VTRC
Virginia Transportation Research Council

We Bring Innovation to Transportation

Determination of Input Data for Stone Matrix Asphalt and Polymer Modified Dense-Graded Mixtures for Use in the Mechanistic-Empirical Pavement Design Guide

http://www.virginiadot.org/vtrc/main/online_reports/pdf/22-r8.pdf

HARIKRISHNAN NAIR, Ph.D., P.E.
Associate Principal Research Scientist
Virginia Transportation Research Council

BIPAD SAHA, P.E
Pavement Engineer
Materials Division
Virginia Department of Transportation

Final Report VTRC 22-R8

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 22-R8	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Determination of Input Data for Stone Matrix Asphalt and Polymer Modified Dense-Graded Mixtures for Use in the Mechanistic-Empirical Pavement Design Guide		5. Report Date: October 2021 6. Performing Organization Code:
Authors: Harikrishnan Nair, Ph.D., P.E., and Bipad Saha, P.E.		8. Performing Organization Report No.: VTRC 22-R8
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 112003
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 14. Sponsoring Agency Code:

15. Supplementary Notes:
This is an SPR-B report.

16. Abstract:

AASHTO's Mechanistic Empirical Pavement Design Guide (MEPDG) and AASHTOWare Pavement ME Design software (hereinafter "Pavement ME Design") provide an improved process for conducting pavement analysis and for developing pavement designs based on mechanistic-empirical principles. The Virginia Department of Transportation (VDOT) officially adopted the MEPDG procedure for new construction (new alignment, lane addition, and total reconstruction) for interstate and primary routes effective January 1, 2018. Pavement ME Design requires asphalt mixture volumetrics (asphalt content, air voids, and unit weight) and mechanical properties (dynamic modulus) as Level 1 (i.e., the most accurate) inputs. Currently, VDOT's dynamic modulus database has limited data on stone matrix asphalt (SMA) and dense-graded polymer modified (designated "SM-E") mixtures.

The purpose of this study was to develop input data for SMA and SM-E mixtures for use in Pavement ME Design. Material properties (dynamic modulus, volumetrics, and in-place density) catalogued from this study will better reflect the rutting characteristics of SM-E mixtures when used in Pavement ME Design. These coefficients are also comparable to those incorporated in the latest version of Pavement ME Design, i.e., Version 2.6 (hereinafter "V2.6 Pavement ME Design").

The study recommends that VDOT's Materials Division consider using the rutting calibration coefficients developed for SM-E mixtures in this study when V2.6 Pavement ME Design is considered for adoption. However, further calibration/validation will still be needed when V2.6 Pavement ME Design is adopted. Limited field performance data indicated that certain SMA mixtures are susceptible to higher in-service rutting and rutting progression as compared to SM-E mixtures. The study recommends a detailed study to address the rutting concern for certain SMA mixtures.

17 Key Words: SMA, MEPDG, polymer modified asphalt mix, rutting, local calibration, dynamic modulus, permanent deformation test		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: 33	22. Price:

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

FINAL REPORT

DETERMINATION OF INPUT DATA FOR STONE MATRIX ASPHALT AND POLYMER MODIFIED DENSE-GRADED MIXTURES FOR USE IN THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

Harikrishnan Nair, Ph.D., P.E.
Associate Principal Research Scientist
Virginia Transportation Research Council

Bipad Saha, P.E
Pavement Engineer
Materials Division
Virginia Department of Transportation

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

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

October 2021
VTRC 22-R8

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

ABSTRACT

AASHTO's Mechanistic Empirical Pavement Design Guide (MEPDG) and AASHTOWare Pavement ME Design software (hereinafter "Pavement ME Design") provide an improved process for conducting pavement analysis and for developing pavement designs based on mechanistic-empirical principles. The Virginia Department of Transportation (VDOT) officially adopted the MEPDG procedure for new construction (new alignment, lane addition, and total reconstruction) for interstate and primary routes effective January 1, 2018. Pavement ME Design requires asphalt mixture volumetrics (asphalt content, air voids, and unit weight) and mechanical properties (dynamic modulus) as Level 1 (i.e., the most accurate) inputs. Currently, VDOT's dynamic modulus database has limited data on stone matrix asphalt (SMA) and dense-graded polymer modified (designated "SM-E") mixtures.

The purpose of this study was to develop input data for SMA and SM-E mixtures for use in Pavement ME Design. Material properties (dynamic modulus, volumetrics, and in-place density) catalogued from this study will better reflect the rutting characteristics of SM-E mixtures when used in Pavement ME Design. These coefficients are also comparable to those incorporated in the latest version of Pavement ME Design, i.e., Version 2.6 (hereinafter "V2.6 Pavement ME Design").

The study recommends that VDOT's Materials Division consider using the rutting calibration coefficients developed for SM-E mixtures in this study when V2.6 Pavement ME Design is considered for adoption. However, further calibration/validation will still be needed when V2.6 Pavement ME Design is adopted. Limited field performance data indicated that certain SMA mixtures are susceptible to higher in-service rutting and rutting progression as compared to SM-E mixtures. The study recommends a detailed study to address the rutting concern for certain SMA mixtures.

FINAL REPORT

DETERMINATION OF INPUT DATA FOR STONE MATRIX ASPHALT AND POLYMER MODIFIED DENSE-GRADED MIXTURES FOR USE IN THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

Harikrishnan Nair, Ph.D., P.E.
Associate Principal Research Scientist
Virginia Transportation Research Council

Bipad Saha, P.E
Pavement Engineer
Materials Division
Virginia Department of Transportation

INTRODUCTION

The Virginia Department of Transportation (VDOT) has adopted the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG) and its accompanying software (AASHTOWare Pavement ME Design) (hereinafter "Pavement ME Design") into its routine pavement design practice. Currently, Pavement ME Design is used for new design, reconstruction, and lane widening projects on primary, interstate, and high volume (>10,000 annual average daily traffic) secondary routes. VDOT completed several steps before implementing the mechanical-empirical (ME) pavement design procedures, including developing traffic inputs, characterizing material properties, calibrating and validating the models, and providing training. One of the important tasks in implementing the ME design process was to perform validation, calibration, and verification of the models to confirm that the predicted pavement performance matched what is observed in Virginia for the distress. VDOT completed local calibration of the MEPDG distress models for asphalt pavements, focusing on fatigue cracking and rutting. VDOT developed one set of local calibration factors for rutting, regardless of the surface mixture types. As a consequence, when Pavement ME Design is run using identical local calibration coefficients for the various VDOT mixtures, the performance of sections with stone matrix asphalt (SMA) mixtures was not better that the performance of dense-graded mixtures (Merine et al., 2019). A similar situation existed with dense-graded Superpave mixtures using polymer modified binders. This was contrary to the expected and observed field performance of these premium mixtures. None of the global calibration values for predicting rutting performance takes into account the difference between mixture types, and dynamic modulus alone, as measured in the laboratory, is not enough to explain the differences between mixtures in terms of rutting.

The technical basis for SMA is a stone skeleton with stone-on-stone contact, unlike traditional dense-graded mixtures where aggregates tend to float in the mixture with little contact between the larger aggregate particles. The stone-on-stone contact between high-quality aggregate resists the shear forces created by applied loads, creating a very rut-resistant mixture.

High percentages of mineral filler and binder create a glue-like mastic to hold the stone together and fill in the spaces in the coarse aggregate skeleton. This mastic-filled skeleton prevents water intrusion and provides excellent durability.

The MEPDG uses dynamic modulus to compute critical responses for hot mix asphalt (HMA) materials. As part of VDOT's implementation of the MEPDG, different surface mixtures were collected and tested for dynamic modulus (Apeagyei and Diefenderfer, 2011; Flintsch et al., 2007). In general, SMA mixtures had lower dynamic modulus (E*) values than dense-graded mixtures when tested conventionally under unconfined compression conditions. In the MEPDG methodology, this would imply greater rutting for SMA mixtures. Current dynamic modulus test protocols do not differentiate between SMA and conventional dense-graded mixtures. In general, there are very few studies reported in the literature regarding the advanced characterization of SMA.

The two main reasons for the growing acceptance of SMA and dense-graded polymer modified mixtures by many states are their improved rut resistance and durability. It is also expected that these mixtures will perform well against top-down fatigue cracking. To ensure that these potential performance advantages are reflected in ME design, it is necessary to provide for more advanced characterization of these materials.

PURPOSE AND SCOPE

The purpose of this study was to develop input data for SMA and dense-graded polymer modified mixtures (designated "SM-E" mixtures) for use in Pavement ME Design. Currently, VDOT's dynamic modulus database has limited data on SMA and SM-E mixtures. Pavement ME Design requires asphalt mixture volumetrics (asphalt content, air voids, and unit weight) and mechanical properties (dynamic modulus) as Level 1 (i.e., the most accurate) inputs. In addition to the mixture properties, binder properties such as complex shear modulus and phase angles are required as Level 1 inputs and were measured and documented in this study.

METHODS

Collection of SMA and SM-E Mixtures

Samples of asphalt mixtures were collected from different VDOT districts. Of the 13 mixtures sampled, 6 were SMA and 7 were SM-E mixtures. Additional details regarding the mixtures sampled and tested in this study including the design asphalt binder content and amount of reclaimed asphalt pavement (RAP) used are shown in Table 1. All samples were sampled loose at the plant and sent to the Virginia Transportation Research Council (VTRC) laboratory for further testing. Samples were stored in a temperature-controlled environment in sealed containers before testing.

Table 1. SMA/SM-E Mixtures

Mix Type	Lab ID	VDOT District	% RAP	Design AC Content	Asphalt Binder Grade
SMA 12.5	18-1016	Fredericksburg	15%	6.4%	PG 64E-22
SMA 9.5	18-1031	NOVA	12%	6.3%	PG 64E-22
SMA 9.5	18-1038	Culpeper	13%	6.4%	PG 64E-22
SMA 12.5	18-1047	Salem	15%	6.8%	PG 64E-22
SMA 12.5	18-1051	Richmond	15%	6.7%	PG 64E-22
SMA 12.5	18-1064	Staunton	0%	6.7%	PG 64H-22
SM 9.5E	18-1011	Culpeper	15%	5.5%	PG 64E-22
SM 12.5E	18-1012	Richmond	15%	5.9%	PG 64E-22
SM 12.5E	18-1022	Salem	15%	5.7%	PG 64E-22
SM 12.5E	18-1042	Fredericksburg	15%	5.2%	PG 64E-22
SM 12.5E	18-1046	Richmond	15%	5.9%	PG 64E-22
SM 12.5E	18-1057	Richmond	15%	5.8%	PG 64E-22
SM 9.5E	18-1059	NOVA	15%	5.4%	PG 64E-22

SMA = stone matrix asphalt; SM-E = dense-graded polymer modified; RAP = reclaimed asphalt pavement; AC = asphalt content; NOVA = Northern Virginia.

Laboratory Testing

Volumetric Analysis

Volumetric and gradation analyses were performed for all sampled mixtures. Gyratory pills, 150 mm in diameter, were compacted to 50 gyrations for volumetric determination in accordance with VDOT specifications. Data collected and compiled for each mixture included asphalt content and gradation; voids in total mixture (VTM); voids in mineral aggregate (VMA); voids filled with asphalt (VFA); dust/asphalt ratio; and effective binder content (Pbe).

Dynamic Modulus Test

The primary material property input for the MEPDG is the dynamic modulus (|E*|) of the asphalt concrete mixture. This property quantifies the modulus of the asphalt concrete over a range of expected temperatures and traffic speeds as a function of loading frequency. The structural response model in Pavement ME Design uses the dynamic modulus for the asphalt layer to calculate the stresses and strains induced in the pavement by traffic loads. Dynamic modulus tests were performed with an asphalt mixture performance tester (AMPT) generally in accordance with AASHTO T 378, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT) (AASHTO, 2019). Tests were performed on specimens prepared from gyratory-compacted asphalt samples (100-mm diameter by 150-mm deep). Four testing temperatures ranging from 4.4 ºC to 54 °C and six testing frequencies ranging from 0.1 Hz to 25 Hz were used. Since dynamic modulus was not tested at -10 ºC (which is a required input in pavement ME analysis), modulus values were estimated from mastercurves using the time-temperature superposition principle. Tests were performed from the coldest to the warmest temperature. At each test temperature, the tests were performed from the highest to the lowest frequency. Load levels were selected in such a way that at each temperature-frequency combination, the applied strain was in the range of 75 to 100 microstrains. Stress versus strain values were captured continuously and used to calculate dynamic modulus. The results at each temperature-frequency combination for each mixture type are reported for three replicate specimens.

As mentioned previously, previous research (Apeagyei and Diefenderfer, 2011) showed a lower dynamic modulus for SMA mixtures than for dense-graded mixtures when tested under the unconfined testing condition. SMA is a gap-graded asphalt concrete mixture that typically consists of 70% to 80% coarse aggregate with fine aggregate, mineral filler, asphalt cement, and a stabilizing agent. There is a need to determine whether confining pressure is an important factor to be considered in assessing the behavior and performance of SMA to reflect realistically the true stiffness of SMA mixtures. Though confined dynamic modulus test protocols are not included in AASHTO T 378, a few tests were conducted in the confined mode (using 10 psi confining pressure) and with different air voids (4.5% and 7%) for SMA mixtures. Several of the mixtures collected for this study were used to explore confined mode impacts, but most of the material was sampled and tested for other studies (Hossain et al., 2020).

Repeated Load Permanent Deformation Test

The rutting performance of asphalt mixtures is characterized in Pavement ME Design using two coefficients, intercept and slope, that are used to define repeated load permanent deformation (RLPD) curves in log-log space. The intercept defines the permanent deformation on the first load cycles, and the slope describes how the permanent deformation increases with increasing number of loading cycles. The permanent deformation intercept and slope are measured using the RLPD test using the AMPT. RLPD tests were conducted at temperatures of 20 ºC, 35 ºC, and 54 ºC. The test temperature of 54 °C is based on LTPPBind software and represents the 50% reliability maximum high pavement temperature at sites in central Virginia. A repeated haversine axial compressive load pulse of 0.1 s every 1.0 s was applied to the specimens. The tests were performed in the confined mode using a deviator stress of 482.6 kPa. Air is used to supply the confining pressure, and it was constant throughout the test at 68.9 kPa. The tests were continued for 10,000 cycles or a permanent strain of 10%, whichever came first. Three specimens were tested at 54 ºC, and two specimens each were tested at 20 ºC and 35 ºC. The accumulated permanent deformation is recorded from the actuator displacement at the end of each loading cycle.

Binder Recovery and Grading

Another material property for the MEPDG is the dynamic shear modulus of the asphalt binder (|G*|). Similar to |E*| testing, |G*| testing is meant to capture the behavior of the asphalt binder over a range of expected temperatures and traffic speeds (by loading frequencies). Extraction of binder from loose mixture was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A (AASHTO, 2019), using n-propyl bromide as the solvent. Binder was recovered from the solvent using the Rotavap recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures (AASHTO, 2019). The extracted binder grading was performed in accordance with AASHTO M 332-20, Performance-Graded Asphalt Binder (AASHTO, 2020).

In-Place Density Evaluation

In-place density of asphalt mixtures is an important input in the MEPDG for performance predictions. Statewide density data (obtained from VDOT's Materials Division) were collected and summarized for SMA and SM-E mixtures placed in 2018. These data include field density values for asphalt mixtures from this study, and the same approach was used for previously catalogued mixtures.

Field Performance Comparison

Rutting distress data for pavements with SMA and SM-E surface mixtures (SMs) from past projects were collected from VDOT's Pavement Management System (PMS). The complete list of projects paved during those years was not considered for analysis; the projects were randomly selected.

RESULTS AND DISCUSSION

Mixture Volumetric Properties

In Pavement ME Design, the material inputs for individual asphalt layers are divided into three groups: asphalt general, asphalt mixture, and asphalt binder. Volumetric properties of the SMA and SM-E mixtures are shown in Tables 2 and 3. As they are required inputs in Pavement ME Design, unit weight and effective binder content (% by volume) were also determined and provided. Tables 4 and 5 show gradations of the SMA and SM-E mixtures.

Table 2. Volumetric Data for SMA Mixtures

Property	SMA-12.5	SMA-9.5	SMA-9.5	SMA-12.5	SMA-12.5	SMA-12.5
Sample ID	18-1016	18-1031	18-1038	18-1047	18-1051	18-1064
%AC	7.01	6.36	6.62	6.74	6.73	6.90
%Air Voids (Va)	3.5	3.6	3.2	3.9	4.9	4.1
%VMA	20.4	19.1	19.5	18.9	20.0	19.6
%VFA	82.9	81.3	83.7	79.5	75.4	78.9
VCA_{MIX}	41.2	35	33.7	41.0	43.8	41.8
VCA_{DRC}	42.4	41.4	41.3	42.5	43	42.8
Effective % Binder (Pbe)	6.85	6.28	6.62	6.65	6.70	6.71
Unit Weight (pcf)	**158.2**	**159.6**	**159.7**	**146.8**	**145.7**	**150.7**
Effective Binder Content (%) (by volume)	**17.50**	**16.07**	**16.80**	**15.65**	**15.85**	**16.17**

Values in bold type indicate required inputs in MEPDG.
SMA = stone matrix asphalt; AC = asphalt concrete; Va = air voids; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; VCA_{MIX} = voids in coarse aggregate of the SMA mixture; VCA_{DRC} = voids in coarse aggregate in dry-rodded condition.

Table 3. SM-E Mixture Volumetrics

Property	SM-9.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-9.5E
Mix ID	18-1011	18-1012	18-1022	18-1042	18-1046	18-1057	18-1059
%AC	5.46	5.42	5.46	5.08	6.55	6.05	5.95
%Air Voids (Va)	2.9	3.4	3.4	5	0.9	3.3	1.9
%VMA	16.3	15.5	15.7	16.7	15.8	16.3	15.9
%VFA	82.4	78.3	78.1	70.3	94.5	79.9	87.9
Effective % Binder (Pbe)	5.19	5.16	5.33	4.89	6.30	5.63	5.76
Unit Weight (pcf)	**166**	**150.8**	**148.2**	**154.3**	**152.6**	**149.2**	**155.8**
Effective Binder Content (%) (by volume)	**13.81**	**12.53**	**12.72**	**12.35**	**15.09**	**13.51**	**14.24**

Values in bold indicate required inputs in MEPDG.
SM-E = dense-graded polymer modified; SM = surface mix; AC = asphalt content; VMA = voids in mineral aggregate; VFA = voids filled with asphalt.

Table 4. Gradation of SMA Mixtures

Mix Type	SMA-12.5	SMA-9.5	SMA-9.5	SMA-12.5	SMA-12.5	SMA-12.5
Sieve	18-1016	18-1031	18-1038	18-1047	18-1051	18-1064
3/4 in (19 mm)	100	100	100	100	99	100
1/2 in (12.5 mm)	90.3	89	92.2	87.9	84	84.2
3/8 in (9.5 mm)	68.5	73.1	69.0	63.5	67.7	64.3
No. 4 (4.75 mm)	26.8	29.2	27.1	27.5	30.7	28.7
No. 8 (2.36 mm)	18.4	19.6	17.5	19.4	20.4	19.5
No. 30 (0.6 mm)	15.1	16.1	13.7	16	16.8	13.5
No. 200 (75 µm)	10.1	9.9	8.5	10.4	10.2	8.0

SMA = stone matrix asphalt.

Table 5. Gradation of SM-E Mixtures

Mix Type	SM-9.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-12.5E	SM-9.5E
Sieve	18-1011	18-1012	18-1022	18-1042	18-1046	18-1057	18-1059
¾ in (19.0 mm)	100	100	100	100	100	100	100
½ in (12.5 mm)	98.8	94.1	96.6	97.2	96.3	97.2	96.0
3/8 in (9.5 mm)	91.7	80.1	83.8	88.0	85.9	87.4	93
No. 4 (4.75 mm)	61.7	52.3	54.8	63.4	63.3	61.4	53.7
No. 8 (2.36 mm)	42	35	40	45.8	43.8	41.5	39.1
No. 30 (0.6 mm)	22.4	17.9	24	22.8	22.7	21.1	23.9
No. 200 (75 µm)	6.2	6.0	6.7	4.8	7.9	5.4	5.8

SM-E = dense-graded polymer modified; SM = surface mix.

Two mixtures were SMA-9.5 mixtures, and four mixtures were SMA-12.5 mixtures. Some of the mixtures did not meet design gradation criteria for certain sieves (i.e., 12.5 mm, 83% to 93%; 9.5 mm, 80% maximum; 4.75 mm, 22% to 28%; 2.36 mm, 16% to 24%; No. 30, 15% to 30%; No. 200, 9% to 11%) but did meet the criteria considered allowable for production tolerance based on VDOT specifications (VDOT, 2020). SMA mixtures require good stone-on-stone contact of the coarse aggregate to be able to function as durable and rut-resistant mixtures. A quantitative method for ensuring stone-on-stone contact suggests limiting the voids in coarse aggregate (VCA) of the SMA mixture (VCA_{MIX}) to be less than the VCA in the dry-rodded condition (VCA_{DRC}). VCA_{MIX} and VCA_{DRC} for all mixtures are shown in Table 2. All mixtures met the criterion of $VCA_{MIX} < VCA_{DRC}$ except for Mix 18-1051. However, most mixtures just barely met this criterion, which could indicate questionable stone-on-stone contact (if VCA_{MIX} > VCA_{DRC}, the fine aggregate fraction and asphalt in the mixture can push the coarse aggregate particles apart and destabilize the mixture structure). It should be noted that SMA-12.5 mixtures use a breakpoint sieve of 4.75 mm and SMA-9.5 mixtures use the 2.38 mm sieve as the breakpoint. SMA is very sensitive to changes in the material passing the respective breakpoint sieve. The significance of the breakpoint sieve is that it identifies the point at which the gap in the gradation begins. Excessive material passing the breakpoint sieve (reduction in coarse aggregate fraction) will cause the mixture to lose stone-on-stone contact. VCA_{MIX} for the SM-12.5 mixtures ranged from 41% to 43.8%, and VCA_{DRC} of the SM-12.5 mixture ranged from 41.3% to 43%.

Three of the SMA mixtures (Mixes 18-1047, 18-1051, and 18-1064) had a lower unit weight compared to other SMA mixtures. This may have been due to the difference in aggregate specific gravities. All the SM-E mixtures met VDOT's volumetric and gradation criteria. In general, gradations of different SM-E mixtures were comparable. Volumetric analysis showed that binder contents of SMA mixtures ranged from 6.3% to 7% and those of SM-E mixtures ranged from 5% to 6.5%. As expected, SMA mixtures had higher binder contents (as per VDOT specifications, a minimum binder content of 6.3% is required for SMA mixtures) than SM-E mixtures (an average of 1% higher effective binder content). Mixtures with higher binder contents usually exhibit higher cracking resistance.

Dynamic Modulus

As a first step, the effect of confinement and air voids on dynamic modulus was evaluated using an SMA mixture collected from another VTRC project (Hossain et al., 2020). Current dynamic modulus test protocols do not differentiate between SMA and conventional dense-graded mixtures. Tests were conducted in both the unconfined mode and confined mode using a confining pressure of 10 psi. To find the effect of air voids, tests were conducted using 4.5% air voids (selected based on field air voids—SMA mixtures in general have higher field density requirements than dense-graded mixtures and hence lower in-place air voids are observed) and 7% air voids. Test results are shown in Figures 1 and 2. It can be seen from the figures that dynamic modulus increased when the confined test protocol was used. However, when the 4.5% air-void specimen was used, the increase in modulus was not significant when the results of confined and unconfined dynamic modulus tests were compared. Also as expected, lower air voids resulted in higher dynamic modulus. The effect of confinement was significant at low reduced frequencies (i.e., high temperature and/or low loading frequency). This finding was somewhat expected because as the temperature increases or loading frequency decreases, asphalt binder becomes softer and the effect of confinement on the aggregate structure becomes more significant. Confinement makes the asphalt-aggregate mixture more resistant to stress in these conditions, and thus the triaxial test (confined) yields a greater dynamic modulus than the uniaxial test.

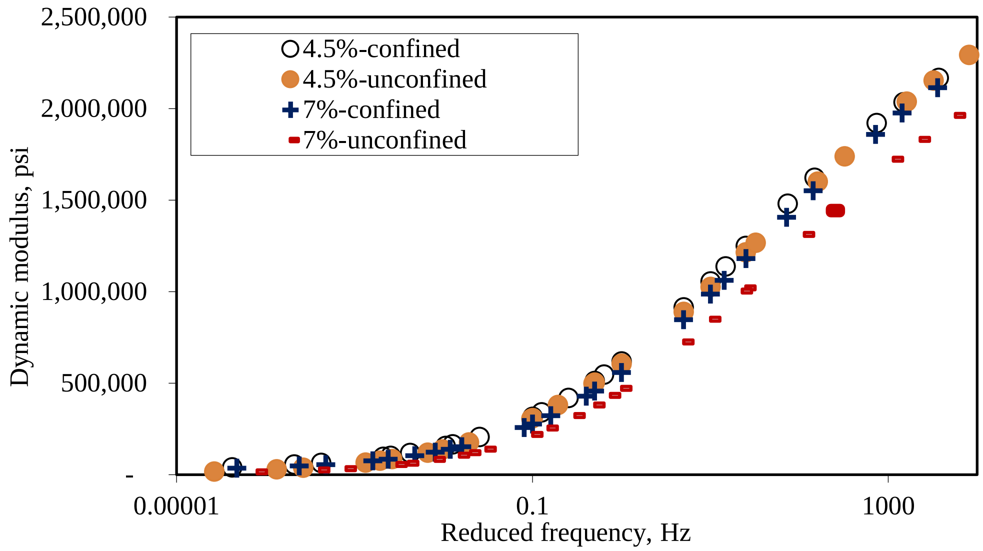

Figure 1. Dynamic Modulus of SMA Mixtures (Confined vs. Unconfined) (Semi-log Scale). SMA = stone matrix asphalt.

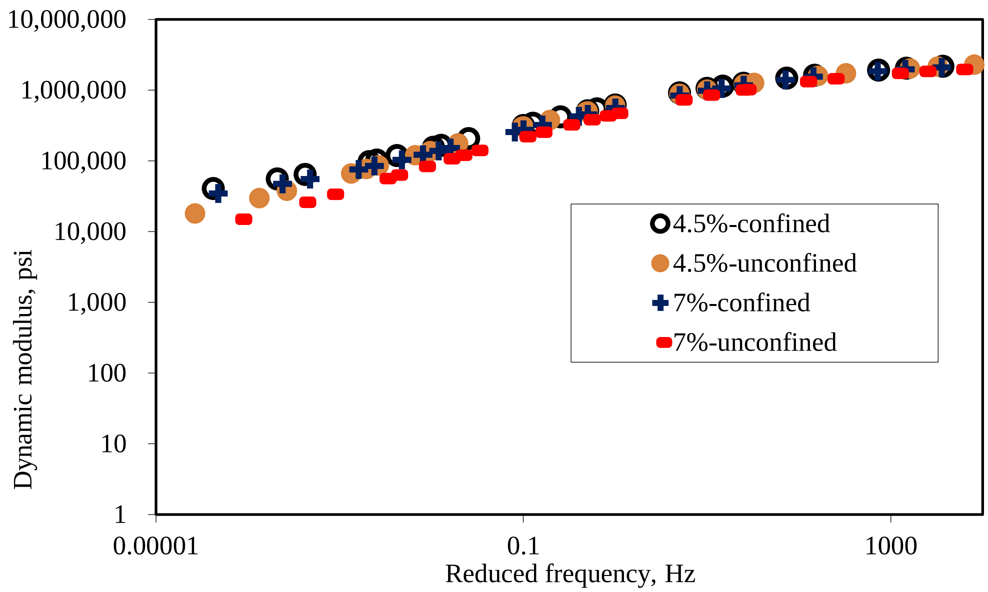

Figure 2. Dynamic Modulus of SMA Mixtures (Confined vs. Unconfined) (Log-Log Scale). SMA = stone matrix asphalt.

Based on the test results, an unconfined dynamic modulus with lower air voids (5 ± 0.5%) was used for further SMA mixture testing. Figures 3 and 4 show the dynamic modulus mastercurves of SMA as tested in this study. An average of previously cataloged (VDOT, 2020) dynamic modulus values for SM mixtures (dense-graded Superpave mixtures) are also shown in Figures 3 and 4 for comparison. For SMA mixtures, all of the mixtures had lower dynamic modulus values as compared to the previously catalogued data. In addition, three of the SMA mixtures (Mixes 18-1051, 18-1064, and 18-1047) had higher dynamic modulus values compared to those of three other SMA mixtures (Mixes 18-1016, 18-1038, and 18-1031).

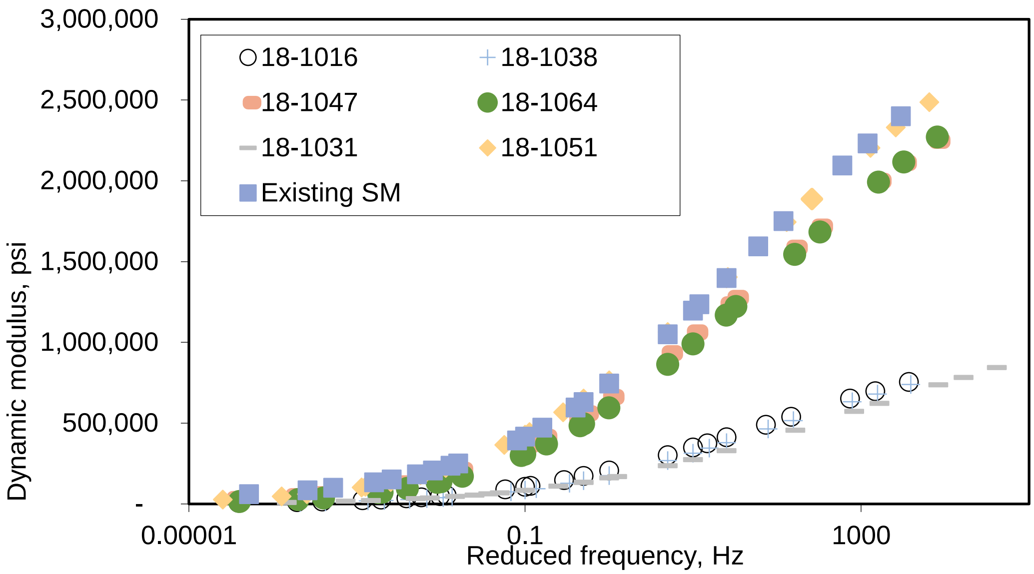

Figure 3. Dynamic Modulus Mastercurves for SMA Mixtures (Semi-Log Scale). SMA = stone matrix asphalt.

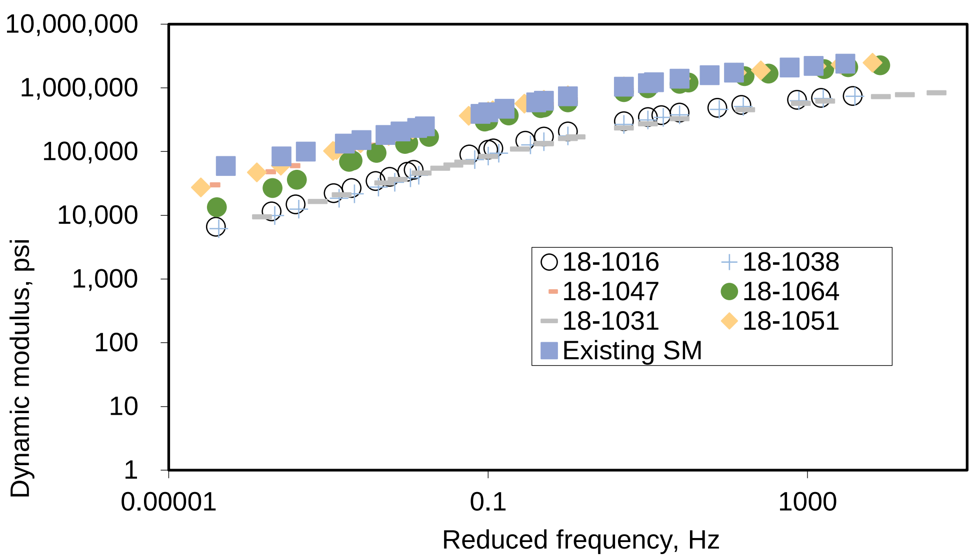

Figure 4. Dynamic Modulus Mastercurves for SMA Mixtures (Log-Log Scale). SMA = stone matrix asphalt.

Dynamic modulus test results for SM-E mixtures are shown in Figures 5 and 6. In general, with one mixture (Mix 18-1059) as an exception, all mixtures had either a similar or higher dynamic modulus than those previously catalogued. Mix 18-1022 had a higher dynamic modulus and a lower unit weight compared to other mixtures. Appendix A shows the dynamic modulus values for SM-E mixtures.

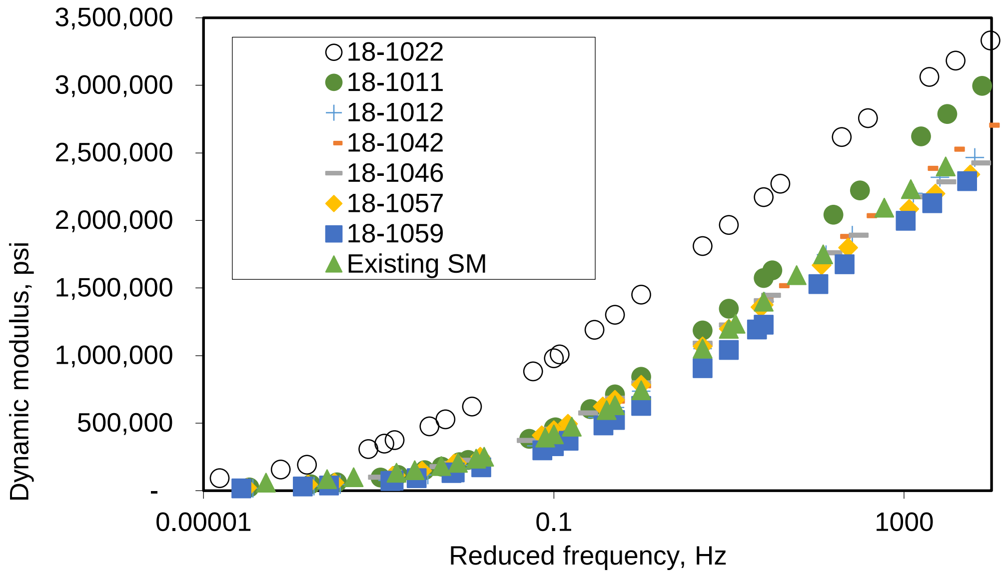

Figure 5. Dynamic Modulus Mastercurves for SM-E Mixtures (Semi-Log Scale). SM-E = dense-graded polymer modified.

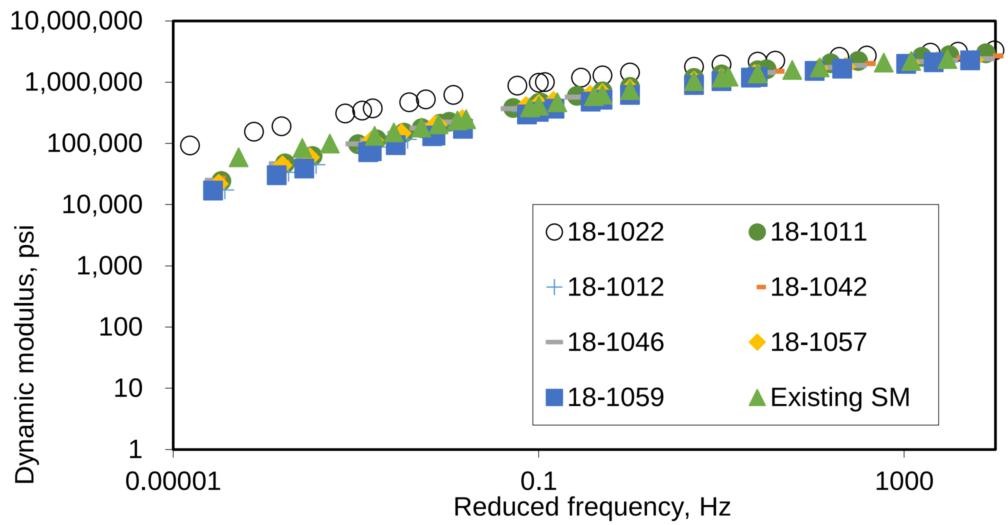

Figure 6. Dynamic Modulus Mastercurves for SM-E Mixtures (Log-Log Scale). SM-E = dense-graded polymer modified.

Two more dynamic modulus tests were conducted with and without confinement using 5 ± 0.5% air voids to confirm the effect of confinement. The results are shown in Figure 7. It can be seen that at lower air voids, similar dynamic values were obtained for both confined and unconfined testing. This shows that SMA mixtures can be tested at low air voids (because of the higher density requirement) and without confinement and still have modulus values comparable to those when tested with confinement.

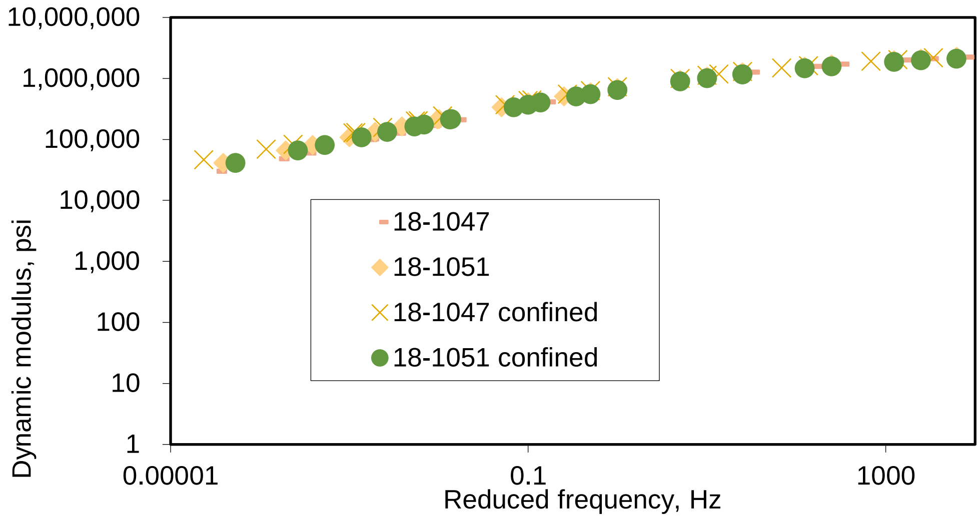

Figure 7. Dynamic Modulus of SMA Mixture (Confined vs. Unconfined) (Log-Log Scale) Using 5 ± 0.5% Air Voids

Repeated Load Permanent Deformation Coefficients

The rutting model used in the MEPDG is shown in Equation 1. As per the local calibration study (Smith and Nair, 2016), only β_1 was adjusted to match predicted rutting with measured rutting. Global (default) coefficients were used as laboratory permanent deformation coefficients (k_1, k_2, k_3), i.e., were not verified with Virginia mixtures. For this study, RLPD tests were conducted to develop rutting coefficients (k_1, k_2, k_3) for SMA and SM-E mixtures.

$$Asphalt\ rutting = \beta_r k_z 10^{k_1} T^{k_2 \beta_2} n^{k_3 \beta_3} \quad \text{[Eq. 1]}$$

where

n = number of axle load repetitions
T = temperature in the asphalt sublayer, ºF
kz = depth correction factor
k_1, k_2, k_3 = laboratory-determined permanent deformation coefficients
β_1, β_2, β_3, = local calibration coefficients.

The RLPD curve has three zones, as shown in Figure 8. The primary zone is where the slope of the permanent strain curve decreases with increasing load cycles. The secondary zone is where the slope of the permanent strain curve is nearly constant. The tertiary zone is where the slope of the permanent strain curve increases with increasing load cycles. The rutting model in Pavement ME Design uses the slope and intercept from the secondary portion of the permanent strain curve. Asphalt mixtures resistant to plastic strain do not exhibit the tertiary zone. In fact, mixtures that exhibit the tertiary response under confined testing conditions can be susceptible to excessive rutting.

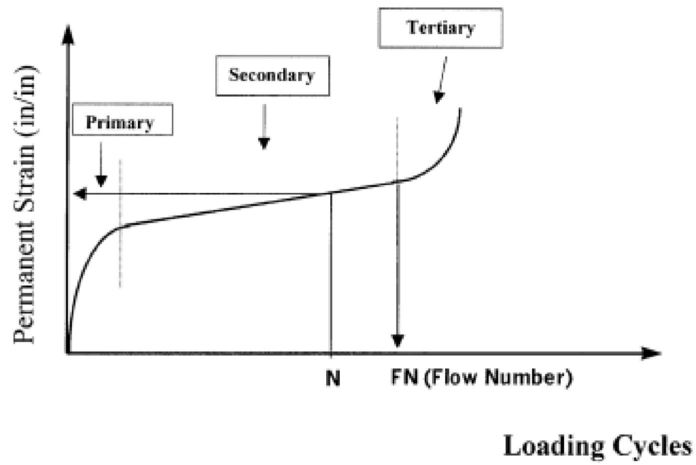

Figure 8. Example of General Relationship Between Permanent Strain and Loading Cycles

The intercept of the secondary zone is k_1. The lower the intercept, the lower the predicted rut depth; k_2 is the temperature exponent and is assumed to be independent of time. The lower the temperature exponent, the less sensitive plastic strains are to temperature and the lower the predicted rut depth. The slope of the secondary zone is k_3. The lower the slope, the lower the growth rate of the predicted rut depth and the lower the predicted final rut depth.

The laboratory-determined permanent deformation coefficients were determined from the slope and intercept of the secondary zone of RLPD curves plotted as the logarithm of the accumulated permanent strain versus the logarithm of the number of loading cycles. Linear regression is used to determine the slope and intercept of the secondary zone of the permanent deformation curve. The lower the intercept and slope, the more resistant the asphalt mixture is to rutting. The primary and tertiary zones of the permanent deformation curve are excluded from the analyses. Figure 9 shows typical laboratory repeated load permanent strain curves for an asphalt mixture used in this study with three testing temperature. Figure 10 shows a log-log chart of permanent deformation data.

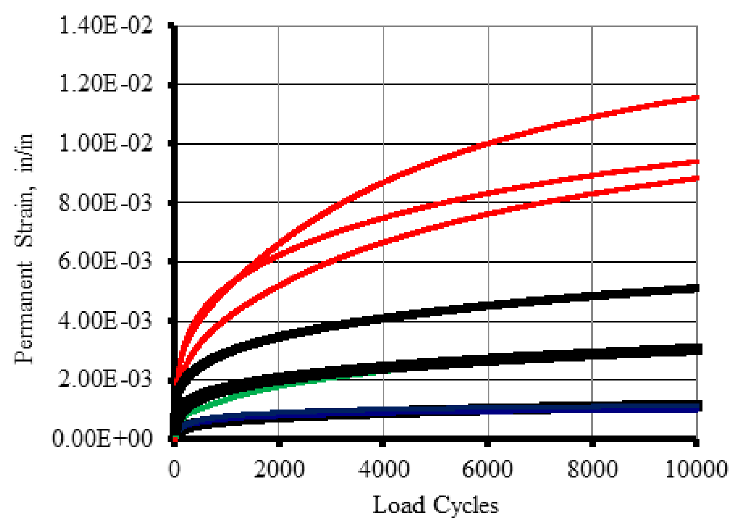

Figure 9. Typical Laboratory Repeated Load Permanent Strain Curve With Three Test Temperatures (Mix 18-1022). Red = data at 54 ºC; green and black = data at 35 °C; blue = data at 20 ºC.

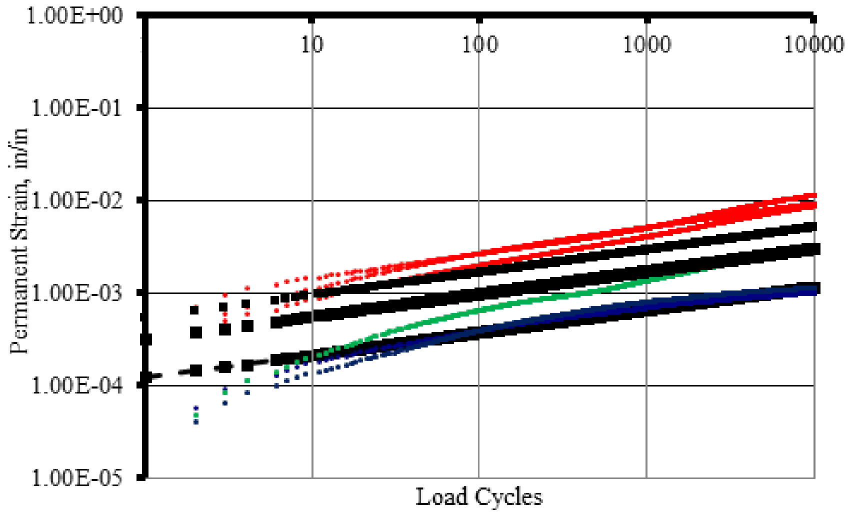

Figure 10. Log-Log Chart of Permanent Deformation Data (Mix 18-1022). Red = data at 54 ºC; green and black = data at 35 ºC; blue = data at 20 ºC.

Permanent deformation coefficients developed for SMA and SM-E mixtures from this study are shown in Tables 6 and 7. Mixtures with slope (k_3) values greater than 0.30 are more susceptible to rutting, and mixtures with values less than 0.20 are more resistant to rutting (Von Quintus et al., 2020). It can be seen that for most of the SMA mixtures, the slope value was higher than 0.30. SMA mixtures, which had lower dynamic modulus (Mixes 18-1016, 18-1038, and 18-1031), had k_3 values that ranged from 0.33 to 0.64, indicating rutting susceptibility.

Table 6. Laboratory Rutting Coefficients for SMA Mixtures

Mix	Rutting Coefficients		
	k_1	k_2	k_3
18-1016[a]	-15.5876	6.2311	0.4690
18-1031[a]	-16.3021	6.2787	0.6394
18-1038[a]	-13.8683	5.7331	0.3336
18-1047	-14.2093	5.3735	0.3032
18-1051	-19.4243	8.3904	0.2411
18-1064	-12.9854	4.7979	0.3056
Average	-15.3962	6.1341	0.3819
Average (excluding 18-1031)	-15.2452	6.110	0.3390

SMA = stone matrix asphalt.
[a] Mixtures with lower dynamic modulus.

Table 7. Laboratory Rutting Coefficients for SM-E Mixtures

Mix	Rutting Coefficients		
	k_1	k_2	k_3
18-1011	-12.8007	4.9993	0.2903
18-1022	-8.0648	2.2665	0.2450
18-1042	-11.9303	4.4893	0.2424
18-1046	-7.9924	2.9425	0.1005
18-1057	-8.1190	2.9667	0.1276
18-1059	-7.9575	2.5001	0.2412
Average	-9.4774	3.3607	0.2078

SM-E = dense-graded polymer modified.

SMA mixtures with a higher dynamic modulus had an average k_3 value of 0.28. SM-E mixtures had an average k3 value of 0.20, indicating superior rut resistance. For the temperature exponent (k_2), mixtures with values greater than 3.5 are more susceptible to rutting and mixtures with values less than 3.0 are more resistant to rutting (Von Quintus et al., 2020). For SMA mixtures, this value was greater than 3.5, indicating rutting susceptibility. For SM-E mixtures, the average value was less than 3.5. The RLPD test includes a specimen load conditioning sequence before the data are collected for the permanent strain curve. The conditioning is 100 load cycles using a confining pressure of 68.9 kPa, repeated deviator stress of 48.3 kPa, and contact deviator stress of 2.4 kPa. The purpose of this conditioning sequence is to seat the load and deformation measuring equipment. Conditioning cycles were not applied during the testing and hence k_1 values were lower for both SMA and SM-E mixtures. The use of a lower k_1 value (intercept value) will predict a lower initial rutting and hence the final rut depth value also will be lower. A virtual pre-conditioning (by removing the first 51 cycles) was applied to the data, as suggested by Gibson and Li (2013). However, the results did not show differences in k_1 values and hence are not reported.

Table 8 shows the rutting coefficients currently used by VDOT, which uses V2.2.6 Pavement ME Design. The k-values are defined by laboratory results, and the β-values (β_1, β_2, β_3) are defined from the field (field shift factors). In V2.6 Pavement ME Design, the laboratory and field coefficient values were separated out. (The global values for β_1, β_2, and β_3 were 0.40, 0.52, and 1.36, respectively.) A major observation from this study is that V2.2.6 Pavement ME Design uses a high coefficient for k_3* β_3, which will predict a higher rutting as truck traffic increases. An explanation for this finding is that the k_3 global value was originally derived from unconfined repeated load plastic deformation tests. NCHRP Project 9-30A (Von Quintus et al., 2012) recommended use of confined repeated load plastic deformation tests. The k_3 value derived from confined repeated load tests was included in V2.6 Pavement ME Design. VTRC laboratory testing showed a similar k_3* β_3 value for SM-E when compared to V2.6 Pavement ME Design. This study also showed a lower k_1* β_1 coefficient compared to V2.6 Pavement ME Design. With lower k_1* β_1 values, predicted rut depth will be lower shortly after construction. In summary, lower k_1* β_1 values will result in lower predicted rut depths shortly after construction and lower k_3* β_3 values will result in less rutting being accumulated for the heavier truck volumes over time. However, these coefficients will still need to be calibrated/validated when VDOT adopts V2.6 Pavement ME Design.

Table 8. Comparison of Rutting Calibration Coefficients

Coefficient	V2.2 (Global Calibration)	VDOT Local Calibration (V2.2)	V2.6 (Default Values)	VTRC Lab Testing	
				SMA	SM-E
k1* β1	-3.35417	-2.304	-0.98	-6.09[a]	-3.79
k2* β2	1.5606	1.5606	1.56	3.17	1.74
k3* β3	0.4791	0.4791	0.2992	0.4610[b]	0.2826

VTRC = Virginia Transportation Research Council; SMA = stone matrix asphalt; SM-E = dense-graded polymer modified.
[a] Used global β1, β2, β3.
[b] Used the average k3 from SMA mixtures (excluding Mix 18-1031, which showed higher k3 values compared to other mixtures).

On the other hand, values were higher for SMA mixtures, which was not expected since SMA mixtures have a reputation for rutting resistance. However, the k_3* β_3 value (average k3 from SMA mixtures [excluding Mix 18-1031]) for SMA mixtures was still lower than current local calibrated values from V2.6 Pavement ME Design. The field rutting performance of SMA mixtures must be considered before the new values are adopted.

Currently, VDOT uses one set of calibration coefficients for surface, intermediate, and base asphalt mixtures. All three mixtures use a slope factor of 0.4791. The ability to enter layer- or mixture-dependent plastic deformation coefficients was added to the software, as shown in Figure 11.

Figure 11. Pavement ME Design Rutting Calibration Coefficients (V2.2.6 Pavement ME Design)

Binder Recovery and Grading

Table 9 shows extracted binder grading and stiffness details from four of the SMA mixtures. SMA and SM-E mixtures used polymer modified binder (PG 64 E-22) and most mixtures had 15% RAP. As expected, the binders had a high temperature PG grade of PG 76. Non-recoverable creep compliance (Jnr) values are also shown in Table 9.

Table 9. Extracted Binder Test Data for Selected Mixtures

Sieve	18-1016 (SMA)	18-1038 (SMA)	18-1047 (SMA)	18-1051 (SMA)
PG grade	PG 76-22	76-22	76-22	76-22
Binder, G* (Pa), 76 °C	2291	3135	3537	2936
Phase Angle, 76 °C	72.59	66.62	66.24	69.16
Non-Recoverable Jnr100Pa	0.3932	0.3733	0.3438	0.3033
Non-Recoverable Jnr3200Pa	0.5144	0.4769	0.4467	0.3711
Avg. % Recovery R100Pa	49.49	62.45	64.13	56.61
Avg. % Recovery R3200Pa	35.22	53.36	53.47	47.46

SMA = stone matrix asphalt.

In general, the lower the Jnr values, the higher the rut resistance. SMA mixtures, which had lower dynamic modulus, had higher Jnr values (for the extreme traffic level, $Jnr_{3.2} \leqslant 0.5$ kPa is required). Further, mixtures that had higher Jnr values also had higher slope values (k3) in the RLPD test, indicating rutting susceptibility.

In-Place Density Evaluation

Statewide density data for SMA and SM-E mixtures placed in 2018 were analyzed and are shown in Table 10. The placement specification for SMA mixtures includes a minimum 94% density requirement (6% in-place air voids) and that for SM-E mixtures includes a minimum 92.5% (7.5% in-place air voids) density requirement. In-place density values were higher for both SMA and SM-E mixtures when compared with other dense-graded mixtures as reported by McGhee and Smith (2021). Higher in-place density generally improves the fatigue life and rutting resistance and hence the service life of the pavement.

Table 10. In-Place Density Data for SMA and SM-E Mixtures

Mix Type	Avg. In-Place Air Voids	Standard Deviation	Range
SMA	4.2%	1.0%	1.7%-6.8%
SM-E	5.8%	1.0%	2.8%-8.8%

SMA = stone matrix asphalt; SM-E = dense-graded polymer modified.

Field Rutting Performance of SMA and SM-E Mixtures

Limited field performance data were collected from VDOT's PMS. Figures 12 and 13 show the SMA mixture and SM-E mixture rutting progression in the field for different projects paved in 2011 and before. From these figures it can be seen that rutting resistance was excellent and performance for both mixtures (SMA and SM-E) was comparable. Figures 14 and 15 show rutting results for 6 SM-E and 10 SMA field projects paved from 2012-2016. The SM-E mixtures continued to show good rutting resistance. However, as can be seen in Figure 15, a few SMA projects had a higher rut depth and rutting progression (4 projects rutting above 0.2 in). VDOT's Materials Division conducted several field investigations (paved from 2012-2016) of these projects, and it was concluded that in some cases substandard binder was the issue. In some of the projects, rutting was due to a weak underlying layer, and in some it was due to substandard compaction during construction. For Pavement ME Design, VDOT currently uses an asphalt rutting criterion of 0.26 in for a 15-year design life. Although 15-year field rutting data were not available for the projects considered here, for SM-E mixtures in general, rutting was below 0.15 in. Rutting was below 0.2 in for SMA mixtures except for a few mixtures. Field rutting data also showed that initial rutting (after construction) ranged from 0.05 in to 0.1 in.

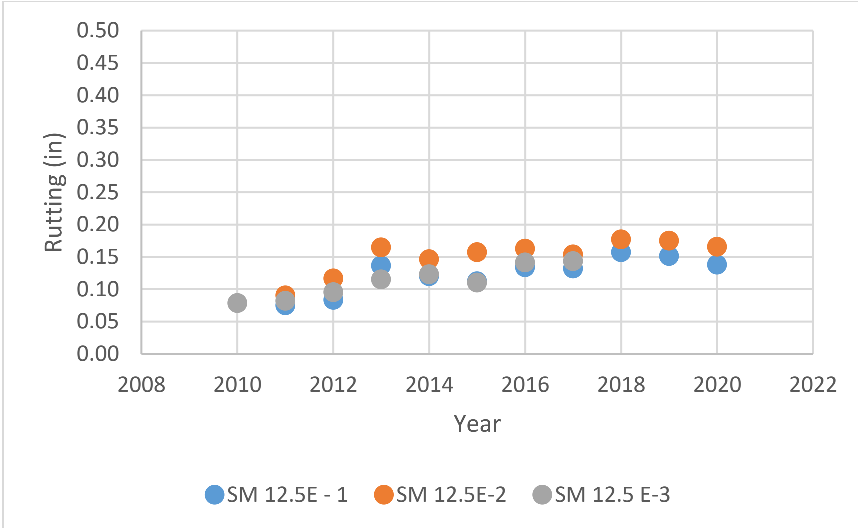

Figure 12. Field Rutting Data for SM-E Mixtures (Paved Before 2011). SM-E = dense-graded polymer modified.

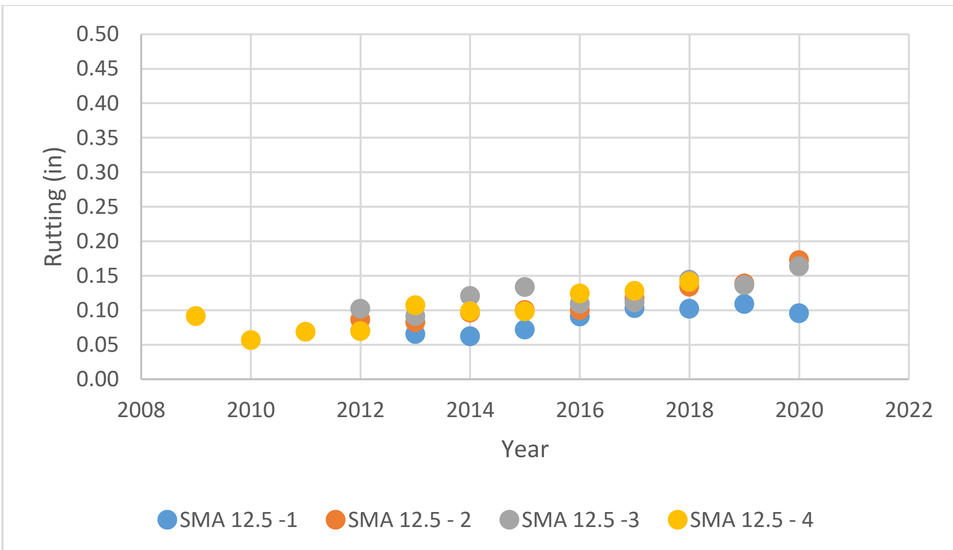

Figure 13. Field Rutting Data for SMA Mixtures (Paved Before 2011). SMA = stone matrix asphalt.

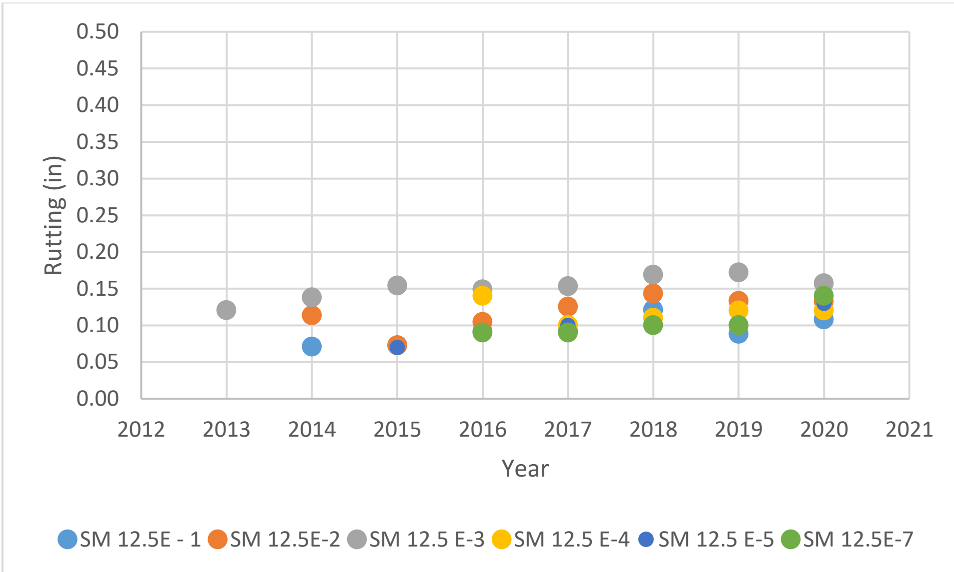

Figure 14. Field Rutting Data for SM-E Mixtures (Paved From 2012-2016). SM-E = dense-graded polymer modified.

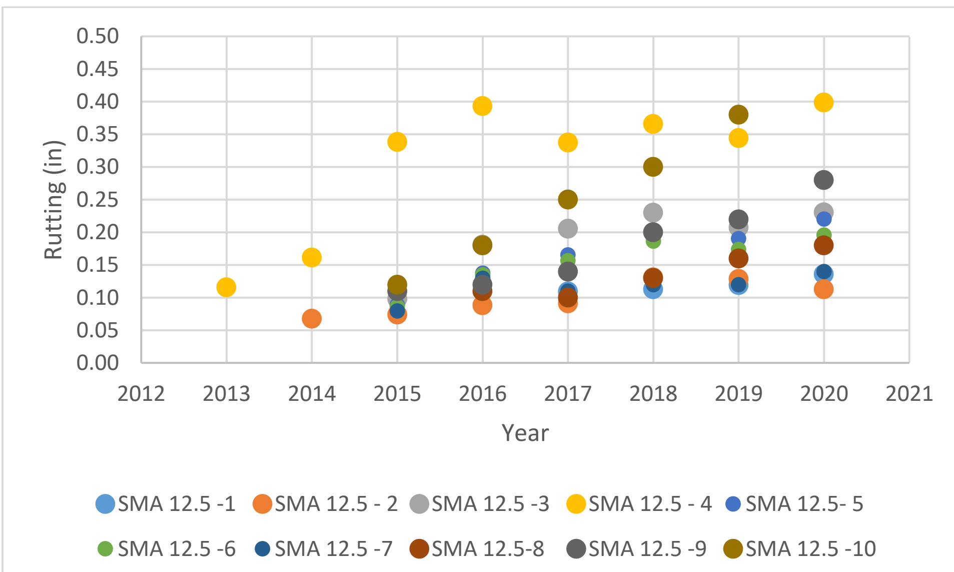

Figure 15. Field Rutting Data for SMA Mixtures (Paved From 2012-2016). SMA = stone matrix asphalt.

To compare with the field rutting performance trend, MEPDG analyses were performed using inputs collected from this project for SM-E mixtures and comparing them with existing inputs used by VDOT. The results are shown in Appendix B. VDOT uses rutting criteria of 0.15 in for 15 years and 6% bottom-up fatigue cracking for 30 years. Analyses were conducted for 8,000 truck traffic levels. The thicknesses assumed for the pavement ME analysis were as follows: surface mixture, 2 in; intermediate mixture, 2 in; and base mixture, 10 in. From Appendix B it can be seen that when the SM-E modulus was very high (Mix 18-1022) compared to the existing SM modulus, lower rutting and a small reduction in bottom-up cracking was observed. However, when the dynamic modulus of Mix 18-1011 and an average of all SM-E moduli from this study were used, only a small reduction in rutting and bottom-up cracking was observed. This confirmed the previously mentioned point that dynamic modulus alone is not enough to explain the differences between mixtures in terms of rutting for SM-E mixtures. Because the dynamic modulus of only the 2 in of SM (of total 14 in AC thickness) was changed in the analysis, a significant reduction in bottom-up cracking was not expected. Several approaches to reduce bottom-up cracking include using improved base mixture properties (e.g., high binder and high modulus, higher in-place density, etc.) and using cement-stabilized aggregate base (using a semi-rigid design approach). Examples of bottom-up cracking reduction using an improved base mixture was shown by Nair in a VTRC technical assistance report (Nair, unpublished data, 2011). Appendix C shows an MEPDG analysis using different $k_1 * \beta_1$ and $k3 * \beta_3$ values. From the data presented in Appendix C, it can be seen that both $k_1 * \beta_1$ and $k3 * \beta_3$ need to be calibrated to match the field rutting performance data.

Summary of Findings

- All SM-E mixtures met VDOT volumetric and gradation criteria.

- Some SMA mixtures were out of specification for design but were within the allowable tolerance for production. All mixtures met the criterion of $VCA_{MIX} < VCA_{DRC}$ except for Mix 18-1051. However, most mixtures were borderline in passing this criterion, indicating that good stone-on-stone contact may not be guaranteed.

- Volumetric analysis showed that the binder content of SMA mixtures ranged from 6.3% to 7% and that of SM-E mixtures ranged from 5% to 6.5%. As expected, effective binder content and VMA for SMA mixtures were higher than for SM-E mixtures.

- Results from dynamic modulus testing showed that the effect of confinement was not significant for SMA mixtures when tested at lower air voids (4.5%). As expected, the dynamic modulus was higher for lower air voids (4.5%) when compared to 7.5% air voids.

- The current dynamic modulus test protocol does not specify confined testing for SMA mixtures. However, since the SMA density requirement is high (<6% in-place air voids), dynamic modulus can be tested at a lower air-void content (5 ± 0.5%) in the unconfined condition.

- For SMA mixtures, all of the mixtures had lower dynamic modulus values compared to previously cataloged (existing) values for SM mixtures.

- Of the six SMA mixtures tested for dynamic modulus, three had lower dynamic modulus values compared to the others. This may have been due to the difference in effective binder content and lower binder stiffness.

- With one mixture as an exception, SM-E mixtures had either similar or higher dynamic modulus values than previously cataloged mixtures (VDOT, 2017).

- The RLPD test results showed that SMA mixtures have a slope factor (k_3) ranging from 0.24 to 0.64, indicating higher rutting susceptibility.

- V2.2.6 Pavement ME Design uses a coefficient for $k_3 * \beta_3$ (0.4791) for SM mixtures, which will result in a higher rutting prediction, especially for high truck traffic.

- Lower $k_3 * \beta_3$ values for SM-E mixtures may be more representative of actual performance, an observation that is more consistent with the coefficients as included in V2.6 Pavement ME Design.

- Rutting coefficients were not comparable to those for V2.6 Pavement ME Design for SMA mixtures.

- In-place density values were higher for both SMA and SM-E mixtures when compared with other dense-graded mixtures as reported by McGhee and Smith (2021).

- Of the limited binder tests conducted, binder extracted from mixtures with lower dynamic modulus had relatively higher non-recoverable creep compliance (Jnr) values. In general, higher Jnr values indicated higher rutting susceptibility.

- A limited PMS field data analysis showed that a few SMA projects had higher rutting (>0.20 in). Based on field investigations by VDOT's Materials Division on limited sites, this was due to substandard binder, a weak underlying layer, or substandard compaction during construction.

CONCLUSIONS

- *Material properties (dynamic modulus, volumetrics, and in-place density) catalogued from this study will better reflect the rutting characteristics of SM-E mixtures when used in Pavement ME Design. Rutting coefficients developed in this study were comparable to those incorporated in V2.6 Pavement ME Design.*

- *One-half of the SMA mixtures had lower stiffness and a higher susceptibility for rutting than conventional mixtures. The tested SMA mixtures had mixed trends in terms of dynamic modulus. Laboratory rutting coefficients developed from this study also showed higher rutting susceptibility of mixtures having lower dynamic modulus. Finally, limited field performance data indicate that certain SMA mixtures are susceptible to higher in-service rutting and rutting progression as compared to SM-E mixtures.*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider using the rutting calibration coefficients developed for SM-E mixtures from this study when V2.6 Pavement ME Design is considered for adoption. However, further calibration/validation is still needed when V2.6 Pavement ME Design is adopted. VDOT's Materials Division should update the Pavement ME Design*

User Manual with SM-E dynamic modulus, volumetric data, and in-place density values from this study, as shown in Appendix A.

2. *VTRC and VDOT's Materials Division should develop a research needs statement for consideration by the VTRC Pavement Research Advisory Committee to evaluate the higher rutting susceptibility of some SMA materials in some applications. The Materials Division should not include SMA materials properties in the Pavement ME Design User Manual until this research is completed.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, VDOT's Materials Division will decide on implementation of V2.6 Pavement ME Design after internal discussion. The dynamic modulus and other materials properties developed in this study will be implemented by the Materials Division after conducting a detailed sensitivity analysis. This analysis will be conducted in spring 2022, and a decision on implementation of the newer version of the software will be made by December 2022.

Regarding Recommendation 2, VDOT's Materials Division formed a subcommittee to address SMA rutting. The subcommittee includes members from VDOT, the Virginia Asphalt Association, and the asphalt industry. After the first meeting, the subcommittee recommended a detailed study to address the rutting concern. A research needs statement was prepared, and the project is scheduled to start in November 2021.

Benefits

Regarding Recommendation 1, the MEPDG will give pavement designers a way to quantify the benefits of special asphalt mixtures, such as mixtures with polymer modified binders. Further, applying the ME design procedure can help develop pavement structures that are optimized to provide the necessary performance in a cost-effective manner.

Regarding Recommendation 2, in general, SMA mixtures are known for their rut resistance; however, since laboratory and field data showed that some SMA mixtures are susceptible to rutting, further evaluation of the issue is needed. Higher rut depths have a greater impact on the VDOT load related distress rating (LDR). For example, average rut depths of 0.3, 0.4, and 0.5 in will result in 22-, 42-, and 60-point deductions in the LDR, respectively.

ACKNOWLEDGMENTS

The authors thank Drew Barbour, Troy Deeds, Donnie Dodds, and Jenny Samuels of VTRC for their outstanding efforts in sample collection and testing. Appreciation is also extended to Linda Evans of VTRC for her editorial assistance. The authors are also appreciative of the technical review panel for their expertise and guidance: Affan Habib, Sungho Kim, Girum Merine, James Peavey, and Bryan Smith of VDOT and Stacey Diefenderfer of VTRC.

REFERENCES

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 39th ed. Washington, DC, 2020.

Apeagyei, A., and Diefenderfer, S. *Asphalt Material Design Inputs for Use With the Mechanistic Empirical Pavement Design Guide.* VTRC 12-R6. Virginia Center for Transportation Innovation and Research, Charlottesville, 2011.

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.

Gibson, N., and Li, S. *Performance Characterization of Oklahoma Asphalt Mixtures.* Federal Highway Administration, McLean, VA, 2013.

Hossain, S., Nair, H., Ozyildirim, C., and Moruza, A. *Assessment of Composite Pavement in Virginia: A Trial Section on US 60.* VTRC 21-R3. Virginia Transportation Research Council, Charlottesville, 2020.

McGhee, K., and Smith, B. *Impact on Compaction of Virginia's Dense-Graded Asphalt Surface Mixtures From Recent Changes to Design and Construction Acceptance Criteria.* VTRC 21-R11. Virginia Transportation Research Council, Charlottesville, 2021.

Merine, G., Nair, H., Habib, A., Saha, B., and Wells, M. Characterization of Stone Matrix Asphalt (SMA) Mixtures for MEPDG: Challenges and Potential Solutions. In *Proceedings of the Transportation Research Board Annual Meeting.* Transportation Research Board, Washington, DC, 2019.

Smith, B., and Nair, H. *Development of Local Calibration Factors and Design Criteria Values for Mechanistic-Empirical Pavement Design*. VTRC 16-R1. Virginia Transportation Research Council, Charlottesville, 2016.

Virginia Department of Transportation. *AASHTOWare Pavement ME User Manual*. Richmond, 2017. http://www.virginiadot.org/VDOT/Business/asset_upload_file108_3638.pdf. Accessed August 4, 2020.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2020.

Von Quintus, H.L., Mallela, J., Bonaquist, R., Schwartz, C.W., and Carvalho, R.L. *NCHRP Report 719: Calibration of Rutting Models for Structural and Mix Design*. Transportation Research Board, Washington, DC, 2012.

APPENDIX A

DYNAMIC MODULUS VALUES FOR SM-E MIXTURES

Temperature (°F) (Frequency [hz])	Dynamic Modulus (psi)						
	18-1011	18-1012	18-1022	18-1042	18-1046	18-1057	18-1059
130 (25)	211,685	166,872	473,353	199,144	202,791	203,570	131,016
130 (10)	151,655	116,755	368,990	145,879	147,500	146,874	93,369
130(5)	116,650	88,262	303,420	114,296	114,612	113,177	71,954
130 (1)	62,004	45,262	189,926	63,598	61,875	59,417	39,242
130 (0.5)	47,008	33,885	154,956	49,184	46,994	44,408	30,364
130 (0.1)	24,847	17,547	97,538	27,137	24,572	22,150	17,165
100 (25)	612,937	543,333	1,230,609	608,858	572,982	623,519	485,603
100 (10)	475,469	414,612	1,038,412	481,228	451,609	495,181	371,832
100 (5)	386,265	332,222	901,942	397,425	371,761	409,635	299,585
100 (1)	227,018	188,468	624,560	244,308	225,721	250,464	174,074
100 (0.5)	177,180	144,741	524,575	194,842	178,600	198,256	135,784
100 (0.1)	96,319	75,822	339,229	111,646	99,738	109,891	74,668
70 (25)	1,539,880	1,396,562	2,162,097	1,409,673	1,401,756	1,376,285	1,236,203
70 (10)	1,333,470	1,197,315	1,970,714	1,219,262	1,221,812	1,199,507	1,047,268
70 (5)	1,180,386	1,050,368	1,820,038	1,079,819	1,088,622	1,068,496	910,966
70 (1)	848,200	735,382	1,461,195	781,290	798,741	782,801	627,526
70 (0.5)	719,918	615,804	1,307,828	667,015	685,772	671,241	523,052
70 (0.1)	466,862	385,128	970,792	441,811	459,144	447,109	326,284
40 (25)	2,783,528	2,473,315	3,129,905	2,623,892	2,436,366	2,342,605	2,303,421
40 (10)	2,642,625	2,324,877	3,040,355	2,472,909	2,294,430	2,199,780	2,139,160
40 (5)	2,526,230	2,202,896	2,963,848	2,350,681	2,179,677	2,084,713	2,006,856
40 (1)	2,224,734	1,890,637	2,754,459	2,043,281	1,891,568	1,797,387	1,678,780
40 (0.5)	2,082,781	1,745,938	2,649,878	1,902,636	1,759,939	1,666,872	1,531,794
40 (0.1)	1,732,528	1,397,047	2,373,275	1,565,257	1,444,549	1,356,165	1,190,281
14 (25)	2,996,949	2,943,473	3,250,424	3,073,519	2,943,530	2,819,458	2,845,505

14 (10)	2,881,561	2,854,995	3,179,927	2,968,612	2,854,194	2,723,600	2,739,033
14 (5)	2,784,828	2,779,584	3,119,154	2,881,247	2,779,541	2,643,901	2,649,567
14 (1)	2,527,782	2,573,800	2,950,130	2,650,699	2,581,272	2,433,956	2,411,012
14 (0.5)	2,403,211	2,471,254	2,864,153	2,539,381	2,484,799	2,332,700	2,295,011
14 (0.1)	2,084,649	2,200,460	2,631,325	2,254,352	2,235,237	2,073,476	1,997,318

APPENDIX B

PAVEMENT ME PREDICTION WITH DIFFERENT DYNAMIC MODULUS VALUES FOR SM-E MIXTURES

Layer type	Material Type	Thickness (in)
Flexible	VDOT SM	2.0
Flexible	VDOT IM	2.0
Flexible	VDOT BM	10.0
NonStabilized	VDOT Avg 21A/21B	6.0
Subgrade	VA A-7-6	Semi-infinite

Figure B1. Thickness of the Example Section

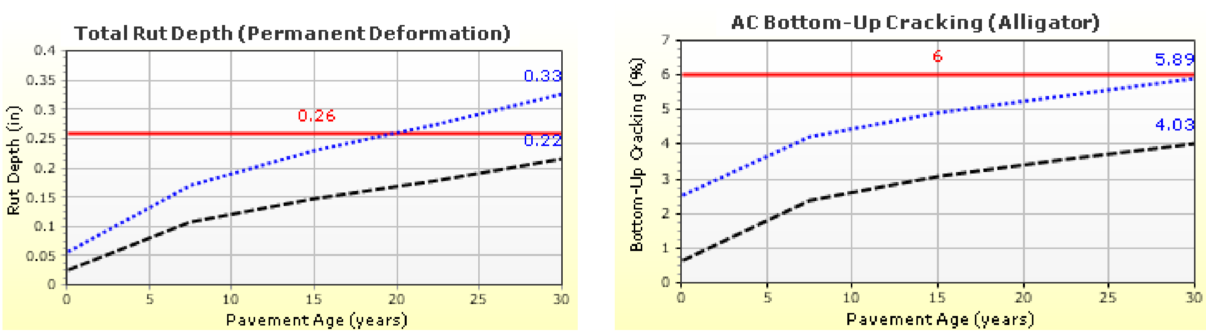

Figure B2. Predicted Rutting and Bottom-Up Cracking (With Existing Catalogued Values for SM, IM, and BM). SM = surface mix; IM = intermediate mix; BM = base mix.

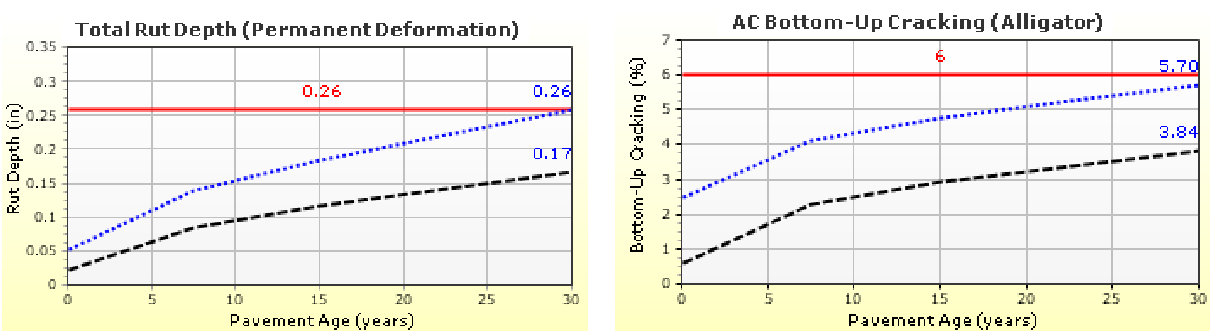

Figure B3. Predicted Rutting and Bottom-Up Cracking (With SM-E Values for Mix 18-1022 and Existing Values for IM and BM). IM = intermediate mix; BM = base mix.

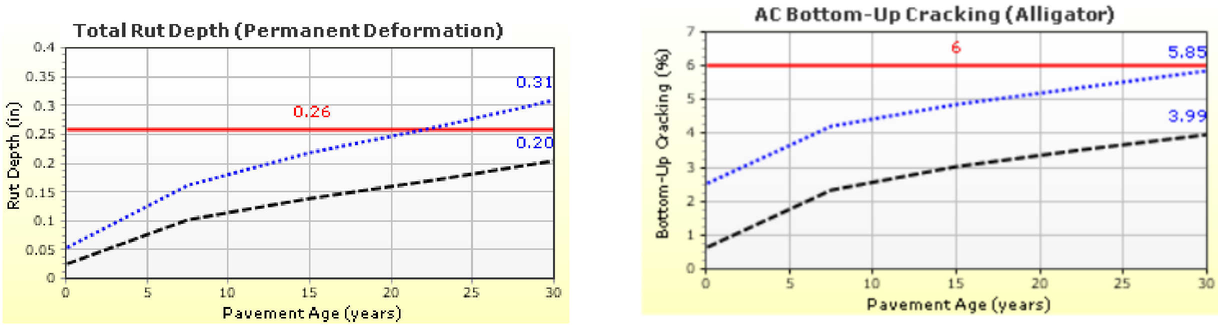

Figure B4. Predicted Rutting and Bottom-Up Cracking (With SM-E Values for Mix 18-1011 and Existing Values for IM and BM). IM = intermediate mix; BM = base mix.

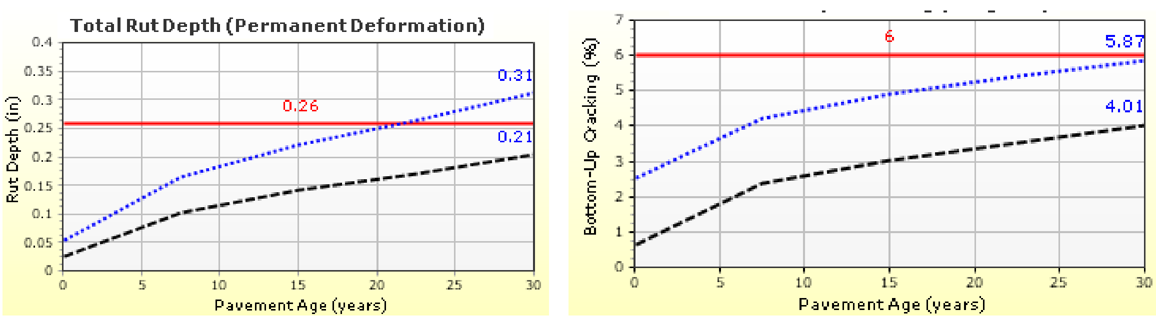

Figure B5. Predicted Rutting and Bottom-Up Cracking With Average SM-E Values From This Study and Existing Values for IM and BM. SM-E = dense-graded polymer modified; IM = intermediate mix; BM = base mix.

APPENDIX C

PAVEMENT ME RUTTING PREDICTION

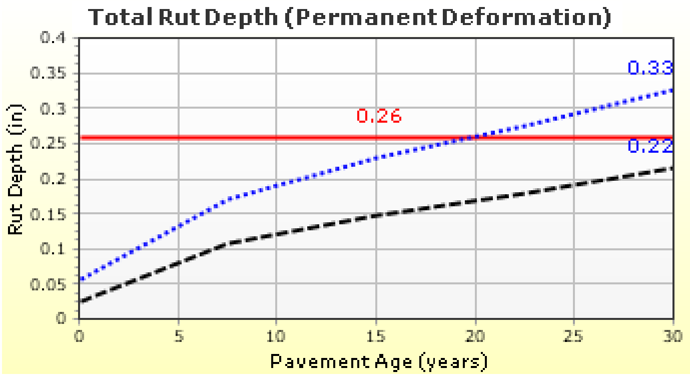

Figure C1. Rutting Prediction Using Existing Rutting Coefficients: k1* β1 = -2.304; k2* β2 = 1.5606; k3* β3 = 0.4791.

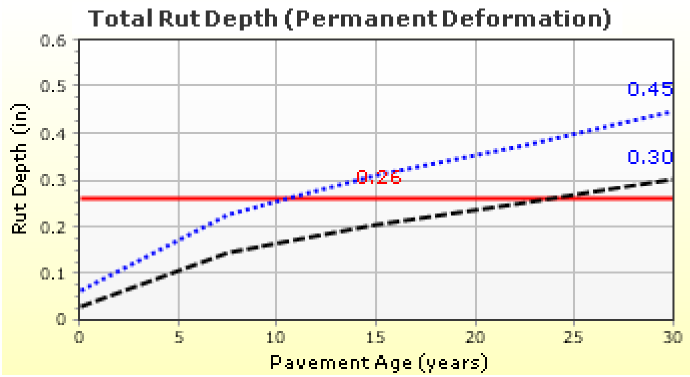

Figure C2. Rutting Prediction Using Different Rutting Coefficients: k1* β1 = -3.35412; k2* β2 = 1.5606; k3* β3 = 0.4791.

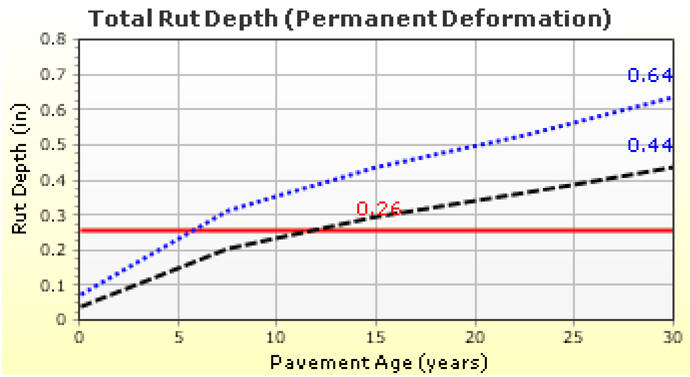

Figure C3. Rutting Prediction Using Different Rutting Coefficients: k1* β1 = -5.03118; k2* β2 = 1.5606; k3* β3 = 0.4791.

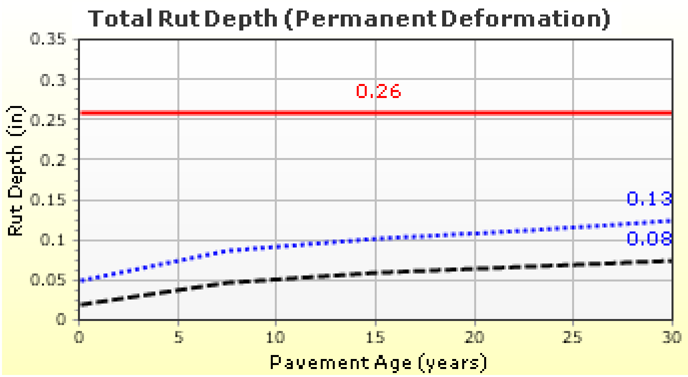

Figure C4. Rutting Prediction Using Different Rutting Coefficients: k1* β1 = -5.03118; k3* β3 = 0.3497; k2* β2 = 1.5606.

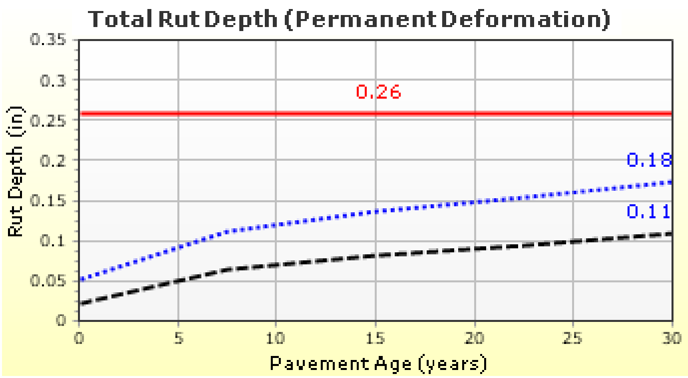

Figure C5. Rutting Prediction Using Different Rutting Coefficients: k1* β1 = -5.03118; k3* β3 = 0.3832; k2* β2 = 1.5606.

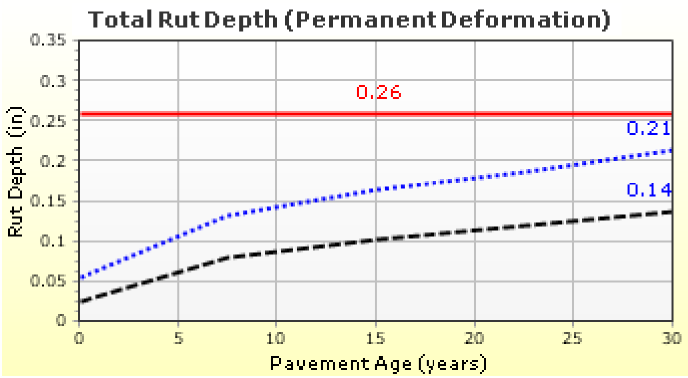

Figure C6. Rutting Prediction Using Different Rutting Coefficients: k1* β1 = -6.708; k3* β3 = 0.3832; k2* β2 = 1.5606.