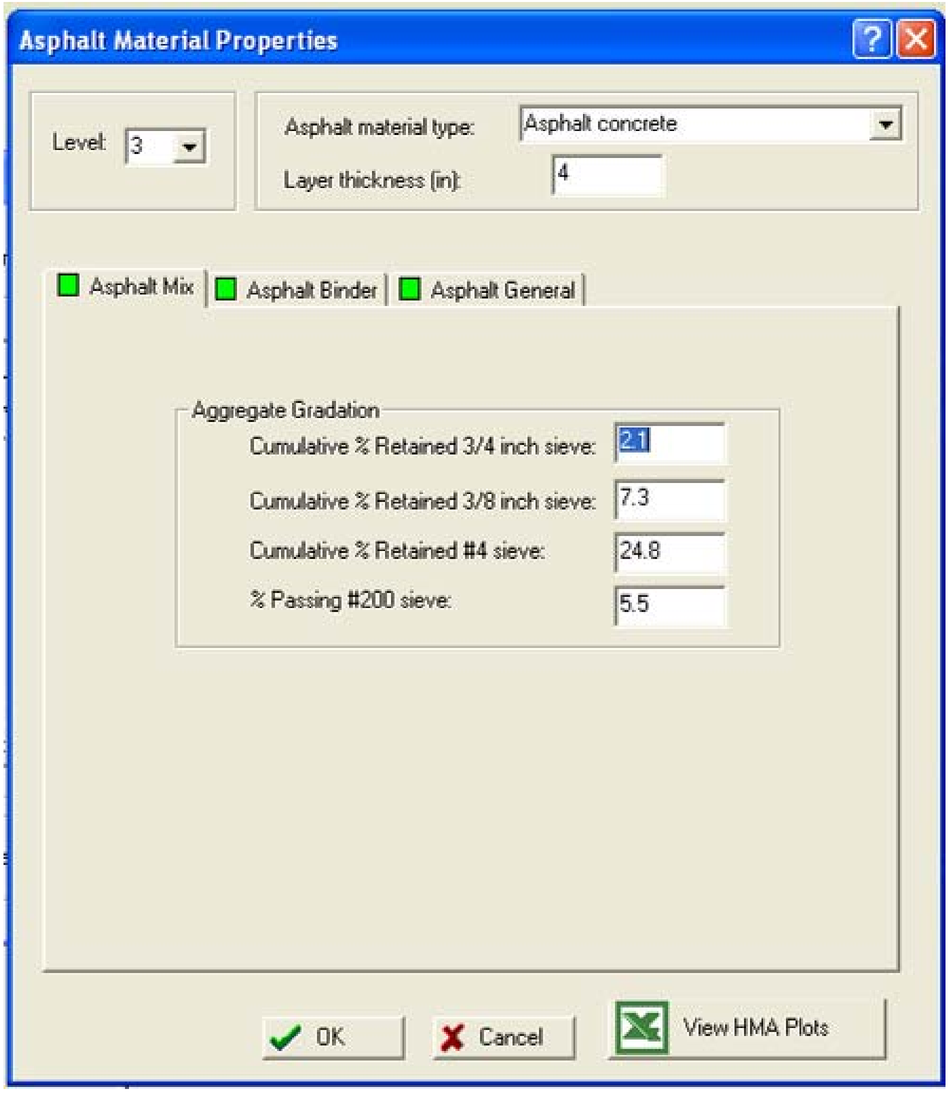

Figure D5. Illustration of Asphalt Mixture Input Level 3 for Intermediate Layer

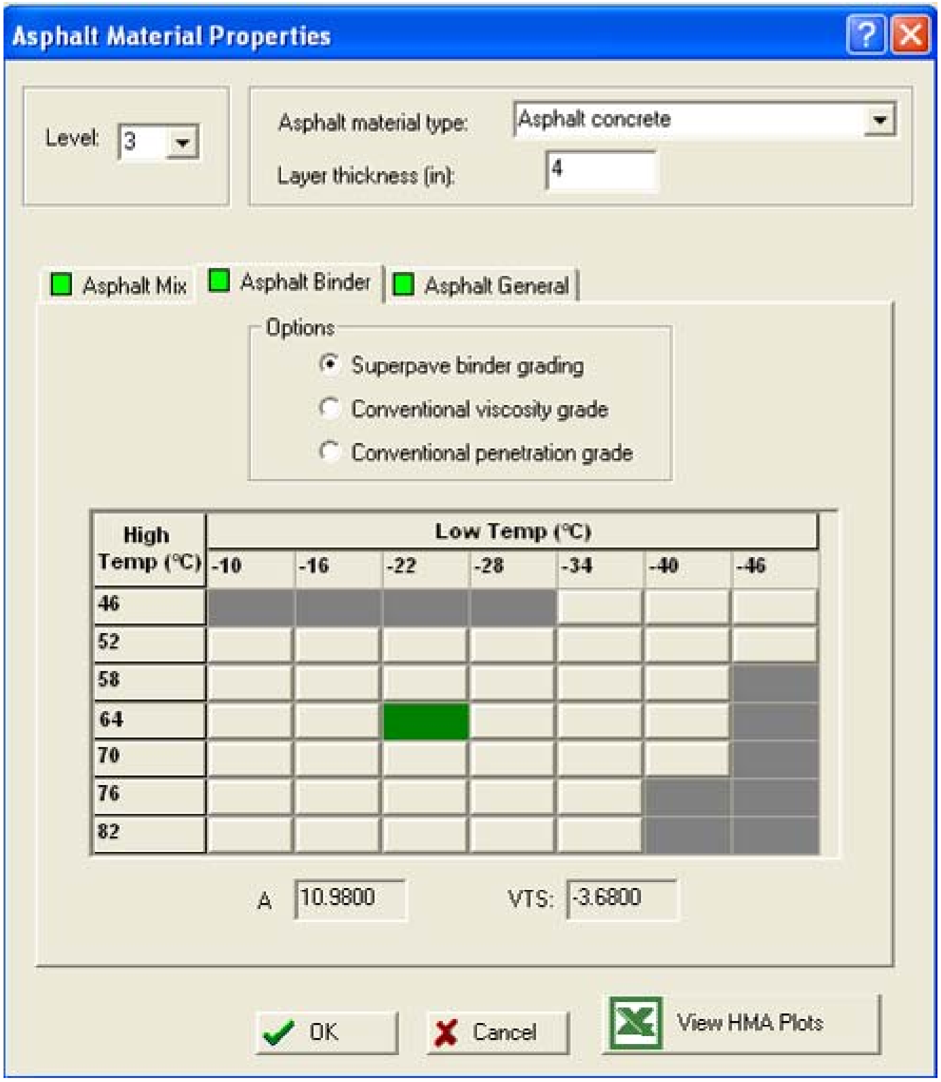

Figure D6. Illustration of Asphalt Binder Input Level 3 for Intermediate Layer

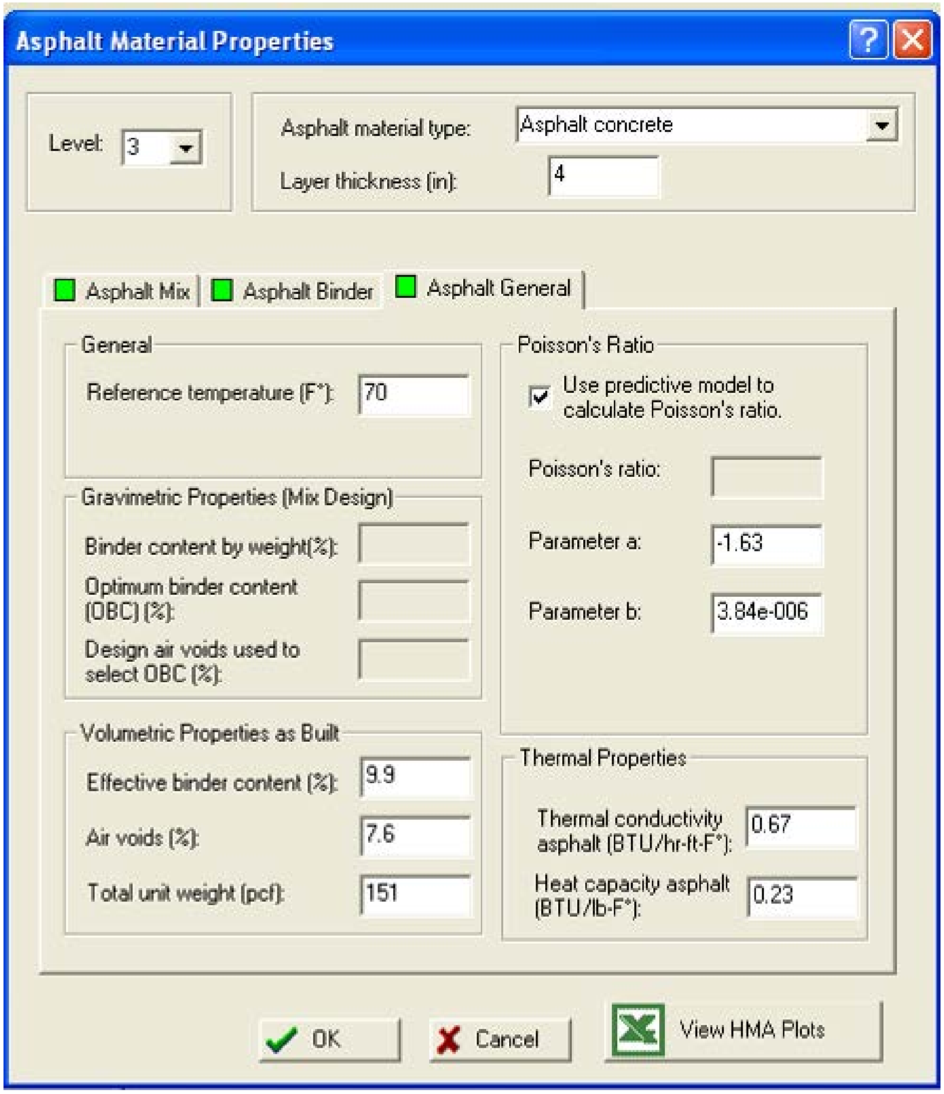

Figure D7. Illustration of Input Level 3 Asphalt Volumetric Properties for Intermediate Layer

Performance Prediction Summary

Table D8 is a summary of the predicted performance for each of the 240 months in the design life. For instance, during the first month, the pavement sustained about 86,000 heavy trucks (FHWA Classes 4 to 13), resulting in less than 0.01% fatigue cracking, no transverse cracking, and 0.175 in of rutting. Over the 20-year design period, the pavement will be subjected to about 31 million cumulative applications of heavy truck loading. Both the predicted fatigue and transverse cracking appear reasonable for the class of pavement and material inputs used. However, total rutting appears to be excessive. As shown in Table D9, the pavement section failed the reliability criteria for rutting. The results illustrate the need for calibrating the rutting models in the MEPDG for Virginia conditions.

Table D8. Summary of Predicted Pavement Distress for New Flexible Pavement

Pavement Age mo	Pavement Age yr	Month	Alligator Cracking (%)	Transverse Cracking (ft/mi)	Subtotal AC Rutting (in)	Total Rutting (in)	IRI (in/mi)	Heavy Trucks (cumulative)	IRI at Reliability (in/mi)
1	0.08	Aug	0.0055	0	0.042	0.175	70	86458	95.09
2	0.17	Sept	0.0097	0	0.051	0.198	71	172915	96.42
3	0.25	Oct	0.0123	0	0.054	0.207	71.3	259373	96.96
4	0.33	Nov	0.0134	0	0.054	0.209	71.5	345831	97.15
5	0.42	Dec	0.0141	0	0.054	0.211	71.6	432289	97.28
6	0.5	Jan	0.0148	0	0.054	0.213	71.7	518746	97.43
7	0.58	Feb	0.0156	0	0.054	0.214	71.8	605204	97.57
8	0.67	Mar	0.0167	0	0.055	0.217	71.9	691662	97.77
9	0.75	Apr	0.0192	0	0.058	0.224	72.2	778119	98.24
10	0.83	May	0.0239	0	0.066	0.24	72.9	864577	99.16
11	0.92	Jun	0.0305	0	0.079	0.259	73.7	951035	100.33
12	1	Jul	0.0381	0	0.093	0.281	74.6	1037490	101.6
13	1.08	Aug	0.0453	0	0.103	0.297	75.3	1127410	102.56
14	1.17	Sept	0.0514	0	0.11	0.307	75.8	1217320	103.21
15	1.25	Oct	0.0544	0	0.111	0.31	76	1307240	103.46
16	1.33	Nov	0.0554	0	0.111	0.311	76.1	1397160	103.58
17	1.42	Dec	0.0562	0	0.111	0.312	76.1	1487070	103.69
18	1.5	Jan	0.0568	0	0.111	0.312	76.2	1576990	103.79
19	1.58	Feb	0.0574	0	0.111	0.312	76.3	1666900	103.9
20	1.67	Mar	0.0582	0	0.111	0.313	76.4	1756820	104.02
21	1.75	Apr	0.0603	0	0.112	0.315	76.5	1846740	104.22
22	1.83	May	0.0639	0	0.115	0.319	76.8	1936650	104.56
23	1.92	Jun	0.0685	0	0.119	0.326	77.1	2026570	105
24	2	Jul	0.0748	0	0.127	0.336	77.6	2116480	105.69
25	2.08	Aug	0.0808	0	0.133	0.344	78	2210000	106.25
26	2.17	Sept	0.0844	0	0.134	0.347	78.2	2303510	106.51
27	2.25	Oct	0.0861	0	0.135	0.348	78.3	2397020	106.67
28	2.33	Nov	0.0871	0	0.135	0.349	78.4	2490540	106.8
29	2.42	Dec	0.0877	0	0.135	0.349	78.5	2584050	106.91
30	2.5	Jan	0.0882	0	0.135	0.349	78.5	2677560	107.03
31	2.58	Feb	0.0889	0	0.135	0.35	78.6	2771070	107.15
32	2.67	Mar	0.0902	0	0.135	0.35	78.7	2864590	107.29
33	2.75	Apr	0.0919	0	0.135	0.351	78.9	2958100	107.46
Etc., over the 240-month design life . . .									
238	19.8	May	0.912	0	0.361	0.659	123.7	30530200	166.47
239	19.9	Jun	0.923	0	0.364	0.663	124	30712400	166.91
240	20	Jul	0.934	0	0.366	0.665	124.4	30894500	167.32

Table D9. Reliability Summary

Performance Criteria	Distress Target	Reliability Target	Distress Predicted	Reliability Predicted	Acceptable
Terminal IRI (in/mi)	172	90	124.4	92.24	Pass
AC Surface Down Cracking (Long. Cracking) (ft/mi)	2000	90	0.1	99.999	Pass
AC Bottom Up Cracking (Alligator Cracking) (%)	25	90	0.9	99.999	Pass
AC Thermal Fracture (Transverse Cracking) (ft/mi)	1000	90	1	99.999	Pass
Chemically Stabilized Layer (Fatigue Fracture)	25	90			N/A
Permanent Deformation (AC Only) (in)	0.25	90	0.37	14.1	Fail
Permanent Deformation (Total Pavement) (in)	0.75	90	0.67	74.79	Fail