Final Report VTRC 11-R3

Virginia Transportation Research Council

research report

Analysis of the Mechanistic-Empirical Pavement Design Guide Performance Predictions: Influence of Asphalt Material Input Properties

http://www.virginiadot.org/vtrc/main/online_reports/pdf/11-r3.pdf

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Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 11-R3	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Analysis of the Mechanistic-Empirical Pavement Design Guide Performance Predictions: Influence of Asphalt Material Input Properties		5. Report Date: August 2010
		6. Performing Organization Code:
7. Author(s): Stacey D. Diefenderfer, Ph.D.		8. Performing Organization Report No.: VTRC 11-R3
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.: 86812
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:		

16. Abstract:

The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (MEPDG) is an improved methodology for pavement design and the evaluation of paving materials. The Virginia Department of Transportation (VDOT) is expecting to transition to using the MEPDG methodology in the near future. The purpose of this research was to support this implementation effort.

A catalog of mixture properties from 11 asphalt mixtures (3 surface mixtures, 4 intermediate mixtures, and 4 base mixtures) was compiled along with the associated asphalt binder properties to provide input values. The predicted fatigue and rutting distresses were used to evaluate the sensitivity of the MEPDG software to differences in the mixture properties and to assess the future needs for implementation of the MEPDG. Two pavement sections were modeled: one on a primary roadway and one on an interstate roadway. The MEPDG was used with the default calibration factors. Pavement distress data were compiled for the interstate and primary route corresponding to the modeled sections and were compared to the MEPDG-predicted distresses.

Predicted distress quantities for fatigue cracking and rutting were compared to the calculated distress model predictive errors to determine if there were significant differences between material property input levels. There were differences between all rutting and fatigue predictions using Level 1, 2, and 3 asphalt material inputs, although not statistically significant. Various combinations of Level 3 inputs showed expected trends in rutting predictions when increased binder grades were used, but the differences were not statistically significant when the calibration model error was considered. Pavement condition data indicated that fatigue distress predictions were approximately comparable to the pavement condition data for the interstate pavement structure, but fatigue was over-predicted for the primary route structure. Fatigue model predictive errors were greater than the distress predictions for all predictions.

Based on the findings of this study, further refinement or calibration of the predictive models is necessary before the benefits associated with their use can be realized. A local calibration process should be performed to provide calibration and verification of the predictive models so that they may accurately predict the conditions of Virginia roadways. Until then, implementation using Level 3 inputs is recommended. If the models are modified, additional evaluation will be necessary to determine if the other recommendations of this study are impacted. Further studies should be performed using Level 1 and Level 2 input properties of additional asphalt mixtures to validate the trends seen in the Level 3 input predictions and isolate the effects of binder grade changes on the predicted distresses. Further, additional asphalt mixture and binder properties should be collected to populate fully a catalog for VDOT's future implementation use.

The implementation of these recommendations and use of the MEPDG are expected to provide VDOT with a more efficient and effective means for pavement design and analysis. The use of optimal pavement designs will provide economic benefits in terms of initial construction and lifetime maintenance costs.

17 Key Words: mechanistic-empirical pavement design guide, implementation, mixture characterization	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: 47	22. Price:

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FINAL REPORT

ANALYSIS OF THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE PERFORMANCE PREDICTIONS: INFLUENCE OF ASPHALT MATERIAL INPUT PROPERTIES

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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

August 2010
VTRC 11-R3

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ABSTRACT

The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (MEPDG), developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A and NCHRP Project 1-40D, is an improved methodology for pavement design and the evaluation of paving materials. The Virginia Department of Transportation (VDOT) is expecting to transition to using the MEPDG methodology in the near future. The purpose of this research was to support this implementation effort.

A catalog of mixture properties from 11 asphalt mixtures (3 surface mixtures, 4 intermediate mixtures, and 4 base mixtures) was compiled along with the associated asphalt binder properties to provide input values. The predicted fatigue and rutting distresses were used to evaluate the sensitivity of the MEPDG software to differences in the mixture properties and to assess the future needs for implementation of the MEPDG. Two pavement sections were modeled: one on a primary roadway and one on an interstate roadway. The MEPDG was used with the default calibration factors. Pavement distress data were compiled for the interstate and primary route corresponding to the modeled sections and were compared to the MEPDG-predicted distresses.

Predicted distress quantities for fatigue cracking and rutting were compared to the calculated distress model predictive errors to determine if there were significant differences between material property input levels. There were differences between all rutting and fatigue predictions using Level 1, 2, and 3 asphalt material inputs, although not statistically significant. Various combinations of Level 3 inputs showed expected trends in rutting predictions when increased binder grades were used, but the differences were not statistically significant when the calibration model error was considered. Pavement condition data indicated that fatigue distress predictions were approximately comparable to the pavement condition data for the interstate pavement structure, but fatigue was over-predicted for the primary route structure. Fatigue model predictive errors were greater than the distress predictions for all predictions.

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INTRODUCTION

The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (MEPDG), developed under National Cooperative Highway Research Program (NCHRP) Project 1-37A (ARA, Inc., 2004) and NCHRP Project 1-40D (NCHRP, 2006), is an improved methodology for the design of pavements and the evaluation of paving materials. Unlike currently used empirical-based pavement design methods, this methodology depends heavily on the characterization of the fundamental engineering properties of paving materials. The MEPDG has an accompanying software package that analyses a user-provided pavement design using material properties to calculate incremental and accumulated pavement damage based on the expected variation in environmental and traffic loading. The pavement response is input into a set of nationally calibrated transfer functions to predict future pavement condition in terms of typical distress levels and smoothness. The distress and smoothness estimates allow the designer to judge whether or not the input design and/or materials achieve expected performance during the design period. To implement the MEPDG fully, users will need to develop catalogs or databases of the required input parameters for design and determine if the predicted performance significantly differs from that using default input parameters. Users must also consider the need for local calibration of the transfer functions used to predict future pavement condition.

The Virginia Department of Transportation (VDOT) currently follows the 1993 American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures* (AASHTO, 1993) for all new and rehabilitation pavement designs. However, VDOT is expecting to transition to using the MEPDG methodology in the near future (VDOT, 2007b). This transition has led to the initiation of several studies to support the implementation efforts. This report details efforts to evaluate the sensitivity of the MEPDG predictive outputs to hot-mix asphalt (HMA) and asphalt binder input parameters.

BACKGROUND

The primary methodology used for pavement design of new and rehabilitated pavements by state highway agencies is the AASHTO pavement design guide. Approximately 80% of the states make use of the 1972, 1986, or 1993 guide (ARA, Inc., 2004), with Virginia using the

1993 guide (VDOT, 2008). All versions of the guide are based on performance equations developed using empirical data collected between 1958 and 1960 at the site of the AASHO road test in Ottawa, Illinois (Highway Research Board, 1962). The 1986 and 1993 guides contain some state-of-the-practice (at the time) refinements in materials input parameters, design reliability, and design procedures for rehabilitation design. However, even with these refinements, designs developed for pavements at high-traffic locations in accordance with the 1993 guide are projected well beyond the inference space of the original AASHO road test data and, as such, may not be the most efficient designs available.

To address the shortcomings of the previous design guides, the AASHTO Joint Task Force on Pavements initiated the effort to develop an improved design guide based as fully as possible on mechanistic-empirical principles. The resulting MEPDG represents a major change in the methodology of pavement design. Trial designs are proposed based on in-situ conditions (traffic, climate, subgrade, and existing pavement condition, if applicable) and then evaluated to determine if the desired performance criteria are met over the design life. If the desired criteria are not met, design revisions occur and the evaluation is repeated. This methodology has the flexibility to consider different design features and materials and is conducive to optimization of the design.

The MEPDG uses a hierarchical structure of inputs for material characteristics and traffic parameters. Level 1 input parameters are measured directly and are considered site or project specific. This level requires the greatest amount of testing and data collection. Level 2 input parameters generally are less detailed data sets that are used with correlations or regressions to estimate the corresponding Level 1 parameters. This level of input data requires less testing and data collection efforts. Level 3 input parameters are either “best estimate” or default values and require the least testing and data collection. The MEPDG allows designers to mix and match the levels of input parameters across many material characteristics and traffic parameters.

The MEPDG identifies and incorporates several fundamental properties and tests for HMA and asphalt binders**.** Standard HMA properties such as asphalt binder content, aggregate gradation, and volumetric properties are required for all three input levels. Level 1 input parameters for HMA consist of fundamental properties such as dynamic modulus, indirect tensile strength, and indirect tensile creep compliance. Level 2 input parameters consist of asphalt binder content, aggregate gradation, and volumetric properties, which are used to predict the Level 1 parameters. Asphalt binder input parameters required for Level 1 and 2 analyses include the complex shear modulus and associated phase angle tested at several temperatures for binder aged in the rolling thin film oven. Level 3 analysis uses default values for all fundamental property inputs. These material properties are used in the MEPDG to compute the expected pavement response and to evaluate the expected performance over the pavement design life.

Previous studies have investigated the degree to which the MEPDG software is sensitive to changes in the asphalt mixture and binder input parameters. Lee (2004) investigated the sensitivity of two mixture sizes and four typical gradations from four sources in Arkansas and did not find performance grade to be a significant factor. Coree et al. (2005) reported that transverse and longitudinal cracking predictions were very sensitive to performance grade whereas alligator cracking was insensitive. Rutting in the asphalt surface was found to have "sensitivity to low sensitivity" to performance grade, although rutting in all other layers was found to be insensitive. Total rutting and smoothness were found to have "sensitivity to low sensitivity" to performance grade.

Kim et al. (2005) evaluated single and paired variable sensitivity in the MEPDG software using two existing Iowa pavements. The study included an evaluation of binder grade sensitivity. Longitudinal cracking was shown to be very sensitive to increasing binder grade for a thin HMA surface layer but only moderately sensitive to increasing binder grade for a thick HMA surface layer. Transverse cracking, surface HMA rutting, and total rutting were found to be moderately sensitive to binder grade. A limited sensitivity analysis performed by Nantung et al. (2005) used typical Indiana values to support their implementation plan for Indiana. During the analysis, binder grade was found to be influential on "mechanical distresses" and thermal cracking, although details regarding the level of significance or magnitude of influence were not given. A matrix of trial runs conducted with the MEPDG software suggested that a higher design level input does not necessarily guarantee a higher accuracy in predicting pavement performance. The software runs also confirmed the need to use input values obtained from local rather than national calibration.

Freeman et al. (2006) evaluated the sensitivity of the MEPDG and developed a strategic plan for MEPDG implementation in Texas Department of Transportation (TxDOT) operations. A general sensitivity analysis was performed using a default set of inputs; single variables were varied through reasonable ranges of typical values to determine the sensitivity. Ranges were determined from TxDOT-acceptable specification values. Because of a division of analysis by climate zone and pavement type, it was unclear how sensitive the MEPDG was found to be with regard to binder inputs. Graves and Mahboub (2006) used a sampling-based global sensitivity analysis methodology to evaluate the sensitivity of the MEPDG to changes in variables. Results of the analysis indicated that binder grade was significant at the 95% confidence level for HMA rutting and total rutting. A comparison of pavement designs done in accordance with the AASHTO 1993 design methodology and the MEPDG methodology was performed by Carvalho (2006). A sensitivity study of flexible pavement inputs was also done. Results indicated the importance of local calibration of performance prediction models, and the study recommended use of Level 1 input parameters for asphalt mixtures.

Stires (2009) conducted a literature review of the implementation plans of several states and performed a limited sensitivity analysis associated with efforts by the South Carolina Department of Transportation (SCDOT) to implement the MEPDG. Analysis of the asphalt properties indicated that layer thickness and dynamic modulus properties, such as air voids and binder content, were the most significant properties. According to the study, the MEPDG software over-predicted rutting and under-predicted fatigue (longitudinal and alligator) cracking. The sensitivity analysis showed questionable fatigue cracking distress predictions for SCDOT pavements. MEPDG Version 1.10 produced "more responsive" cracking predictions when compared to those of Version 1.003, but large input changes still showed "minor prediction responses." Currently, NCHRP Project 01-47 (Transportation Research Board, undated) is evaluating the sensitivity of the MEPDG software for all types of rigid and flexible pavements; however, the project will not be completed until 2011.

PURPOSE AND SCOPE

When the MEPDG methodology is used to design a pavement, the material characterization values used by the MEPDG software can be provided by the results of laboratory testing (Level 1), by predictive equations (Level 2), or by default values (Level 3). However, both (1) the accuracy of the incorporated predictive equations and default values and (2) the sensitivity of predicted distresses to changes in these values still need to be verified for locally produced mixtures before they can be used with confidence by VDOT in the design of new or rehabilitated pavements. The MEPDG software uses the material characterization values of the HMA mixtures to calculate the incremental and accumulated damage with the expected variation in both environmental and traffic conditions. This process together with the selected reliability level allows the designer to judge whether or not the selected thickness and/or materials meet their performance expectation during the selected design period.

The purpose of this study was to support VDOT's implementation of the MEPDG. This was accomplished in two parts. First, material properties from a sampling of asphalt mixtures tested in a previous study (Flintsch et al., 2007) were supplemented with the associated asphalt binder properties to compile an initial catalog of asphalt material input properties. Second, these properties were used to investigate the effect of changes in asphalt binder and mixture properties on the predicted distress levels for two trial pavement designs to assess the need for additional testing of mixtures. Two pavement sections were modeled: a primary roadway section and an interstate roadway section. Although it is expected that VDOT will implement the MEPDG using Level 1 asphalt material inputs, both sections were evaluated using Level 1, 2, and 3 asphalt material inputs for this study.

METHODS

Materials Testing

Prior to the analyses using the MEPDG software, asphalt mixture data were collected. Combinations of 11 mixtures were used for the analysis of the pavement structures presented in this study: 3 surface mixtures, 4 intermediate mixtures, and 4 base mixtures. The designations and general descriptions of each mixture are provided in Table 1.

Table 1. Designations and Descriptions of Mixtures Evaluated

Designation	Mixture Type	NMAS, mm	Binder Grade
Surface 38	Surface	9.5	PG 64-22
Surface 40			
Surface 69			
Intermediate 44	Intermediate	12.5	PG 64-22
Intermediate 49			
Intermediate 52			
Intermediate 58			
Base 50	Base	25.0	PG 64-22
Base 53			
Base 66			
Base 70			

NMAS = Nominal maximum aggregate size.

General mixture properties were determined at the Virginia Transportation Research Council (VTRC); these properties included gradation (AASHTO T30, Mechanical Analysis of Extracted Aggregate); asphalt content (AASHTO T308, Determining the Asphalt Binder Content of Hot-Mix Asphalt by the Ignition Oven); bulk specific gravity (AASHTO T166, Bulk Specific Gravity of Compacted Hot-Mix Asphalt Using Saturated Surface Dry Specimens); and mixture maximum theoretical (Rice) specific gravity (AASHTO T209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures) (AASHTO, 2009). The input values required by the MEPDG software include percent air voids, unit weight, effective volumetric binder content (calculated as the voids in mineral aggregate minus the percent air voids), and several gradation points. Dynamic modulus data were measured by Flintsch et al. (2007). A summary of the mixture data is presented in Appendix A.

The MEPDG also requires complex shear modulus (G*) and phase angle (δ) data at several temperatures on binder residue aged in a rolling thin film oven for Level 1 and 2 asphalt inputs. This testing was performed on asphalt binders sampled at the same time as the mixtures. A summary of the binder data is presented in Appendix A. Although binder testing was conducted at six temperatures (10°C, 25°C, 40°C, 55°C, 70°C, and 85°C), only data collected at four temperatures (40°C, 55°C, 70°C, and 85°C) were used as inputs to the MEPDG software.

MEPDG Analysis

Version 1.0 of the MEPDG software was released in April 2007 and was initially used for the evaluation conducted during this study. However, in September 2009, an updated version was released as MEPDG Version 1.1 (NCHRP, 2009a) and support of Version 1.0 was discontinued. In order to provide current recommendations, all analyses were performed using Version 1.1, and these results are reported herein. The release notes for Version 1.1 (NCHRP, 2009b) do not note any significant changes in the flexible pavement analysis procedure.

The MEPDG software analyzes a pavement based on inputs describing the materials, traffic, climate, and pavement structure and outputs the predicted pavement condition over the design life of the pavement. This study evaluated the sensitivity of the pavement condition predicted by the MEPDG software to changes in the choice of specific mixtures and asphalt binder grades. This required trial pavement sections that could be used to compare the resultant predicted pavement condition from the different inputs. Two pavement sections and traffic levels in Virginia were used to represent interstate and primary highways for this study. The traffic volumes from the interstate and primary highway locations with the highest truck traffic volumes were selected as the traffic levels for this study to amplify the amount of load-related distresses that would be predicted during the analysis; the locations selected were I-81 in Augusta County and U.S. 17 in Stafford County.

Default MEPDG traffic and climate inputs used for this analysis are shown in Table 2. The values were based on the default MEPDG values or recommended VDOT values for pavement design (VDOT, 2008). The weather station location was chosen for simplicity so that the same site could be used during all analyses. Different average daily truck traffic (ADTT) and default vehicle class distribution sets were used for the interstate and primary highways. The

Table 2. Default MEPDG Test Section Traffic and Climate Inputs

Traffic	
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
Climate	
Weather station location	Charlottesville, Virginia
Depth of water table, ft	5

values used for these inputs are shown in Table 3. ADTT values were based on VDOT traffic volume estimates (VDOT, 2007a). Different vehicle class distribution factors were chosen from the MEPDG-provided default distributions to represent best the distribution at the interstate and primary sites. A 95% reliability input was used for interstate MEPDG trials, and a 90% input was used for primary trials; however, all predicted pavement condition values were considered at the 50% (default) reliability level at the end of the pavement design life.

Two trial flexible pavement structures were analyzed to represent interstate and primary highways. The interstate trial pavement structure is described in Table 4, and the primary in Table 5. These trial pavement sections were designed based on layer properties and thicknesses typical of Virginia highways. One trial structure for each administrative classification was considered to simplify the analysis. The modulus values for Layers 4, 5, and 6 are assumed values. The subgrade was subdivided into two layers (Layers 5 and 6) to represent compacted subgrade and natural subgrade. The interstate highway trial structure was designed for a structural number of 6.2, and the primary highway trial structure for a structural number of 4.75; these values represent average structural numbers for interstate and primary highways based on the recommendations of VDOT pavement engineers (Smith and Diefenderfer, 2010). A 20-year design life was used during the flexible pavement analysis to make the MEPDG analysis more computationally efficient. However, the VDOT-recommended design life for a new flexible interstate or primary highway is 30 years (VDOT, 2008).

To determine if the differences in predicted pavement condition using various asphalt properties and input levels were significant, two methods of analysis were used. Analyses of variance (ANOVA) techniques were applied to the results to identify the statistically significant factors affecting the predicted distresses; the standard deviation of each evaluated predicted

Table 3. MEPDG Interstate and Primary Traffic Inputs

MEPDG Input	Interstate Section	Primary Section
Two-way ADTT	19,470	8,170
Vehicle Class Distribution	Default–TTC Group 1	Default–TTC Group 2
Reliability Input	95%	90%

ADTT = average daily truck traffic; TTC = truck traffic classification.

Table 4. Interstate Trial Flexible Pavement Structure

Layer No.	Material	Thickness, in	Properties	Modulus, psi
1	Surface mixture	2	Varied	
2	Intermediate mixture	2.5	Varied	
3	Base mixture	7	Varied	
4	21-B	12	Default	42,000
5	A-7-6	12	Default	12,000
6	A-7-6	Infinite	Default	8,000

Table 5. Primary Trial Flexible Pavement Structure

Layer No.	Material	Thickness, in	Properties	Modulus, psi
1	Surface mixture	2	Varied	
3	Base mixture	6	Varied	
4	21-B	10	Default	42,000
5	A-7-6	12	Default	12,000
6	A-7-6	Infinite	Default	8,000

distress was also determined. The MEPDG software includes formulas that describe the standard deviation of each predicted pavement distress; these were determined and used to evaluate the statistical significance of changes in the input values. Since the predicted distresses do not follow a standard distribution format, the standard deviation changes as the distress value changes. Therefore, calculations are required to determine the standard deviation at a specific distress level. Equations 1 through 4 were used to calculate the standard deviation of the flexible pavement “bottom-up” fatigue and material rutting distresses, respectively (ARA, Inc., 2004).

$$SD_{\mathrm{Bottom\,Up}} = 1.13 + \frac{13}{\left(1 + e^{-7.57-15.5\times\log(\mathrm{BOTTOM}+0.0001)}\right)} \quad \text{[Eq. 1]}$$

$$SD_{\mathrm{AC\,Rutting}} = 0.24 \times \mathrm{ACRut}^{0.8206} + 0.001 \quad \text{[Eq. 2]}$$

$$SD_{\mathrm{Base\,Rutting}} = 0.1477 \times \mathrm{BaseRut}^{0.6711} + 0.001 \quad \text{[Eq. 3]}$$

$$SD_{\mathrm{Subgrade\,Rutting}} = 0.1235 \times \mathrm{SubRut}^{0.5012} + 0.0001 \quad \text{[Eq. 4]}$$

where

$SD_{\mathrm{Bottom\,Up}}$ = standard error of prediction for bottom-up fatigue cracking
Bottom = cumulative damage index at the bottom of the HMA layers
$SD_{\mathrm{AC\,Rutting}}$ = standard error of prediction for rutting in the HMA layers
ACRut = plastic deformation in the HMA layers
$SD_{\mathrm{Base\,Rutting}}$ = standard error of prediction for rutting in the aggregate base layer
BaseRut = plastic deformation in the aggregate base layers

$SD_{Subgrade\ Rutting}$ = standard error of prediction for rutting in the subgrade
SubRut = plastic deformation in the subgrade.

Pavement Condition Data

Pavement condition data collected by VDOT's Maintenance Division were assembled for segments of I-81 and U.S. 17, the two routes from which the evaluated example structures originated. The condition data were collected and evaluated by VDOT's Maintenance Division in accordance with VDOT guidelines (VDOT, 2007c). For this study, only segments composed solely of bituminous pavement were considered. Condition data for U.S. 17 were taken from data collected in 2009 in VDOT's Fredericksburg District, and condition data for I-81 were collected in 2010 and consisted of segments from the entire length of I-81 through Virginia. Fatigue cracking is expressed as a percentage of the *wheelpath area,* defined as two 3.5-ft widths, and is rated as severity Level 1, 2, or 3, with an increasing number indicating greater severity. Rutting is calculated as the average rut depth per 0.1-mi segment based on transverse profile measurements; the rut depths presented are average values for the segment evaluated.

RESULTS AND DISCUSSION

Primary Route Structure Analysis

As discussed previously, one typical primary route pavement structure was analyzed to determine the sensitivity of the MEPDG software to changes in the asphalt properties. Analyses with Level 1, 2, and 3 asphalt material inputs were performed using all combinations of the three surface mixtures and four base mixtures. Additional analyses were performed using the Level 3 asphalt inputs to include PG 70-22 and PG 76-22 binders; Level 1 and 2 input data were not available for mixtures with these binders. Table 6 summarizes the combinations of binder grades evaluated.

Figure 1 summarizes the predicted fatigue cracking for these combinations. The predicted fatigue cracking was significantly affected by the properties of the base asphalt material; this was verified statistically by ANOVA. There was a slight impact on the Level 3 input predictions when the surface mixture asphalt binder grade was increased from PG 64-22 to PG 70-22 and PG 76-22. A much more pronounced effect would be expected if the base mixture binder grade were changed because of the greater influence of the base mixture properties on the predicted fatigue cracking. An analysis of the standard error of prediction of the fatigue model found in every case that the error of prediction was greater than the predicted cracking. The

Table 6. Binder Grade Combinations for Primary Structure Level 3 Inputs

Mixture	**Binder Grade Combinations**		
Surface	PG 64-22	PG 70-22	PG 76-22
Base	PG 64-22	PG 64-22	PG 64-22

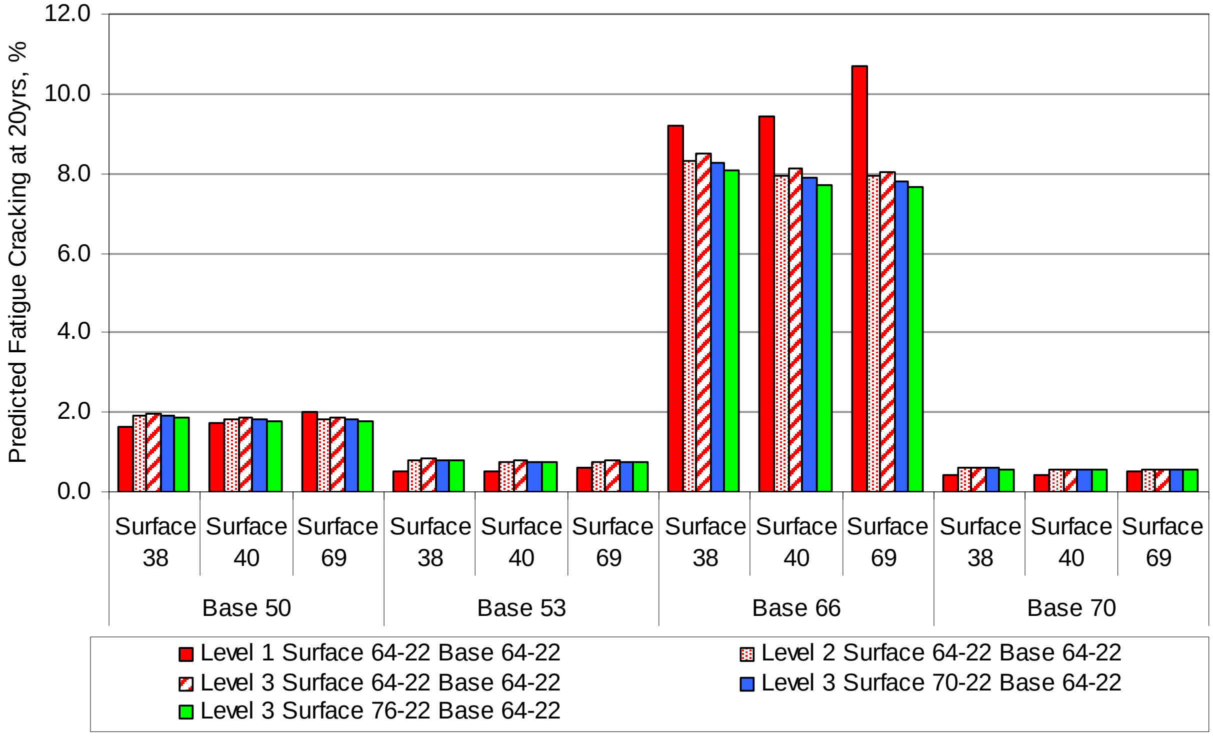
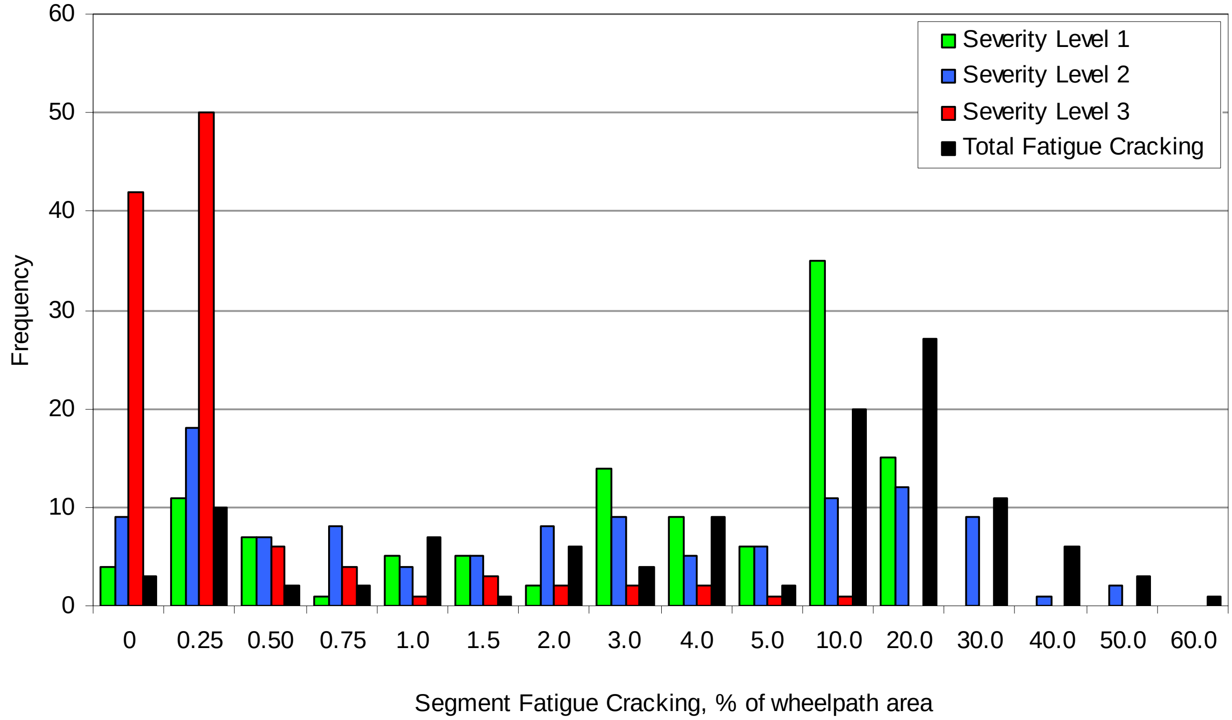


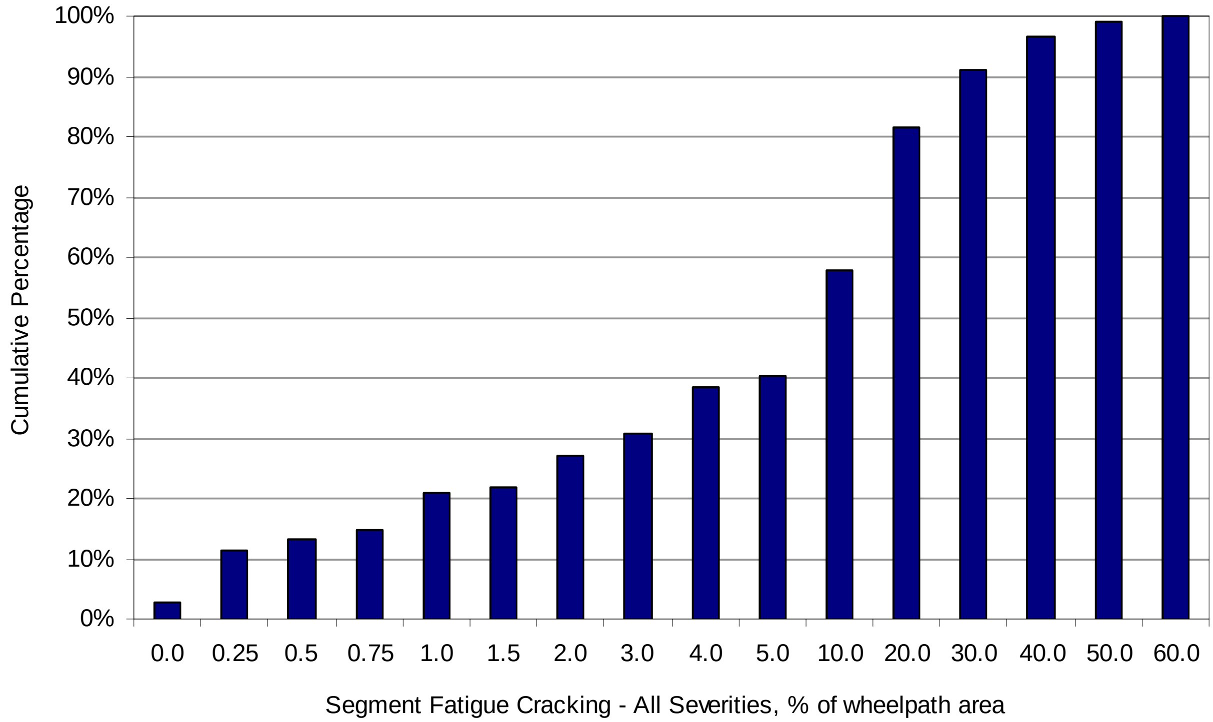
Figure 1. Predicted Fatigue Cracking for Primary Pavement Structures

error function increases and approaches an asymptote of 14% (AASHTO, 2008) as the fatigue cracking prediction approaches and exceeds 10%. In this case, the errors resulted in the conclusions regarding the evaluated mixtures that there was no significant difference in fatigue performance and that no significant fatigue cracking may be expected to occur over the 20-year analysis period.

Figure 2 shows the distribution of fatigue cracking by severity type for the flexible pavement segments of U.S. 17 and the cumulative percentage of total fatigue cracking. This provides a comparison point to determine if the predictions from the MEPDG software were within the bounds of what is expected to occur in the field. However, several things are of note about Figure 2. First, as mentioned previously, fatigue data are collected by VDOT only within the wheelpaths (VDOT, 2007c); the MEPDG predictions are expressed as percentage of the entire lane. Second, fatigue predictions from the MEPDG software are not expressed with any associated distress severity; thus they should be comparable to the total fatigue cracking rather than any single severity level. Figure 2(b) indicates that 90% of the occurrences of fatigue cracking should be expected to have an area of 30% or less of the wheelpath area, with the 50th percentile occurring at levels between 5% and 10% of the area. If it is assumed that the amounts of wheelpath cracking are proportional to that in the entire lane, it would appear from Figure 1 that the MEPDG software is under-predicting fatigue cracking.



(a)



(b)

Figure 2. Fatigue Cracking for Flexible Pavement Segments of U.S. 17 in the Fredericksburg District Showing (a) Histogram of Severity Levels, and (b) Cumulative Percentage of Total Fatigue Cracking

Figures 3 through 5 show the predicted rutting in the asphalt layers for each surface mixture in combination with the various base mixtures. In general, the predicted rutting results for the Level 2 and 3 inputs followed the same trend, regardless of the unique surface and base mixture used. The Level 1 inputs resulted in predicted rutting that appeared to be more dependent on the input properties of the surface and base asphalt mixture. However, the standard errors of prediction for the model (shown by the I-bars in the figures) indicate there was no statistical difference between any of the input levels evaluated.

Figures 6 through 8 show the predicted rutting in each layer of the total pavement structure. As expected, the differences in predicted rutting were primarily seen in the asphalt layers. This was because the same aggregate base and subgrade layer properties were assumed for all primary pavement structures. As in Figures 3 through 5, the trends shown for the various surface and base mixture combinations differed for the Level 1 inputs whereas those for the Level 2 and 3 inputs followed similar trends.

The Level 3 mixture input rutting predictions shown in Figures 3 through 8 followed expected performance trends with respect to increasing binder grade (i.e., the predicted rutting decreases as the binder grade is increased); however, the predictions were not indicative of the expected relative changes in performance indicated in the field by use of the higher binder grades. It is expected that significant differences would be seen between the predicted results for increased binder grades based on field experience.

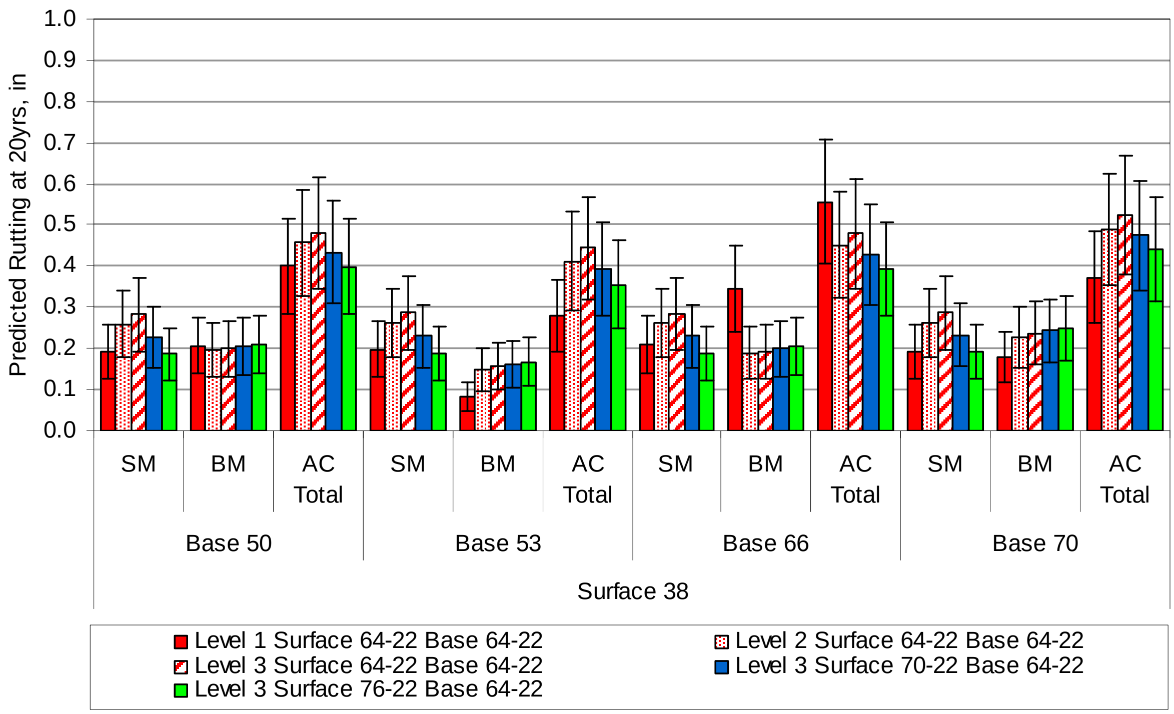


Figure 3. Predicted Rutting in Asphalt Layers for Primary Pavement Structures with Surface Mixture 38 (I-Bars Indicate Standard Error of Prediction)

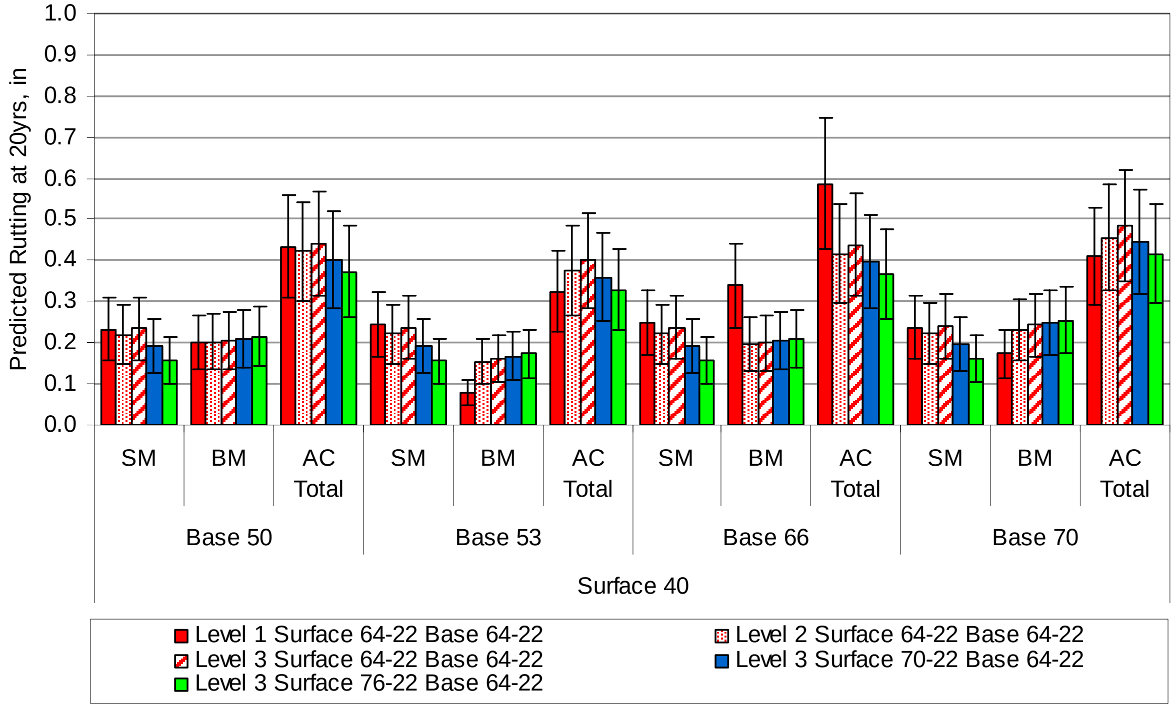


Figure 4. Predicted Rutting in Asphalt Layers for Primary Pavement Structures with Surface Mixture 40 (I-Bars Indicate Standard Error of Prediction)

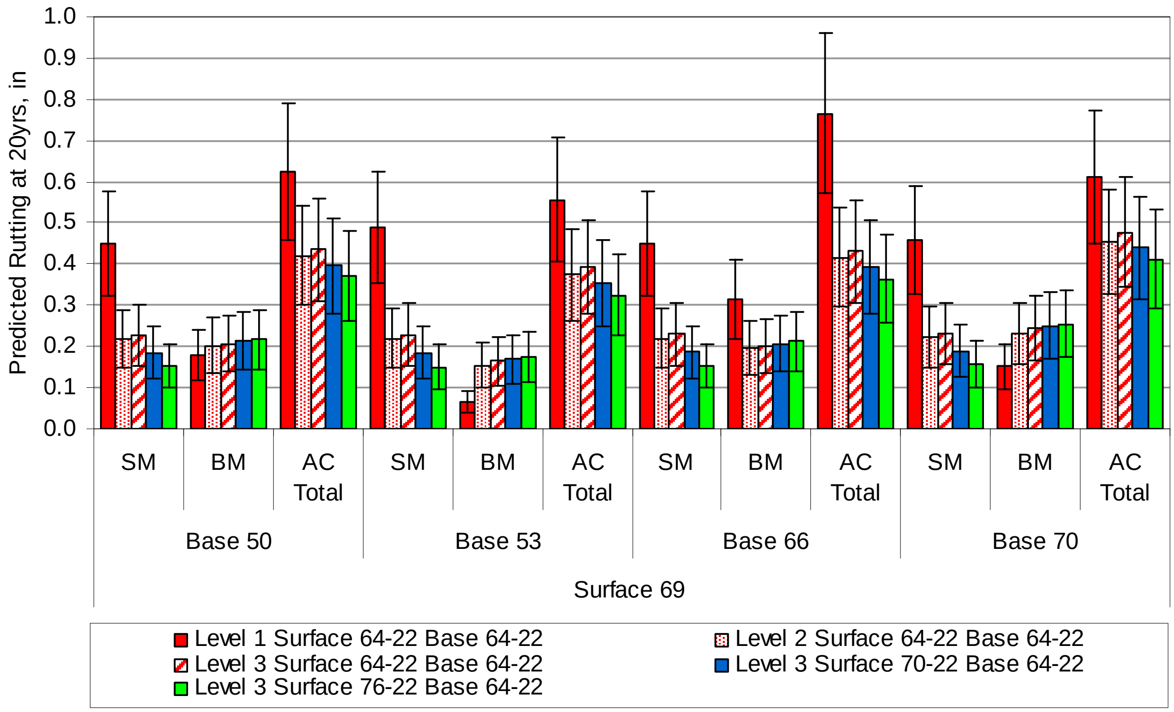


Figure 5. Predicted Rutting in Asphalt Layers for Primary Pavement Structures with Surface Mixture 6 (I-Bars Indicate Standard Error of Prediction)

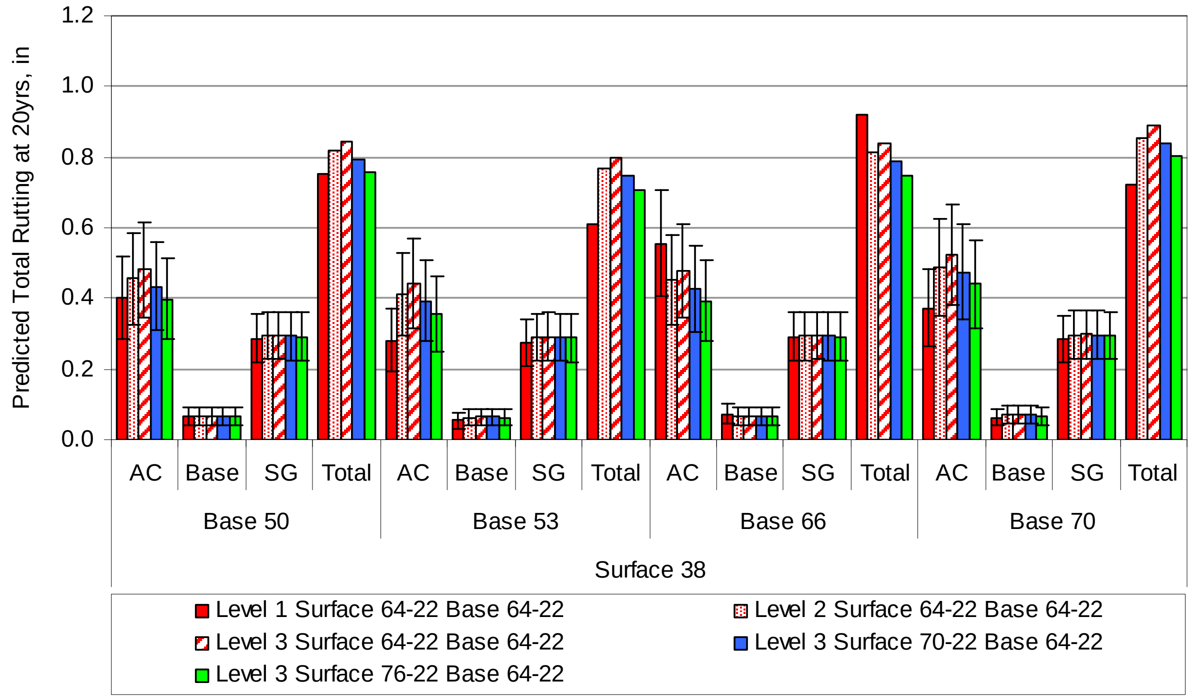


Figure 6. Predicted Rutting in Each Material for Primary Pavement Structures with Surface Mixture 38 (I-Bars Indicate Standard Error of Prediction)

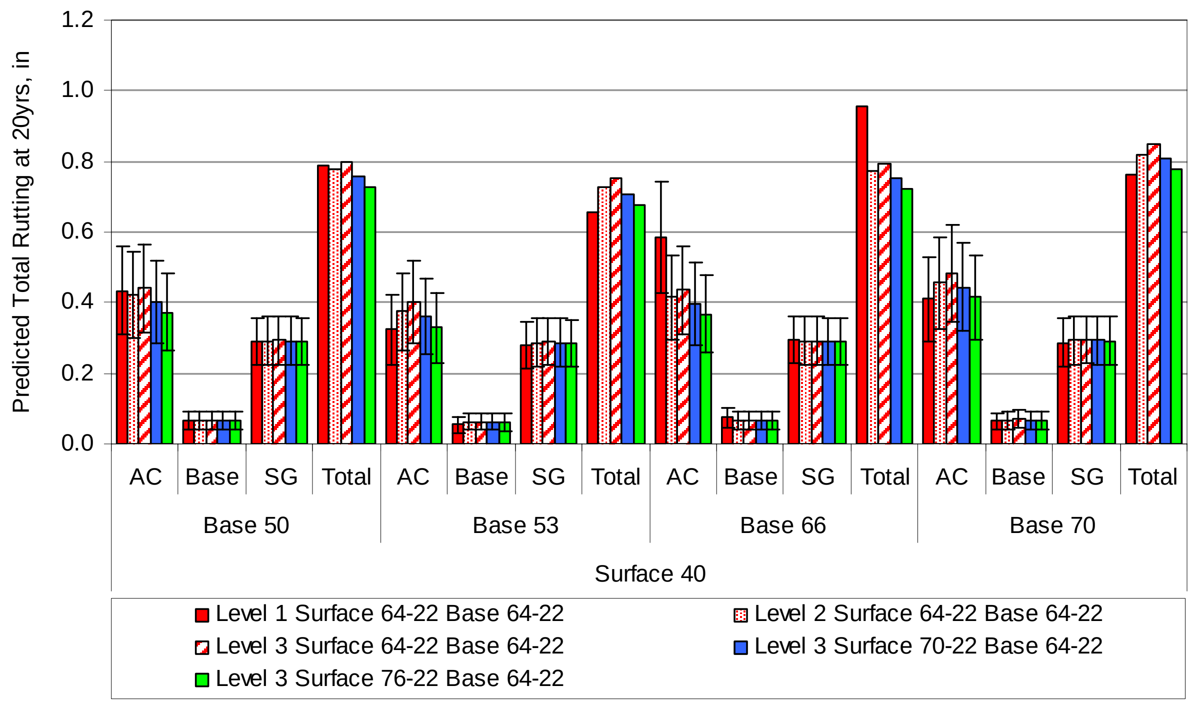


Figure 7. Predicted Rutting in Each Material for Primary Pavement Structures with Surface Mixture 40 (I-Bars Indicate Standard Error of Prediction)

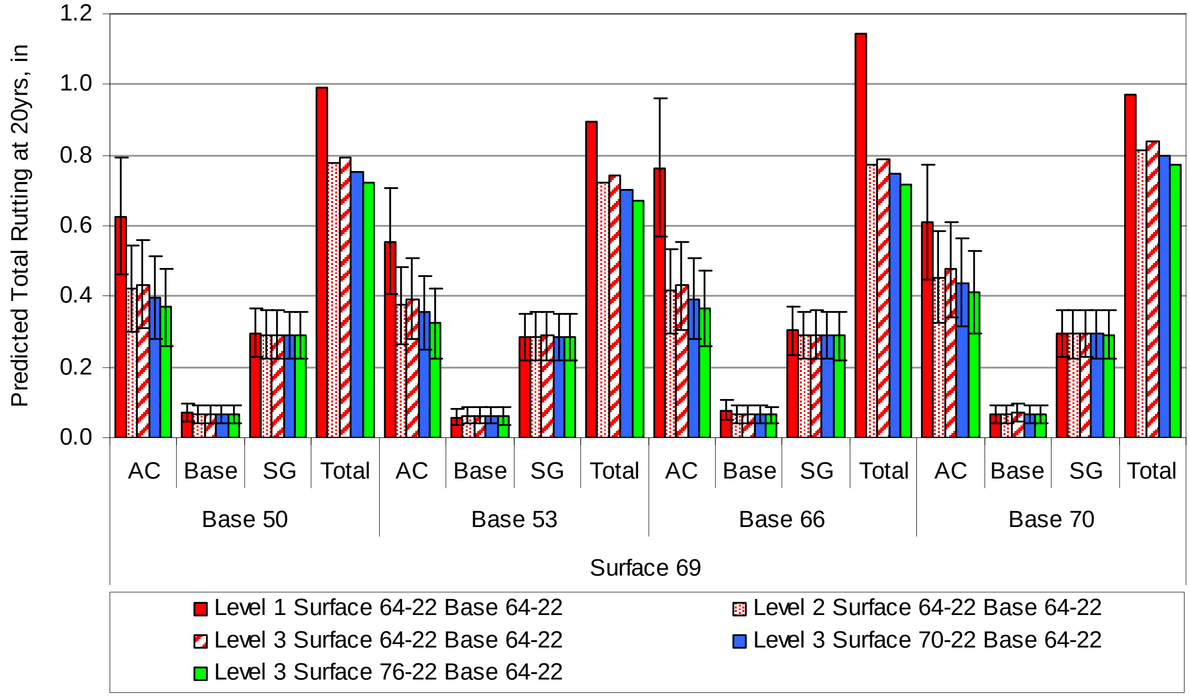


Figure 8. Predicted Rutting in Each Material for Primary Pavement Structures with Surface Mixture 69 (I-Bars Indicate Standard Error of Prediction)

Figure 9 shows a histogram of average rut depths measured on the flexible pavement segments of U.S.17 in the Fredericksburg District and the cumulative percentage of average rut depths. For these segments, the most common occurrence of average rutting was 0.1 to 0.0125 in. From the cumulative percentage, it can be seen that 90% of the average rutting occurring on U.S. 17 in this district is at a depth of 0.25 in or less. Unfortunately, the age of each segment is unknown, so comparisons with the predictions of the MEPDG software must be drawn carefully as they were evaluated assuming a 20-year lifespan. If it is assumed that the measured rutting on U.S. 17 is comparable to the total predicted rutting from the MEPDG analysis shown in Figures 6 through 8, the results indicated that the MEPDG software was over-predicting the occurrence of rutting as no total rut depth was predicted to be less than 0.60 in.

Figure 10 illustrates the evolution of rutting over time for one of the evaluated primary pavement structures and indicates that approximately one half of the 20-year lifetime rutting in the structure is accumulated by year 5 of the pavement's life. If a more conservative comparison is made of total rutting and the predictions shown in Figures 6 through 8 are halved to indicate a shorter analysis period, the predictions were still greater than approximately 90% of the observed occurrences even though they were closer to the observed rutting performance. These comparisons indicate that work should be performed to apply local calibration to the rutting models used in the MEPDG.

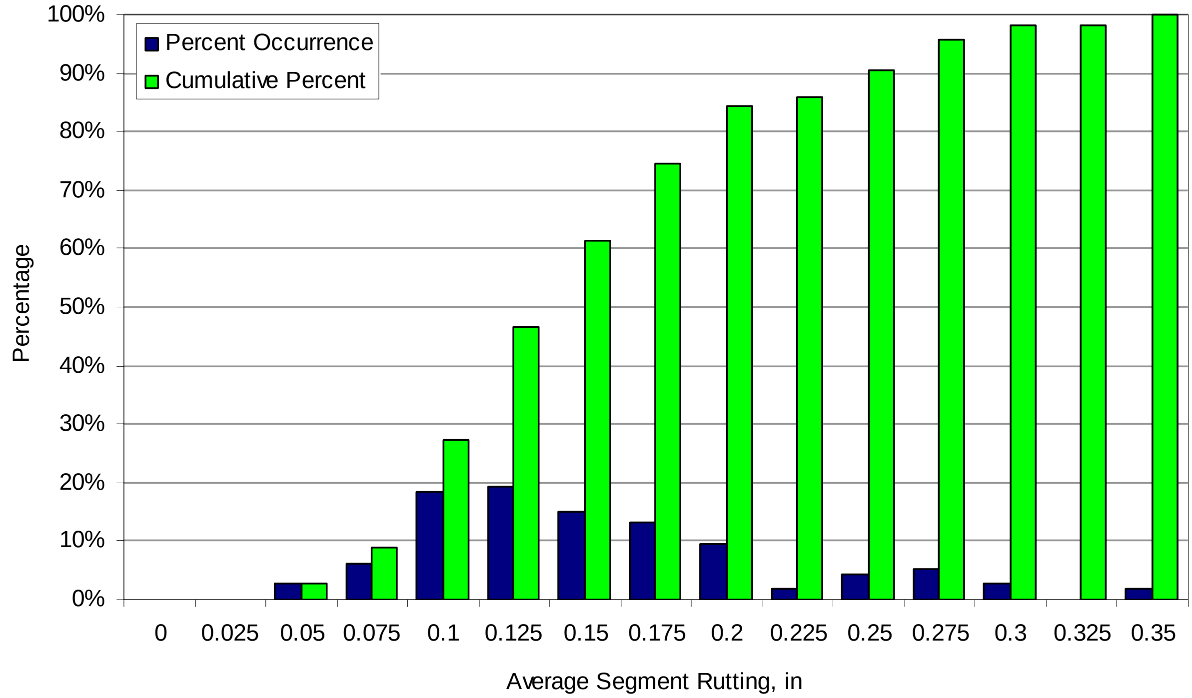


Figure 9. Frequency Distribution and Cumulative Frequency of Average Segment Rutting for Flexible Pavement Segments of U.S. 17 in the Fredericksburg District

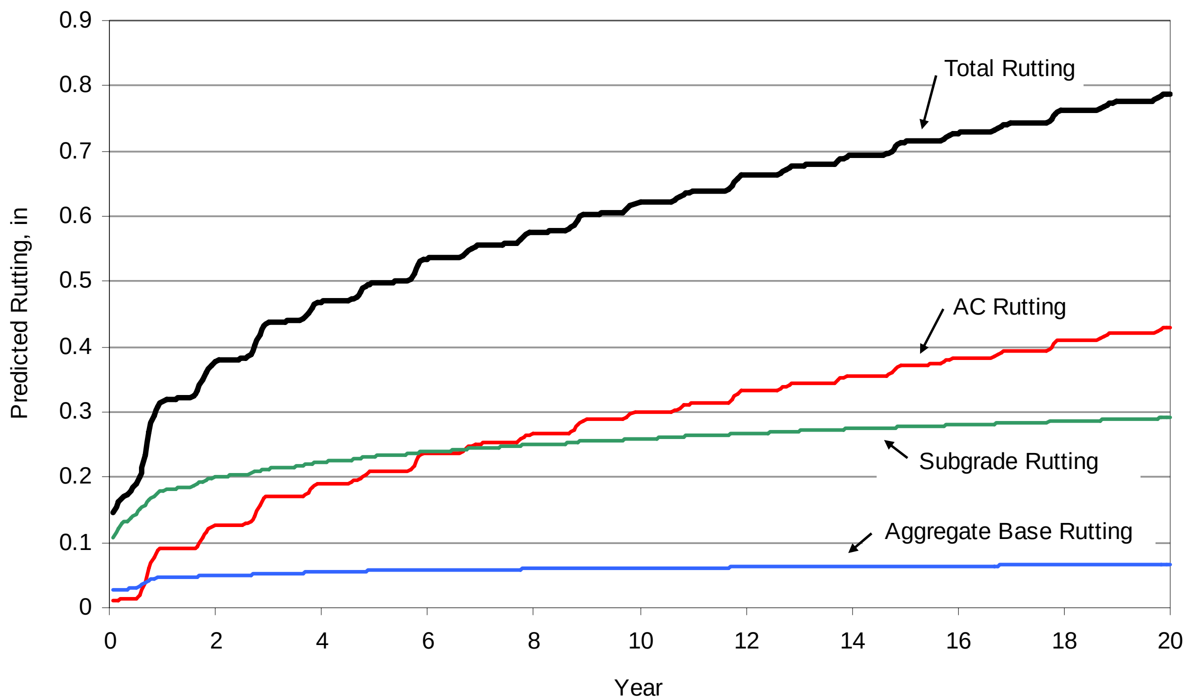


Figure 10. Example of Evolution of Rutting Over Time Using MEPDG for Primary Pavement Structure With Surface 69 and Base 66

Interstate Route Structure Analysis

As with the primary route analysis, one typical interstate route pavement structure was analyzed to determine the sensitivity of the MEPDG software to changes in the asphalt properties. Analyses with Level 1, 2, and 3 asphalt material inputs were performed using all combinations of the three surface mixtures, four intermediate mixtures, and four base mixtures. As with the primary structure analysis, only data using PG 64-22 binders were available for the Level 1 and 2 input analyses. During the Level 3 input analyses, the surface mixture asphalt binder grade was varied from PG 64-22 to include PG 70-22 and PG 76-22. In addition, the intermediate mixture binder grade was varied to include PG 70-22. Table 6 summarizes the five interstate structure Level 3 binder grade combinations evaluated in this study.

Figures 11 through 14 show the predicted fatigue cracking for the interstate structures using each of the four base mixtures using Level 1, 2, and 3 inputs. The standard error of prediction is not illustrated in the figures as it was found to be greater than the magnitude of the prediction in every examined case, as found with the results for the primary structure analysis.

Table 6. Binder Grade Combinations for Interstate Structure Level 3 Inputs

	Binder Grade Combination				
Mixture	**1**	**2**	**3**	**4**	**5**
Surface	PG 64-22	PG 70-22	PG 70-22	PG 76-22	PG 76-22
Intermediate	PG 64-22	PG 64-22	PG 70-22	PG 64-22	PG 70-22
Base	PG 64-22	PG 64-22	PG 64-22	PG 64-22	PG 64-22

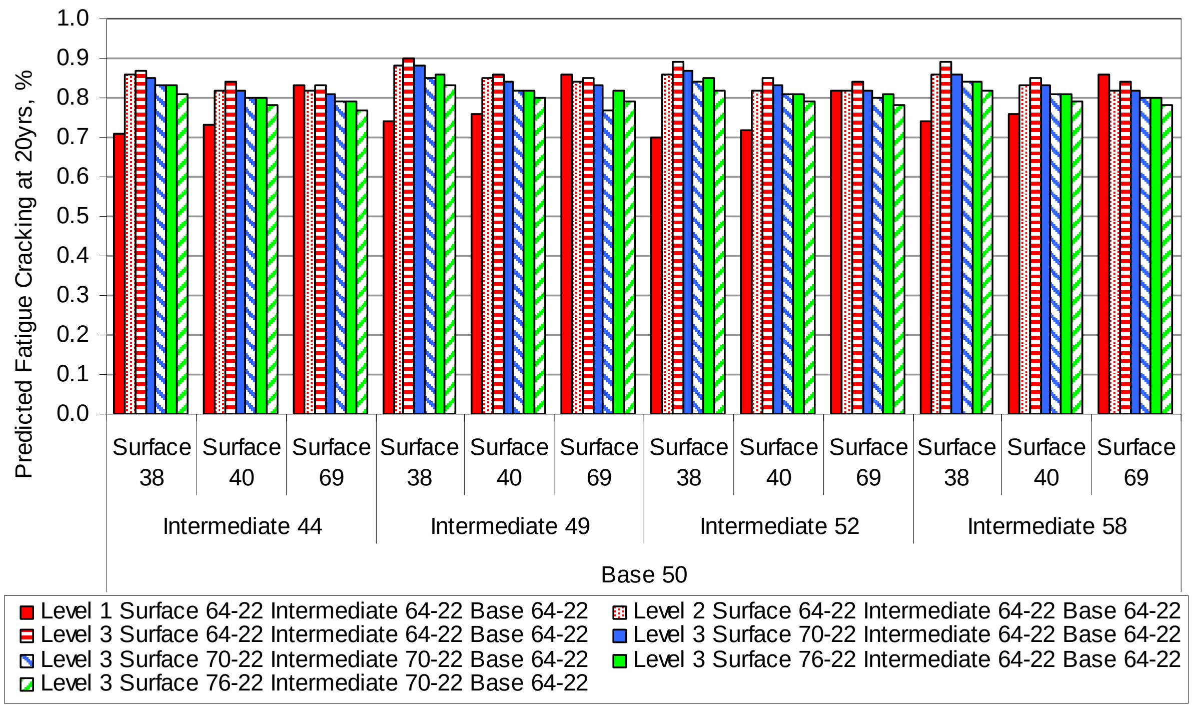


Figure 11. Predicted Fatigue Cracking for Interstate Pavement Structures with Base Mixture 50 Using Level 1, 2, and 3 Inputs

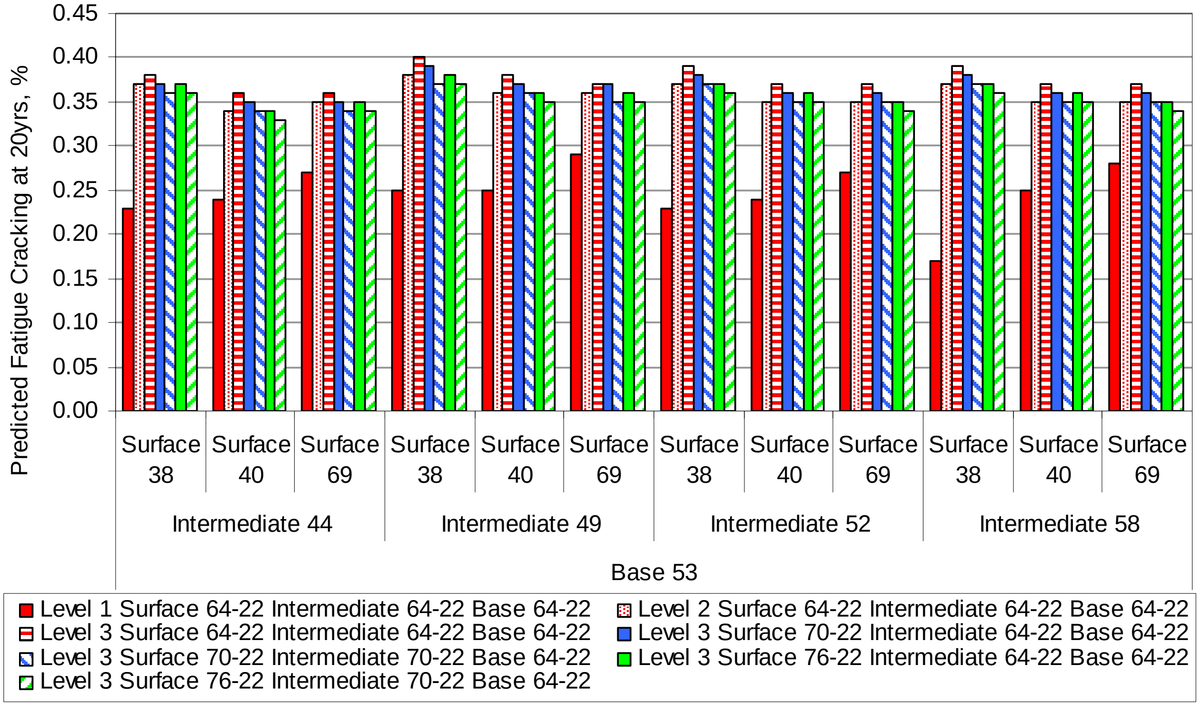


Figure 12. Predicted Fatigue Cracking for Interstate Pavement Structures with Base Mixture 53 Using Level 1, 2, and 3 Inputs

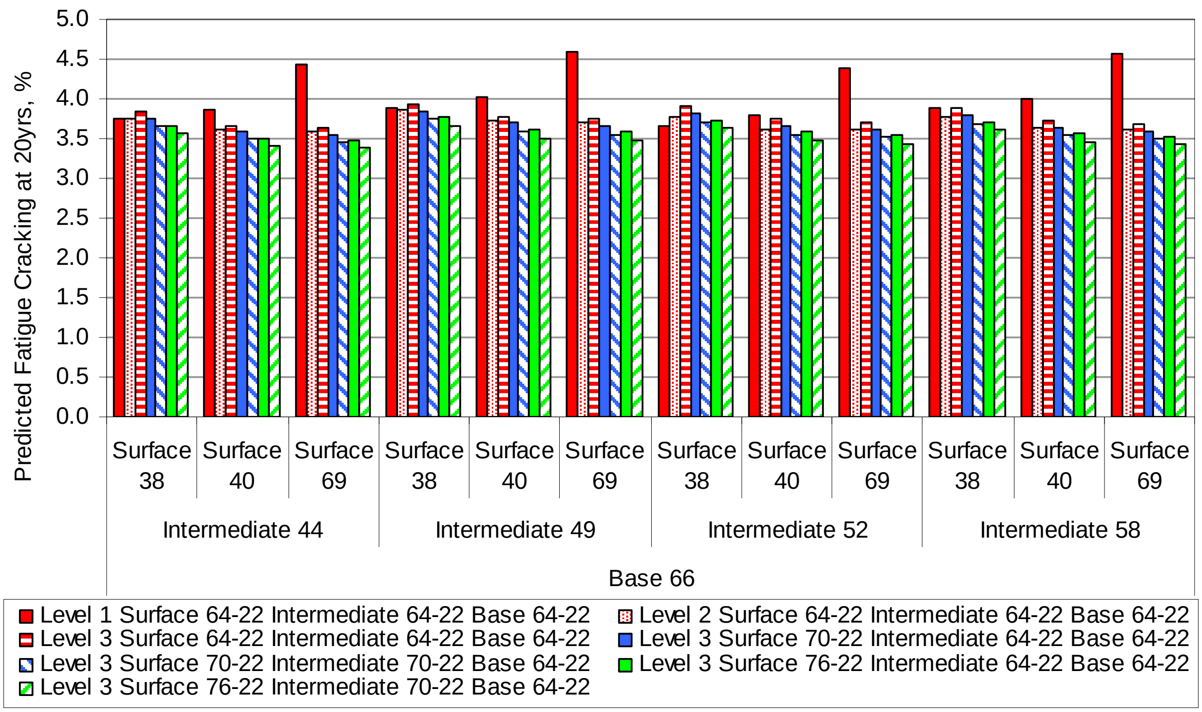


Figure 13. Predicted Fatigue Cracking for Interstate Pavement Structures with Base Mixture 66 Using Level 1, 2, and 3 Inputs

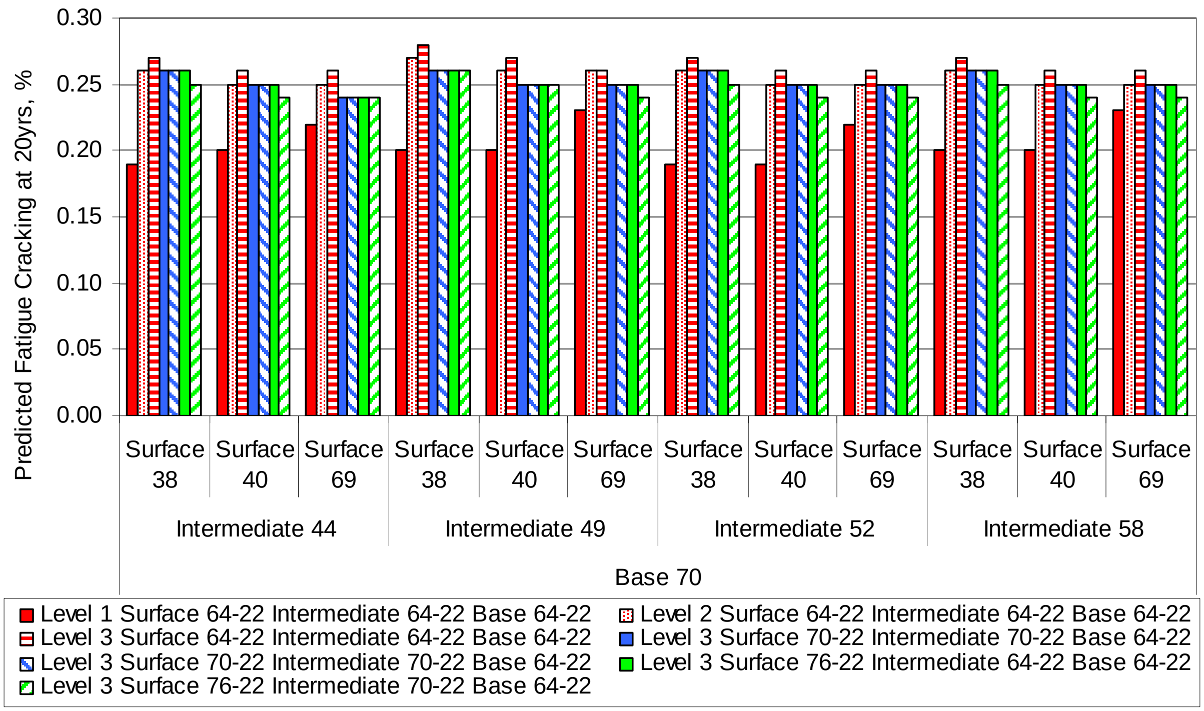
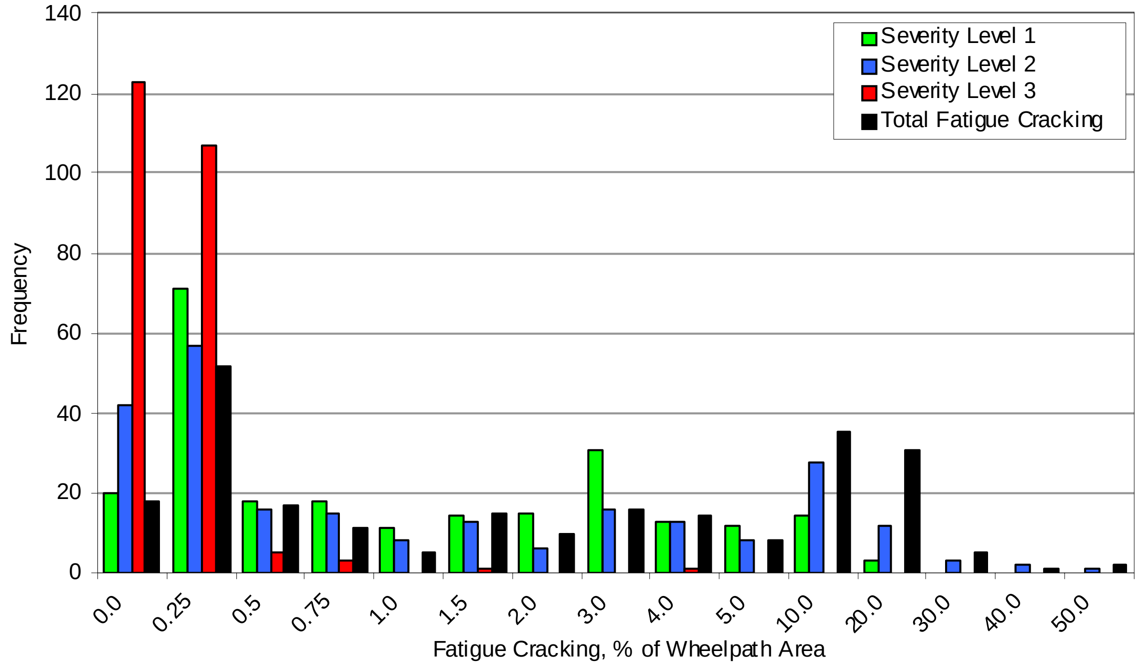


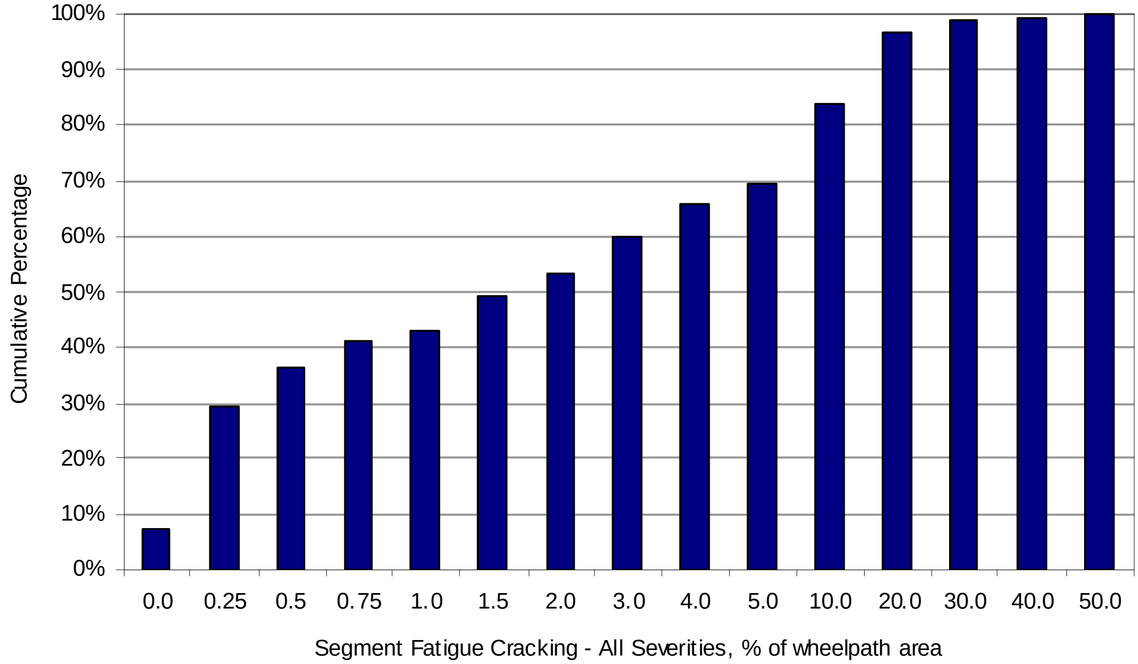
Figure 14. Predicted Fatigue Cracking for Interstate Pavement Structures with Base Mixture 70 Using Level 1, 2, and 3 Inputs

The predictions shown in Figures 10 through 14 indicate differences in magnitude of predictions for the four base mixtures. Predictions for the Level 1 inputs showed slightly different trends with the various structure combinations; however, predictions made using the Level 2 and 3 inputs followed the same trends relative to each other (with differing magnitudes) regardless of the structure. The Level 3 input predictions suggested decreased fatigue cracking as the surface mixture asphalt binder grade was increased from PG 64-22 to PG 70-22 and PG 76-22. A slight impact was also shown when the intermediate mixture binder grade was changed from PG 64-22 to PG 70-22, but neither of these effects was significant compared to the predictive error.

Figure 15 shows the distribution of fatigue cracking by severity type for flexible pavement segments of I-81 and the cumulative percentage of total fatigue cracking. This may be compared with the predictions from the MEPDG software to gain insight into their accuracy relative to in-situ pavement segments. As noted with the primary route analysis, the fatigue data are collected by VDOT only within the wheelpaths (VDOT, 2007c) and the MEPDG predictions are expressed as percentage of the entire lane. In addition, as previously discussed, fatigue predictions from the MEPDG software are not expressed with any associated distress severity; thus, they should be comparable to total fatigue cracking. Figure 15(b) indicates that 90% of the occurrences of fatigue cracking should be expected to have an area of 20% or less of the wheelpath area, with the 50th percentile occurring at levels less than 2%. Figure 16 provides an indication of the ages of the pavement segments represented in Figure 15. No clear relationship was shown between age and quantity of cracking, although a general trend of less cracking and less scatter in the quantity of cracking was seen for younger surface mixtures, as expected. It should also be noted that none of the evaluated segments was older than 18 years, with most



(a)



(b)

Figure 15. Fatigue Cracking for Flexible Pavement Segments of I-81 Showing (a) Histogram of Severity Levels, and (b) Cumulative Percentage of Total Fatigue Cracking

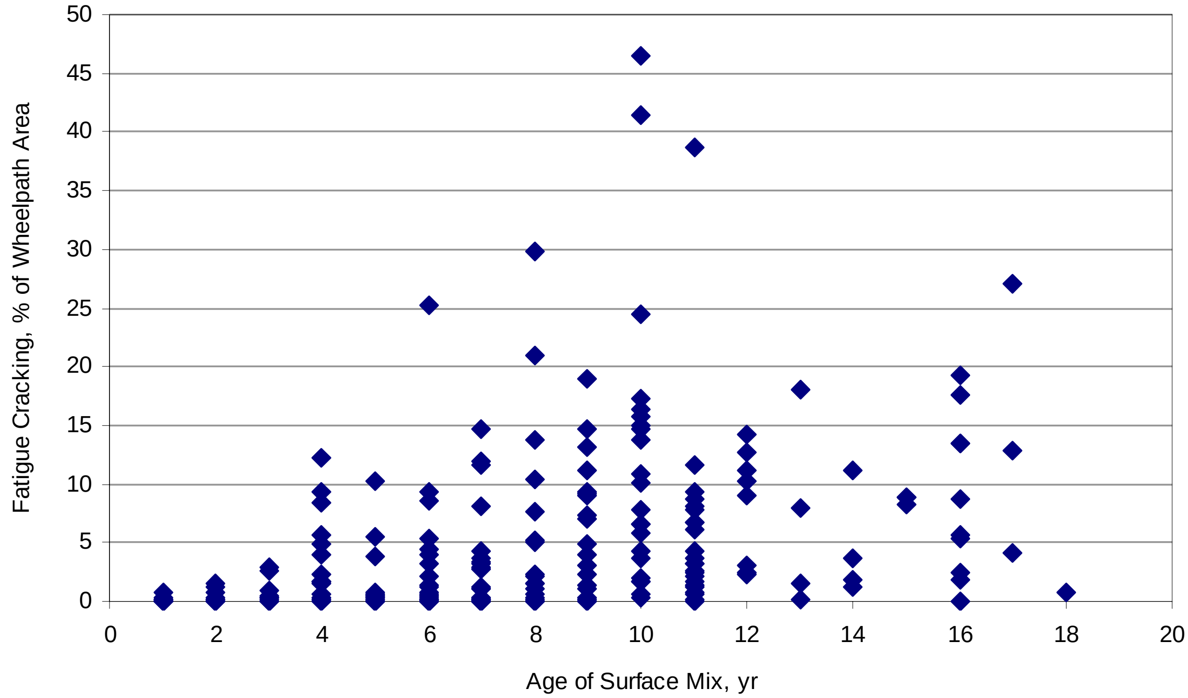


Figure 16. Fatigue Cracking Related to Age of Surface Mixture for Flexible Pavement Segments of I-81

surfaces being between 6 and 10 years of age. Despite the influence of age on the data collected from I-81, if it is assumed that the amounts of wheelpath cracking are proportional to those in the entire lane, it would appear from Figures 10 through 14 that for the interstate structures, the MEPDG predictions of fatigue cracking were within the ranges expected for interstate pavements.

An example of the predicted rutting in each pavement material layer is shown in Figure 17 for Surface Mixture 38 and Intermediate Mixture 44 in combination with all four base mixtures. Results for all mixture combinations are presented in Appendix B. As expected, there were minimal changes in the prediction of aggregate base material or subgrade material rutting with changes in the level of asphalt material inputs or with changes in the asphalt material properties. This is because the aggregate base and subgrade materials were held constant throughout the analysis process.

Expected trends in the predicted rutting for the asphalt layers are shown in Figure 17. For Surface Mixture 38, predictions for Level 1 inputs were less than those for the Level 2 and 3 inputs. However, this trend did not hold for all surface mixtures. Figure 18 shows the predicted rutting in each pavement layer for combinations of Surface Mixture 69 with the same intermediate and base mixtures; in this case, the predictions using the Level 1 inputs showed an increase in rutting as compared to the Level 2 and 3 inputs. This change in trend does indicate a sensitivity of the prediction model to changes in the Level 1 input variables, as the predictive trends for the Level 2 and 3 input variables were consistent, regardless of the specific mixture used in the analysis.

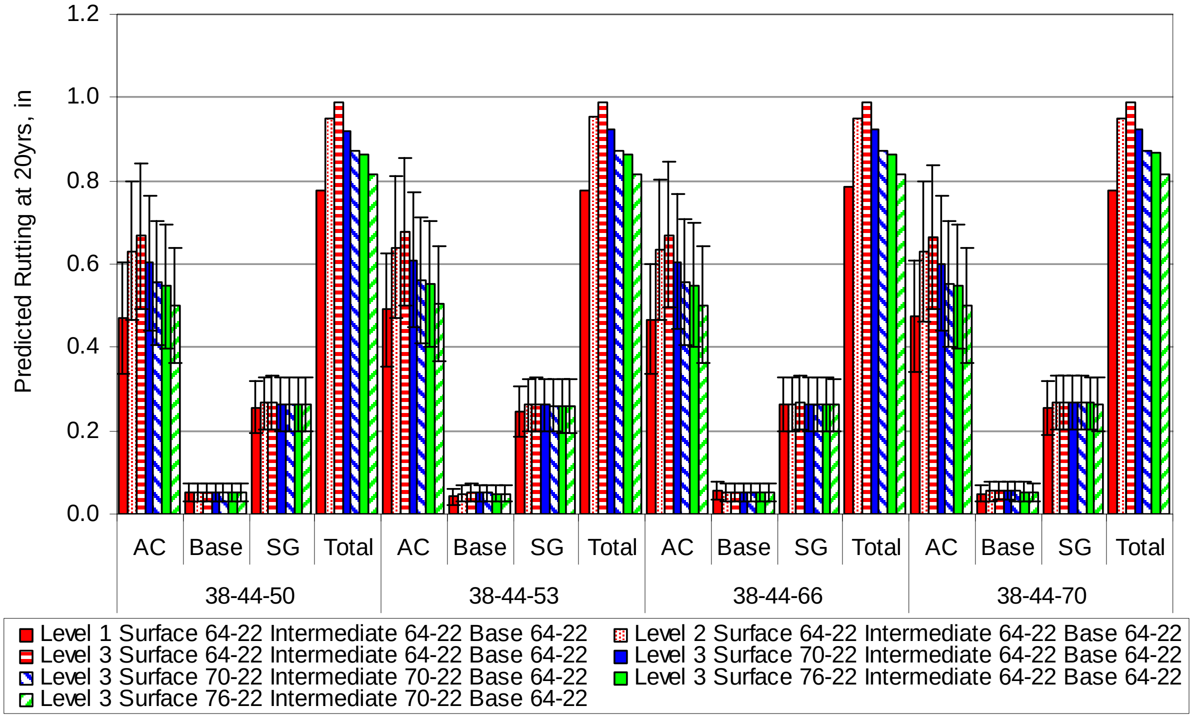


Figure 17. Example of Predicted Rutting in Each Pavement Material Using Surface Mixture 38, Intermediate Mixture 44, and All Base Layer Combinations (I-Bars Indicate Standard Error of Prediction)

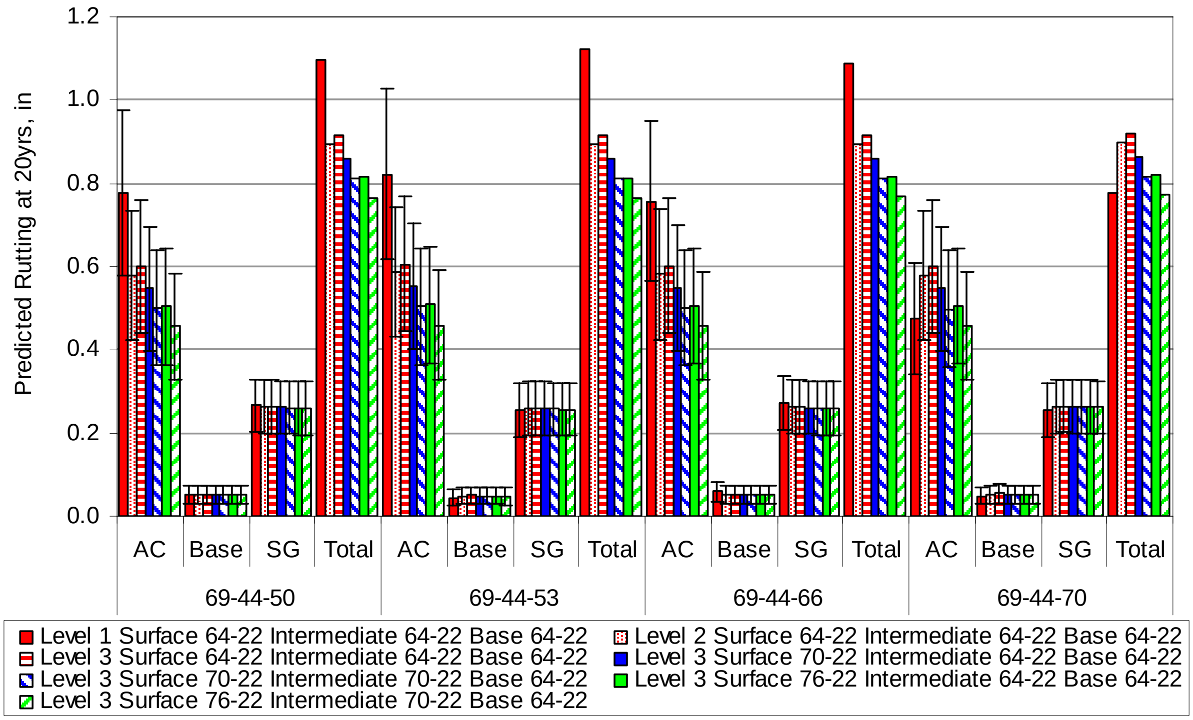


Figure 18. Example of Predicted Rutting in Each Pavement Material Using Surface Mixture 69, Intermediate Mixture 44, and All Base Layer Combinations (I-Bars Indicate Standard Error of Prediction)

In general, it was shown that increasing the surface mixture binder grade increases the resistance to rutting, as does increasing the intermediate mixture binder grade. Interestingly, the results showed that increasing the intermediate binder grade from PG 64-22 to PG 70-22 when a PG 70-22 surface binder grade is used provides a similar resistance to rutting as provided by a structure having a PG 76-22 surface mixture and a PG 64-22 intermediate mixture.

Figure 19 shows the predicted asphalt rutting in the surface and intermediate layers and total asphalt layers for an example surface and intermediate mixture in combination with four base mixtures. The predicted rutting for the base mixture was not included as the predicted maximum value was less than 0.03 in for all cases. There were no significant differences among the various levels of asphalt mixture inputs.

Figure 20 shows the distribution and cumulative frequency of occurrence of rutting in flexible pavement segments of I-81. It is clear from Figure 20(a) that the measured rutting followed an approximate normal distribution around a mean of 0.15 in; Figure 20(b) indicates that 90% of the occurrences of rutting were less than 0.25 in. For I-81, the age of the surface mixture versus the average rutting is shown in Figure 21. The relationship between the observed rutting of various segments and their age followed a trend similar to that shown in Figure 10 based on the MEPDG predictions for a primary structure: rutting appeared to occur at an accelerated rate for approximately 5 to 6 years then slowed to a steady rate of accumulation thereafter. Based on this, observations may be made about the rutting on I-81 at various ages and the MEPDG predictions for the interstate pavement structure. In general, it appears as if the MEPDG over-estimates rutting when compared to that available from pavement condition data;

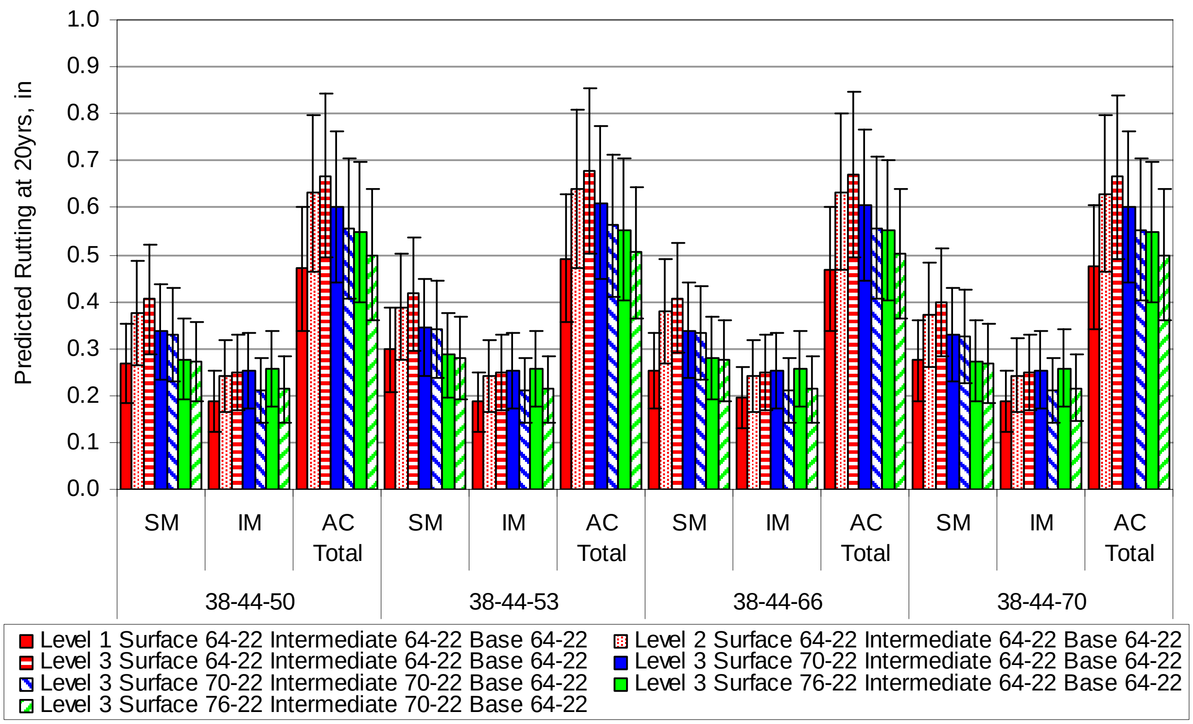


Figure 19. Example of Predicted Rutting in Surface and Intermediate Asphalt Layers (I-Bars Indicate Standard Error of Prediction) and Total Predicted Asphalt Layer Rutting Using Surface Mixture 38, Intermediate Mixture 44, and All Base Layer Combinations

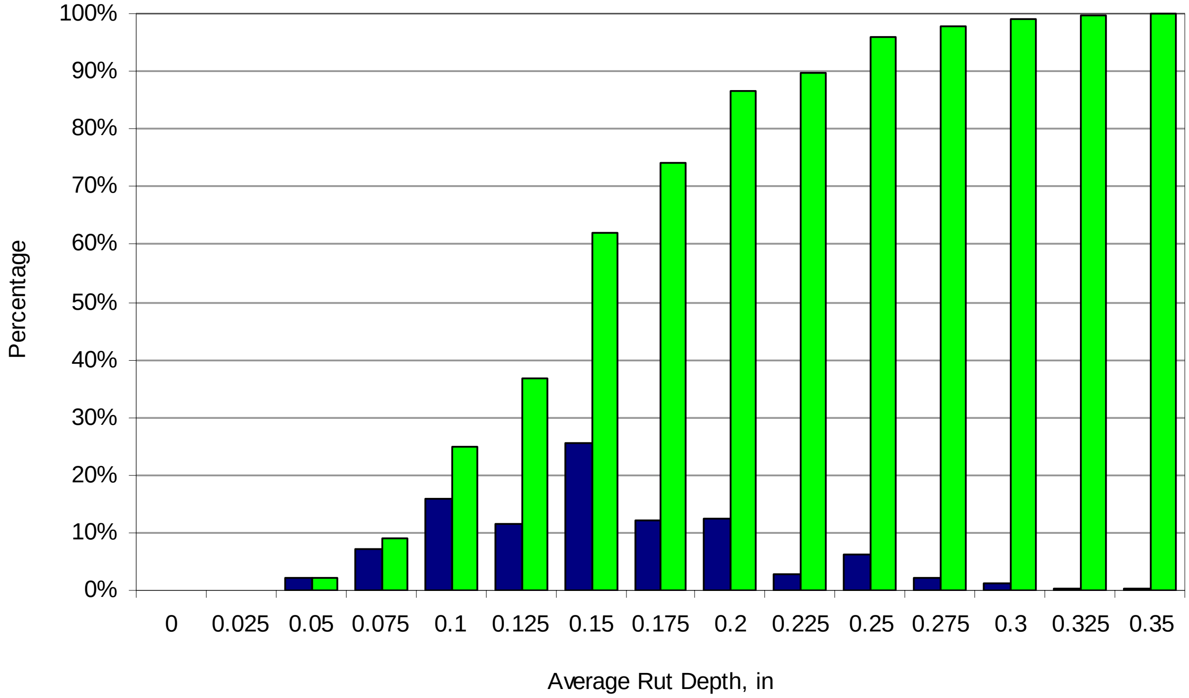


Figure 20. Frequency Distribution and Cumulative Frequency of Average Segment Rutting for Flexible Pavement Segments of I-81

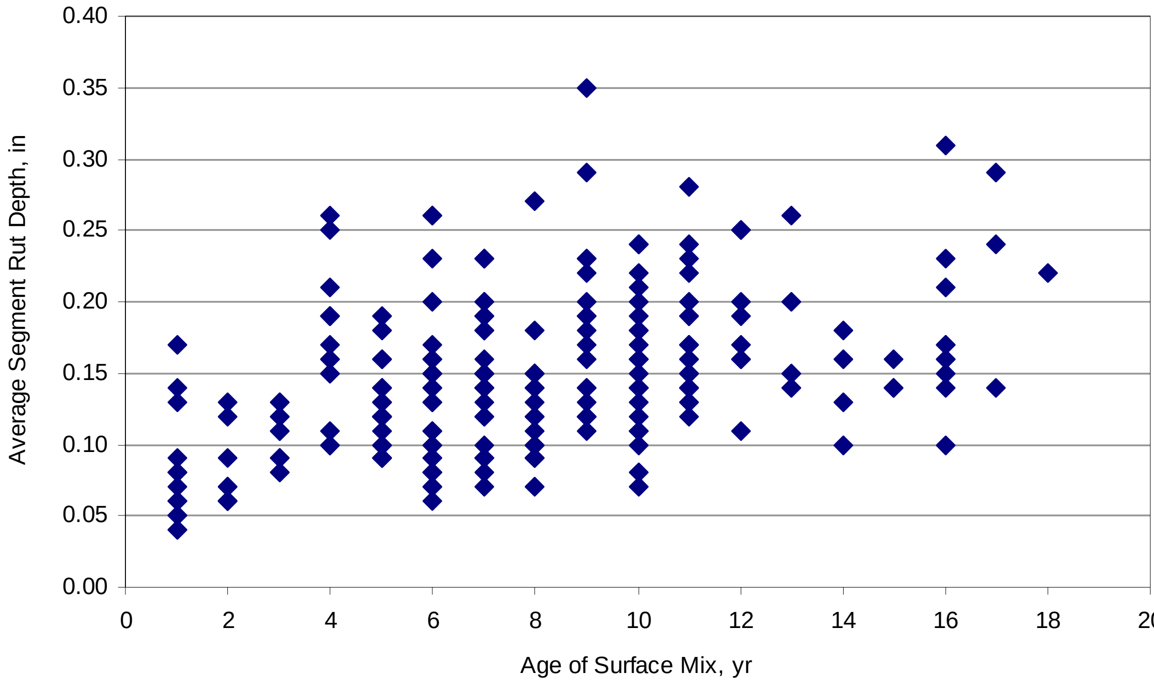


Figure 21. Average Segment Rutting Related to Age of Surface Mixture for Flexible Pavement Segments of I-81

however, if maintenance activities have been carried out as a result of excessive rutting on any segments (such as that predicted by the MEPDG), the segments will no longer indicate the higher rut depths and can thus influence the interpretation of the data. However, if the assumption is made that the predicted rutting from the MEPDG should be halved (as with the conservative evaluation of the primary rutting) for comparison with the data measured on I-81, the results still indicate an over-prediction of rutting, as the MEPDG results were greater than the 85th percentage of the measured results.

SUMMARY OF FINDINGS

- The fatigue predictive model provided predictions that were generally comparable to the results of pavement condition evaluations for "bottom-up" fatigue cracking in the evaluated interstate pavement; however, when a primary pavement structure was analyzed, the model over-predicted bottom-up fatigue cracking as compared to pavement condition data.

- The fatigue predictive model results did not significantly differentiate among Level 1, 2, and 3 asphalt material inputs. The standard error of prediction for the fatigue model resulted in errors that were greater than any of the predicted distresses for the structures and materials evaluated in this study.

- Fatigue predictions using the Level 3 asphalt inputs showed slight differences attributable to binder type, following a trend of reduced fatigue cracking with the use of stiffer binders; however, the differences were not statistically significant.

- The rutting predictive model generally over-predicted the expected rutting for both the interstate and primary pavement structures as compared to that indicated by pavement condition data.

- The rutting predictive model results did not significantly differentiate among Level 1, 2, and 3 asphalt material inputs.

- Rutting predictions using the Level 3 asphalt inputs showed slight differences attributable to binder type, and they followed the expected trend (reduced rutting using stiffer binders). However, the differences were not statistically significant and, more important, were not as pronounced as expected from field experiences with the relative performance of binders.

CONCLUSIONS

- *Further refinement or calibration of the predictive models is necessary in order for the benefits of their use to be realized.*

- *Local calibration and verification of the rutting predictive model are needed to provide predictions that are consistent with distress quantities indicated by pavement condition data.*

- *Local calibration and verification of the fatigue predictive model using local sites are needed to verify further the accuracy and sensitivity of the model.*

- *Additional analyses may be necessary after refinement and calibration have been performed to assess further the impacts on the sensitivity of the models to the asphalt materials input levels and to determine the final choice of asphalt materials input levels for implementation of the MEPDG methodology.*

RECOMMENDATIONS

1. *VDOT's Materials Division and VTRC should complete a local calibration process to modify the predictive models such that they accurately predict the conditions found on Virginia's roadways* . If the predictive models are modified, the results may significantly impact the findings and recommendations resulting from this study.

2. *VDOT's Materials Division should consider implementing the MEPDG using Level 3 asphalt material inputs.* Based on the results of this study from a limited number of mixtures and binder grades, there is no justification at this time for full implementation using Level 1 asphalt material inputs. However, local calibration of the predictive models and further evaluation using additional mixtures and binders may significantly impact (or reverse) this recommendation.

3. *VTRC should continue to evaluate the sensitivity of the MEPDG software using Level 1 inputs from mixtures with different binder grades.* Level 1 data were available for this study only from mixtures produced with PG 64-22 binders. Additional Level 1 data are necessary to validate the trends seen from the Level 3 analysis in this study and to examine fully the sensitivity of the predictive models.

4. *VTRC should continue to evaluate the sensitivity of the MEPDG software using Level 2 asphalt material inputs.* A limited evaluation was performed during this study, but additional work is needed to determine the sensitivity at this input level to various binder grades.

5. *VTRC should continue to collect mixture and binder data to populate fully a catalog of asphalt mixture properties to be used in the implementation of the MEPDG.* Although the current study indicated that Level 1 asphalt material inputs do not provide significant changes in predictions compared to Level 3 asphalt material inputs, it is anticipated that local calibration may improve the predictive accuracy such that use of Level 1 asphalt material inputs will be implemented during the pavement design process.

BENEFITS AND IMPLEMENTATION PROSPECTS

This study directly supported the implementation efforts currently under way to initiate statewide use of the MEPDG. Sensitivity analyses are required to validate the appropriate level of input parameters that should be used for MEPDG implementation. This study provided initial guidance on the effect of input values on the distresses predicted by the MEPDG software. In addition, this study supported the efforts under way to provide a catalog of asphalt properties needed for use of the MEPDG. Level 1 through 3 input properties for 11 mixtures and their corresponding binder properties were compiled into an initial catalog. The results of this study also confirmed the need to perform local calibration of the flexible pavement distress prediction models used in the MEPDG software. Once this calibration is performed, it is expected that the predicted distresses will more accurately reflect the performance of typical Virginia pavements. This will allow pavement designers to provide efficient designs with confidence in the resulting pavement's ability to perform well over its expected lifetime.

The predicted pavement condition results of the MEPDG analysis are only as reliable as the quality and accuracy of the input data. Thus, the various input factors are critical components to consider in the analysis. The implementation of the recommendations from this study and the use of the MEPDG will provide VDOT with a more efficient and effective means for pavement design and analysis. The use of optimal pavement designs will provide economic benefits to VDOT in terms of initial construction and lifetime maintenance costs.

ACKNOWLEDGMENTS

This study would not have been possible without the assistance of Troy Deeds, Donnie Dodds, and the VTRC Asphalt Laboratory staff in the collection and testing of samples. Thanks are extended to Tanveer Chowdhury and Raja Shekharen for providing pavement condition data. The assistance of Alex Apeagyei in reviewing the inputs is deeply appreciated. Appreciation is also extended to the project review panel, composed of Alex Apeagyei, Trenton Clark, Brian Diefenderfer, Mohamed Elfino, Affan Habib, and G. W. "Bill" Maupin, for their guidance during this project. Finally, the author thanks Ed Deasy and Linda Evans for their support in the graphics and editorial process.

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APPENDIX A

MEPDG MIXTURE INPUT VALUES

Table A1. MEPDG Mixture Inputs for Asphalt Mixtures

Mixture Designation		V_{be}[a]	VTM[b]	Unit Weight, lb/ft^3	Cumulative % Retained		% Passing	
					3/4 in Sieve	3/8 in Sieve	No. 4 Sieve	No. 200 Sieve
Surface	38	12.7	5.6	156.9	0.0	10.1	42.8	5.0
	40	12.7	2.7	161.9	0.0	3.7	42.9	6.3
	69	14.1	1.6	159.9	0.0	8.6	44.2	6.3
Intermediate	44	11.3	2.6	152.1	0.0	12.5	47.0	6.6
	49	9.9	4.8	151.3	2.4	26.7	58.5	3.8
	52	10.6	5.7	149.3	3.6	30.5	54.4	5.5
	58	12.8	5.5	148.1	1.2	24.6	41.5	5.9
Base	50	9.0	5.0	163.0	5.6	34.0	53.7	5.4
	53	9.2	3.9	152.4	26.2	33.4	57.1	5.5
	66	7.7	7.3	154.3	12.4	35.2	52.0	6.1
	70	10.5	3.5	152.2	4.5	29.4	58.9	3.9

[a]V_{be} = Volumetric effective binder content, %, calculated as voids in mineral aggregate – voids in total mix.
[b]VTM = voids in total mix, %.

Table A2. Complex Modulus Input Values for Surface Mixtures

Temperature, °F	Frequency, Hz 0.1	0.5	1.0	5.0	10.0	25.0
Surface 38						
50	3,107,564	3,398,156	3,593,345	3,960,157	4,057,174	4,333,753
104	1,157,226	1,539,602	1,727,045	2,138,302	2,311,719	2,561,795
158	306,046	498,585	631,343	958,007	1,122,966	1,362,312
212	72,904	114,743	153,699	277,108	352,416	454,691
266	40,497	46,315	51,859	76,424	95,259	132,327
Surface 40						
50	2,604,254	3,054,520	3,131,922	3,363,188	3,500,470	3,705,351
104	1,130,616	1,537,341	1,735,005	2,155,579	2,349,322	2,605,739
158	249,712	416,784	537,074	832,710	981,677	1,197,146
212	63,936	95,673	122,753	223,332	291,607	397,175
266	33,564	39,090	43,888	62,538	76,410	103,406
Surface 69						
50	1,998,823	2,364,427	2,508,401	2,838,067	2,965,681	3,118,667
104	640,852	947,119	1,104,987	1,466,752	1,629,681	1,856,929
158	143,138	235,317	310,035	513,274	625,520	787,588
212	41,927	58,109	71,838	120,719	154,431	217,539
266	19,822	24,792	28,606	41,232	50,118	68,341

Table A3. Complex Modulus Input Values for Intermediate Mixtures

	Frequency, Hz					
Temperature, °F	**0.1**	**0.5**	**1.0**	**5.0**	**10.0**	**25.0**
Intermediate 44						
50	2,571,769	2,870,548	2,978,339	3,227,220	3,312,687	3,461,416
104	1,284,699	1,663,575	1,834,202	2,225,520	2,393,572	2,623,756
158	336,641	539,565	670,097	975,987	1,123,062	1,321,791
212	80,740	130,677	176,801	314,886	399,620	521,003
266	32,541	43,622	52,812	85,996	109,943	154,504
Intermediate 49						
50	1,955,701	2,198,715	2,311,520	2,541,902	2,642,516	2,815,327
104	1,018,784	1,337,059	1,487,172	1,824,980	1,968,579	2,163,868
158	272,047	433,575	549,171	820,714	954,540	1,121,221
212	72,851	111,376	144,960	253,583	321,829	422,372
266	35,179	43,438	50,043	75,332	95,082	133,846
Intermediate 52						
50	3,326,528	3,713,052	3,840,073	4,106,860	4,223,722	4,426,732
104	1,635,917	2,102,497	2,305,456	2,759,829	2,942,922	3,214,045
158	386,216	616,840	767,755	1,127,285	1,314,062	1,572,842
212	88,272	140,477	184,529	326,940	414,640	543,349
266	43,913	53,340	61,165	92,999	116,423	160,356
Intermediate 58						
50	2,473,688	2,679,825	2,783,487	3,010,592	3,094,851	3,350,092
104	1,276,337	1,711,667	1,904,156	2,336,393	2,529,051	2,798,348
158	252,015	428,687	550,875	856,234	1,007,854	1,222,337
212	57,882	86,691	112,830	206,863	272,370	376,564
266	32,328	37,939	42,812	60,416	74,603	104,840

Table A4. Complex Modulus Input Values for Base Mixtures

	Frequency, Hz					
Temperature, °F	**0.1**	**0.5**	**1.0**	**5.0**	**10.0**	**25.0**
Base 50						
50	2,839,652	3,204,125	3,359,428	3,702,575	3,830,124	4,030,155
104	1,211,658	1,642,136	1,842,732	2,301,929	2,496,564	2,756,767
158	279,654	456,054	584,862	894,451	1,048,595	1,253,220
212	70,445	108,528	142,006	250,424	318,904	416,070
266	32,931	41,799	48,862	74,348	93,043	130,238
Base 53						
50	3,661,075	4,029,961	4,168,011	4,477,887	4,599,756	4,750,695
104	2,067,593	2,610,845	2,491,871	2,927,127	3,098,337	3,328,466
158	637,234	1,015,309	1,247,578	1,784,765	2,032,723	2,349,581
212	135,949	222,046	294,554	520,460	654,499	865,027
266	53,486	69,292	82,494	131,368	167,283	236,527
Base 66						
50	3,008,263	3,653,482	3,855,447	4,243,483	4,411,571	4,544,481
104	878,760	1,311,087	1,547,927	2,037,902	2,229,072	2,544,837
158	181,177	290,557	375,539	614,713	745,277	934,918
212	73,874	92,297	107,170	165,368	206,827	281,470
266	47,915	53,635	57,411	70,669	81,765	106,016
Base 70						
50	3,217,537	3,581,760	3,755,448	4,064,134	4,175,796	4,271,832
104	1,319,760	1,684,928	1,869,669	2,200,672	2,377,548	2,770,466
158	344,319	549,956	686,846	1,020,407	1,187,309	1,419,351
212	83,818	130,464	170,875	299,115	380,242	477,717
266	40,574	50,632	58,776	91,675	114,367	156,248

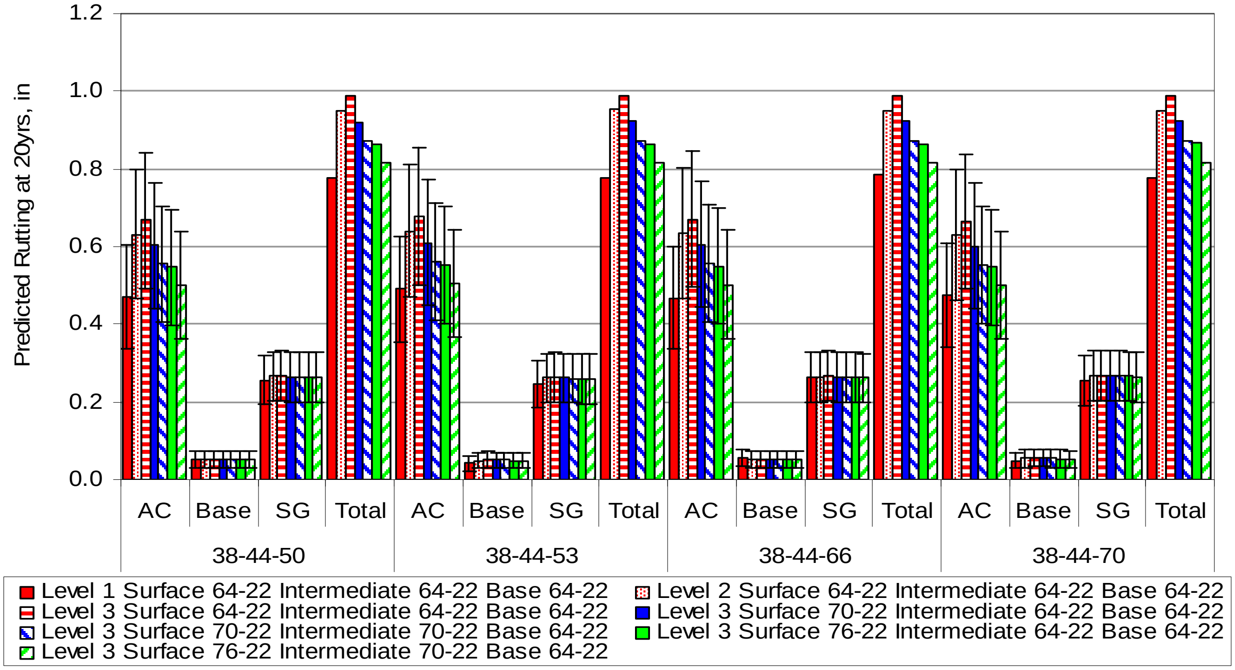
Table A5. Asphalt Binder Complex Shear Modulus and Phase Angle Input Values

Mixture Designation[a]	**Parameter**	**Temperature, °F**					
		50	**77**	**104**	**131**	**158**	**185**
37/38	G*, Pa	1.95E+07	1.60E+07	1.54E+05	12760	1578	282.1
	delta, °	41.6	60.1	71.4	80.1	85.8	88.7
40	G*, Pa	2.06E+07	2.01E+06	1.53E+05	12100	1542	269.3
	delta, °	42.9	61.1	72.4	80.1	86.1	88.8
44	G*, Pa	1.64E+07	1.43E+06	1.29E+05	13990	1827	337.9
	delta, °	46.2	61.8	71.1	78.1	84.1	87.8
49/50	G*, Pa	1.55E+07	1.37E+06	1.27E+05	12190	1675	304.1
	delta, °	46.6	61.9	71.1	78.8	84.4	87.9
52	G*, Pa	1.94E+07	1.94E+06	1.66E+05	14900	1864	330.9
	delta, °	41.7	58.4	69.6	78.2	84.4	88
53	G*, Pa	2.29E+07	1.91E+06	1.47E+05	12540	1532	271.8
	delta, °	42.7	61.8	73.3	81.1	86.2	88.8
58	G*, Pa	2.34E+07	2.08E+06	1.50E+05	12870	1555	264.2
	delta, °	42.3	61.4	73.2	81	86.2	88.9
66	G*, Pa	1.53E+07	1.29E+06	1.20E+05	13230	1731	326.6
	delta, °	45.5	61	69.5	77	83.6	87.6
69	G*, Pa	1.44E+07	1.27E+06	1.23E+05	12580	1711	316.1
	delta, °	45.9	60.9	69.5	77	83.5	87.4
70	G*, Pa	1.65E+07	1.46E+06	1.34E+05	14060	1905	350.4
	delta, °	44.8	60.8	69.9	77.3	83.6	87.5

[a]Multiple designation numbers indicate that the same binder was used in more than one mixture.

APPENDIX B

PREDICTED RUTTING RESULTS



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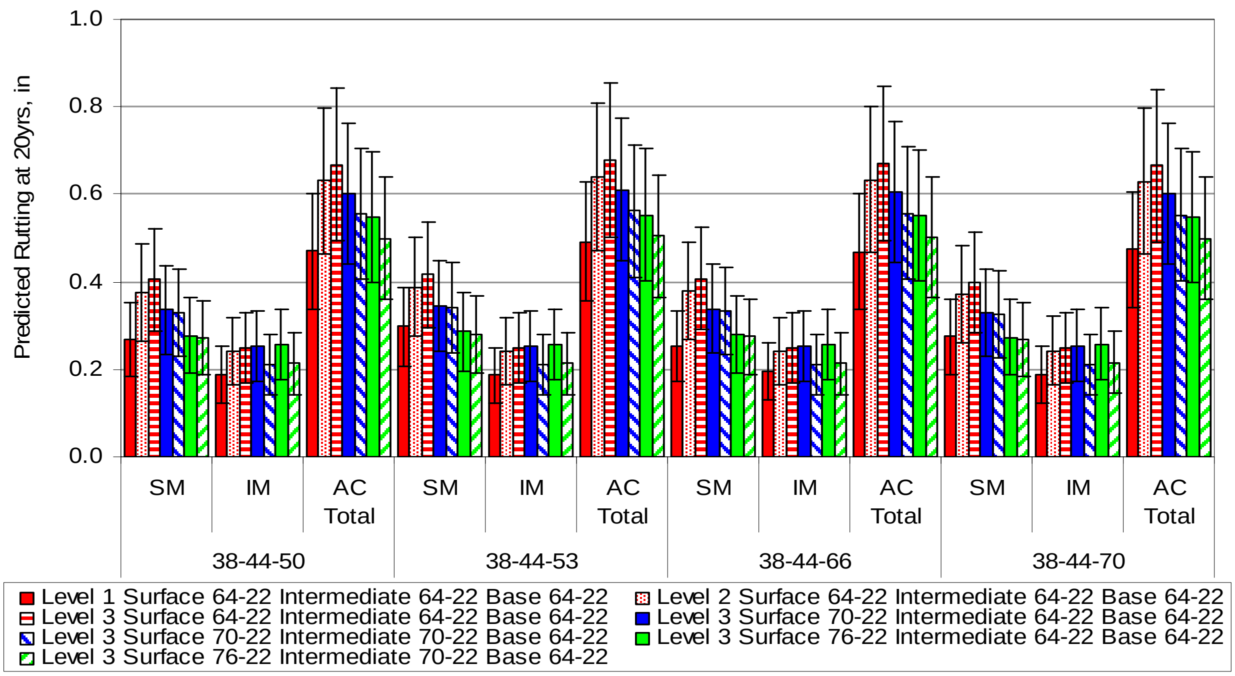
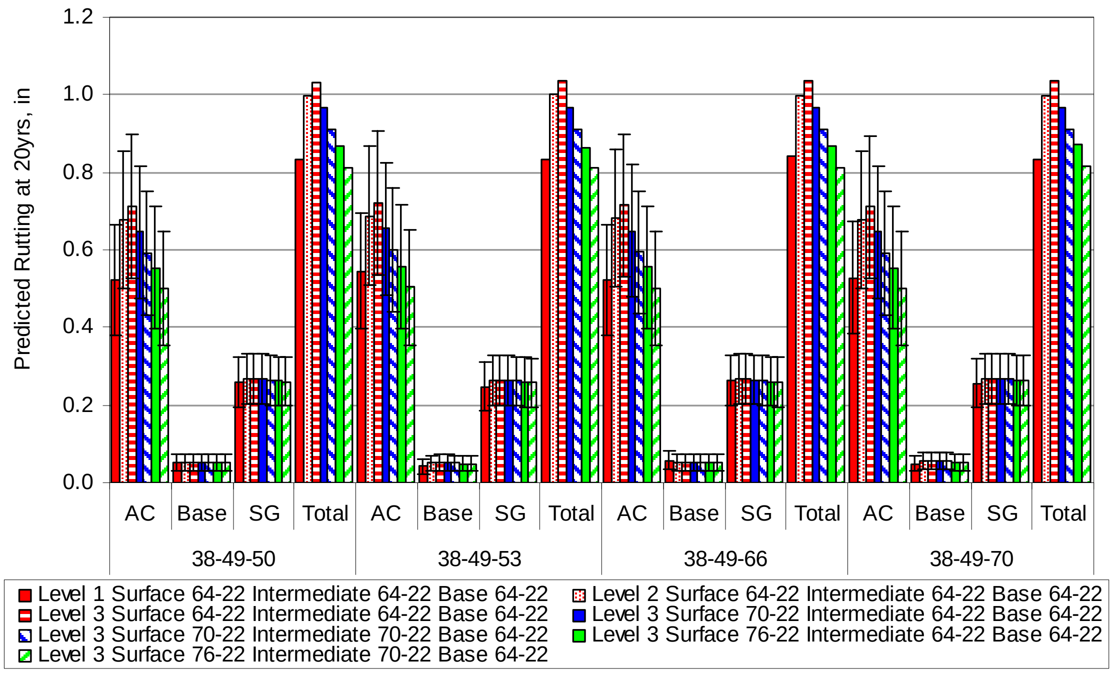


(b)

Figure B1. Predicted Rutting using Surface Mixture 38, Intermediate Mixture 44, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)



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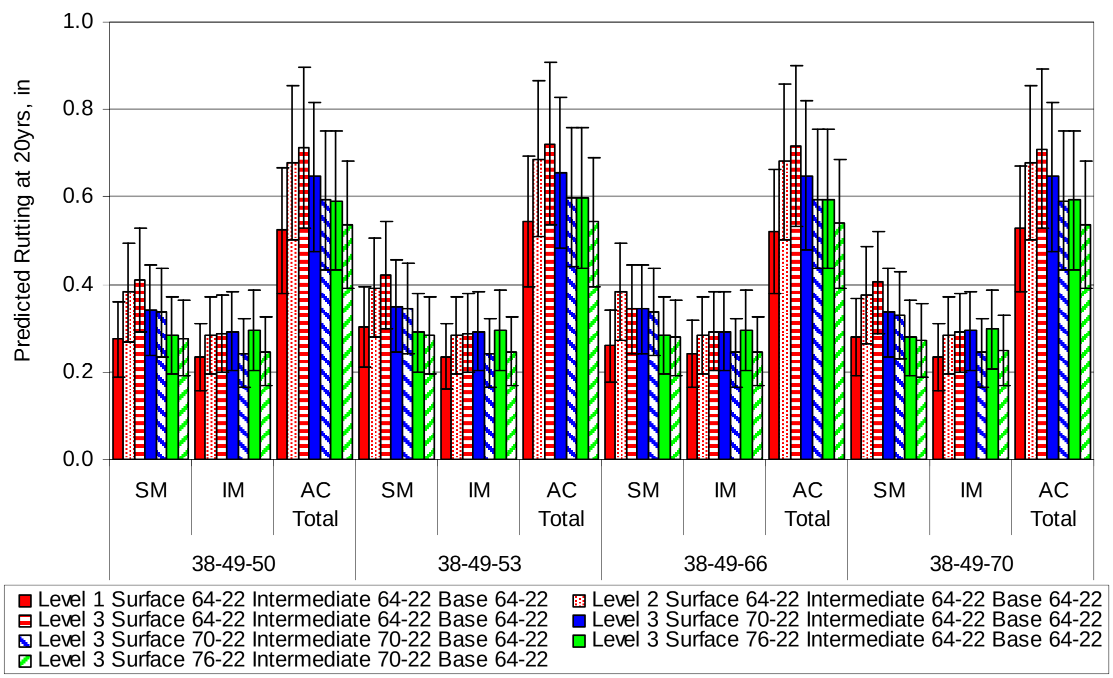
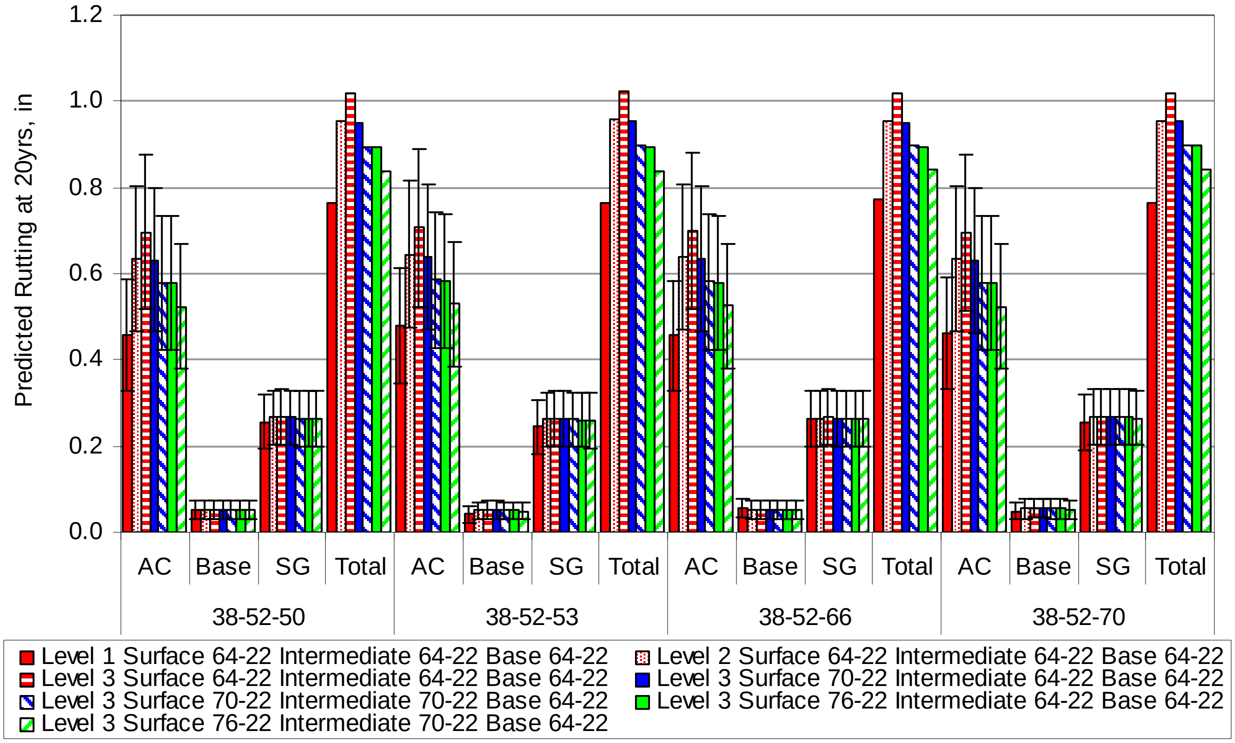


(b)

Figure B2. Predicted Rutting Using Surface Mixture 38, Intermediate Mixture 49, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)



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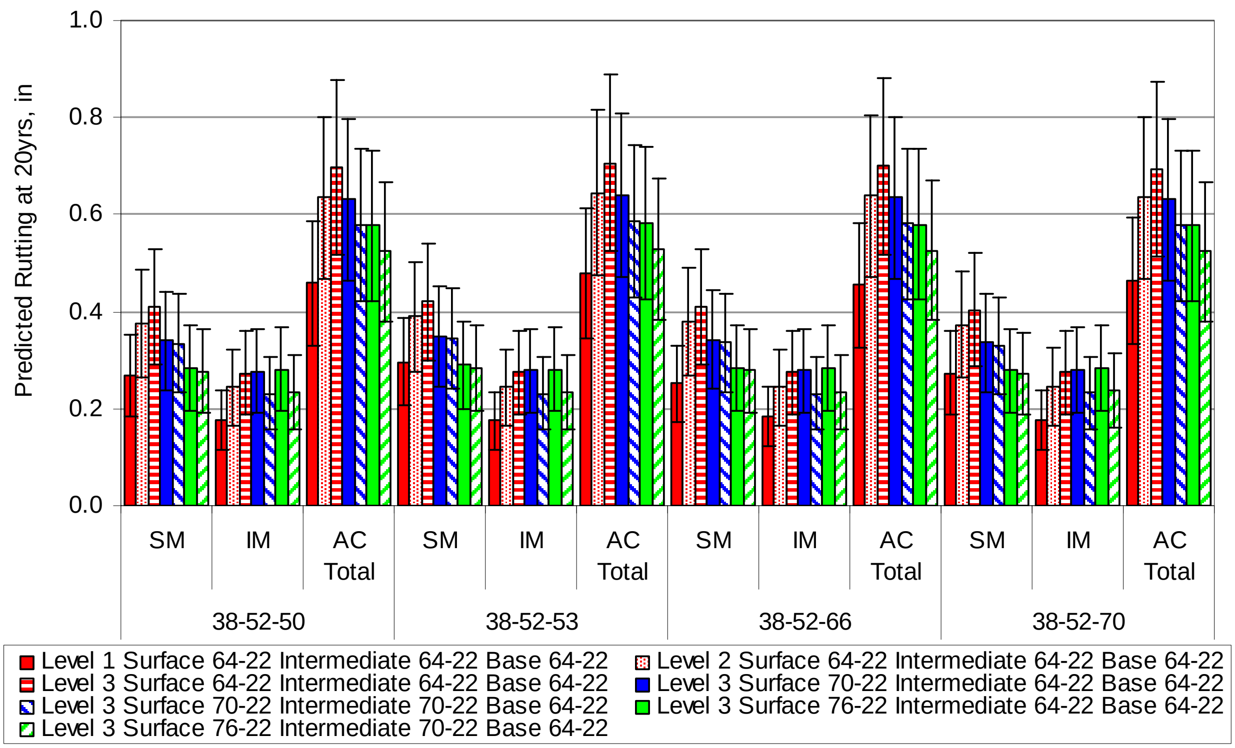
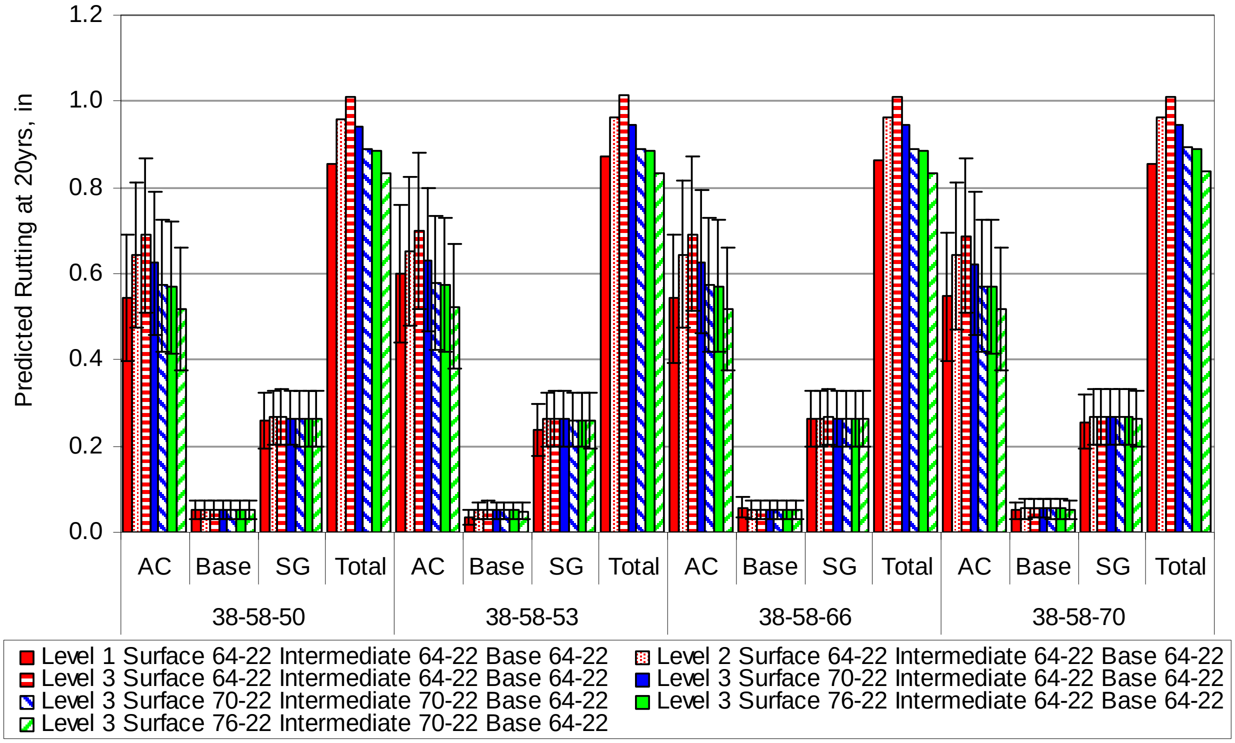
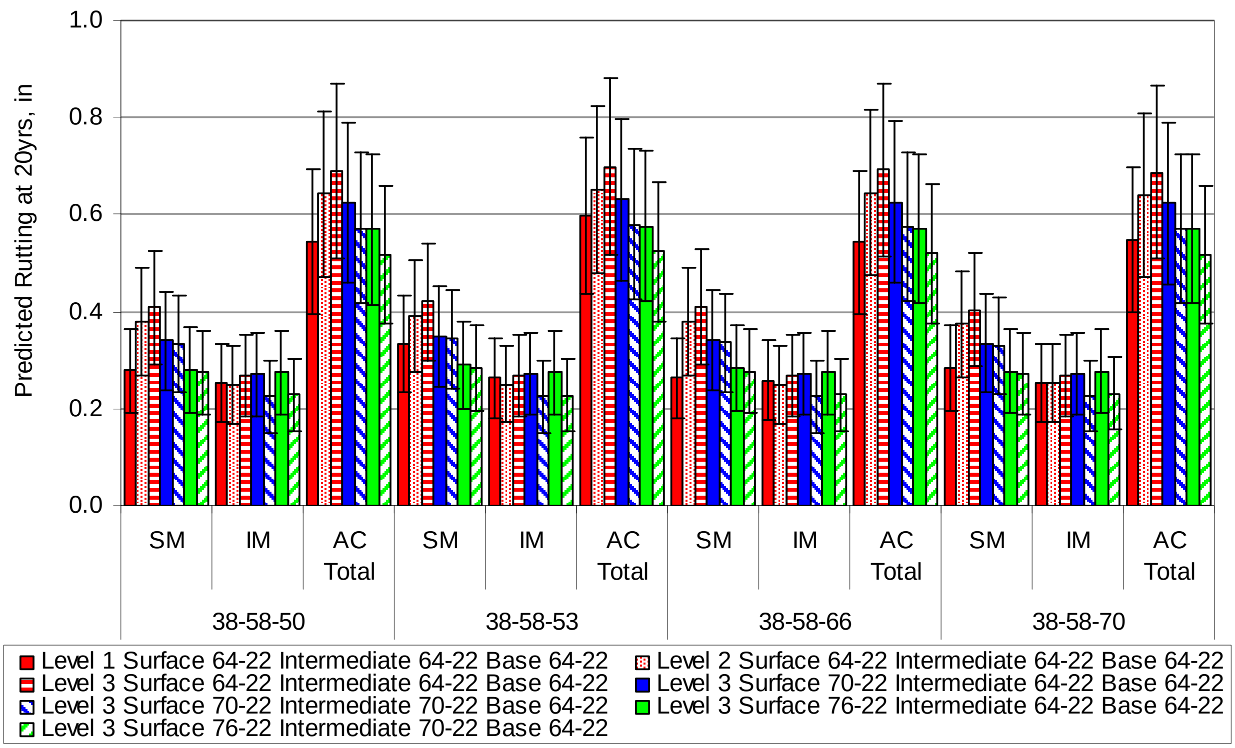


(b)

Figure B3. Predicted Rutting using Surface Mixture 38, Intermediate Mixture 52, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

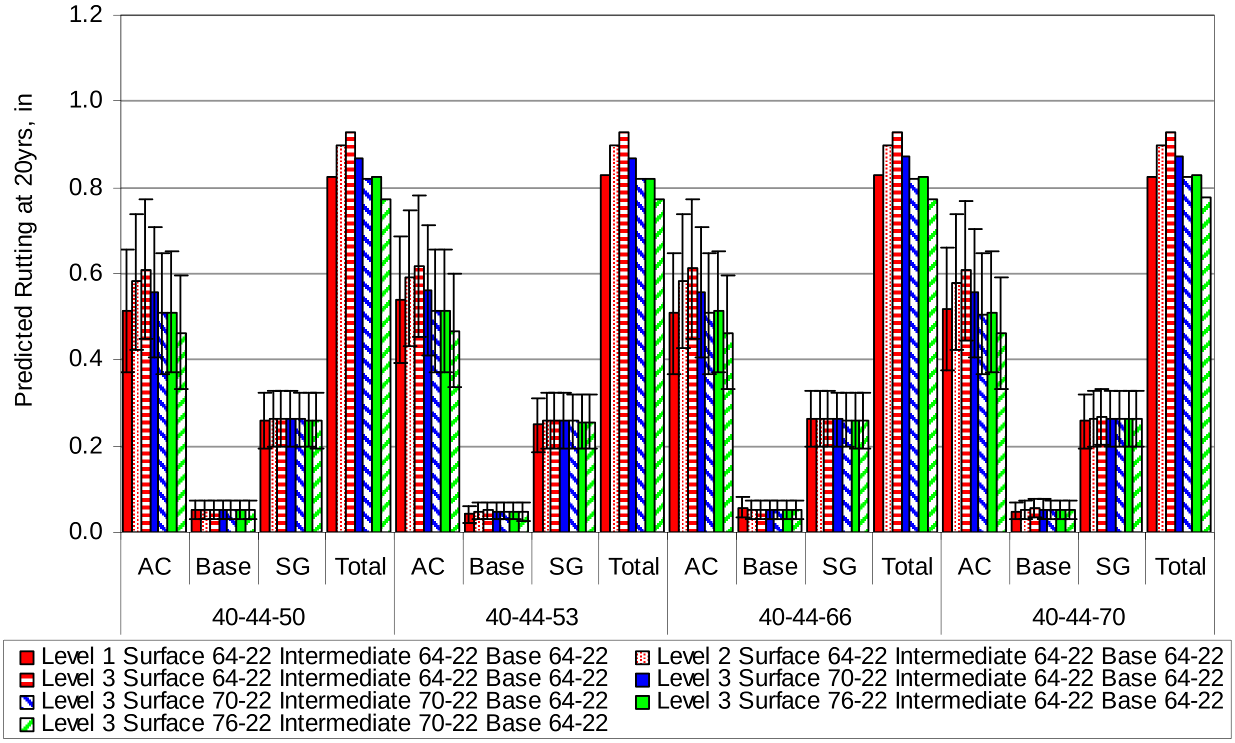


(a)



(b)

Figure B4. Predicted Rutting Using Surface Mixture 38, Intermediate Mixture 58, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)



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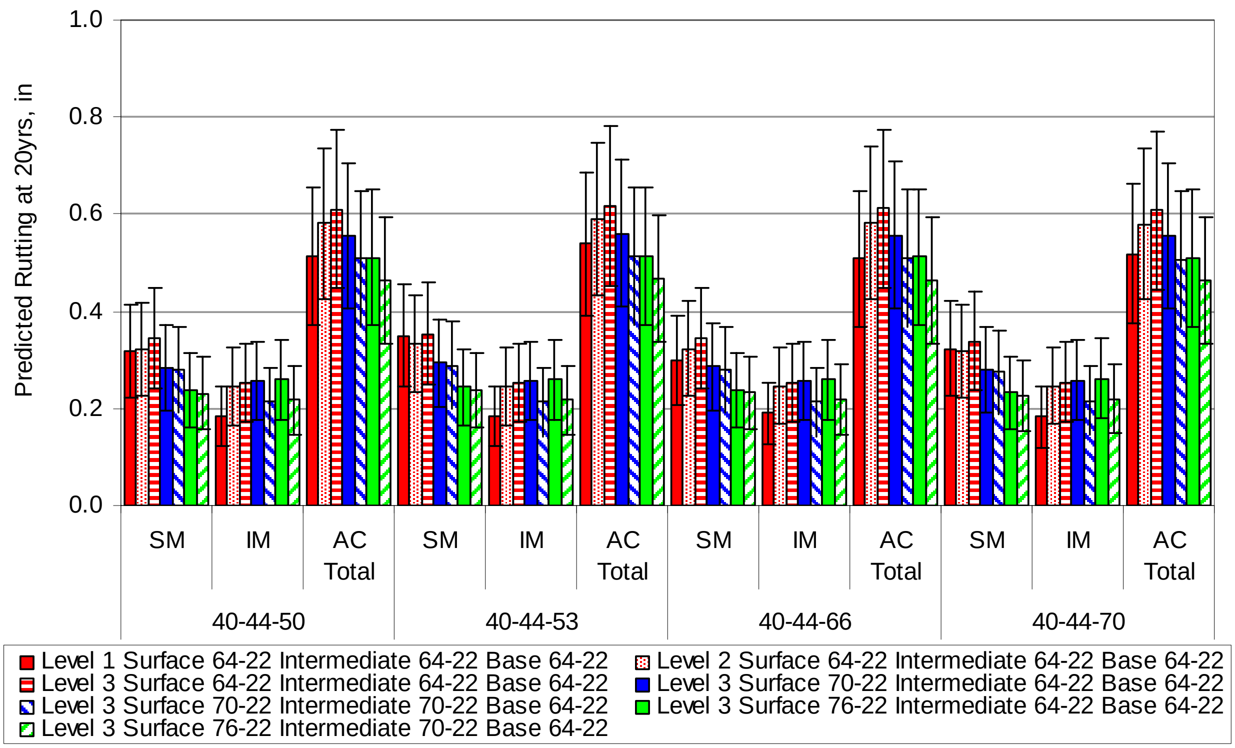


(b)

Figure B5. Predicted Rutting Using Surface Mixture 40, Intermediate Mixture 44, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

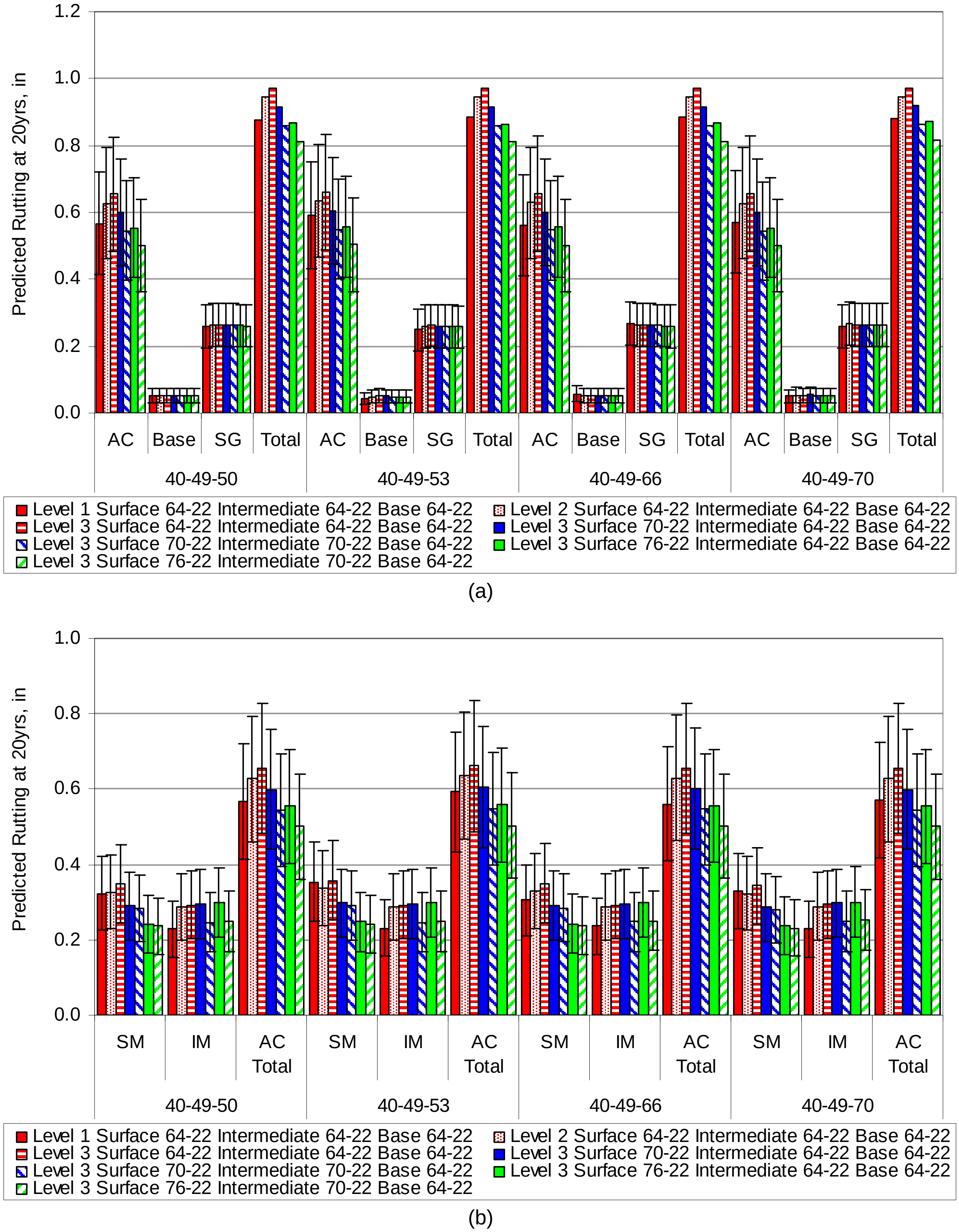
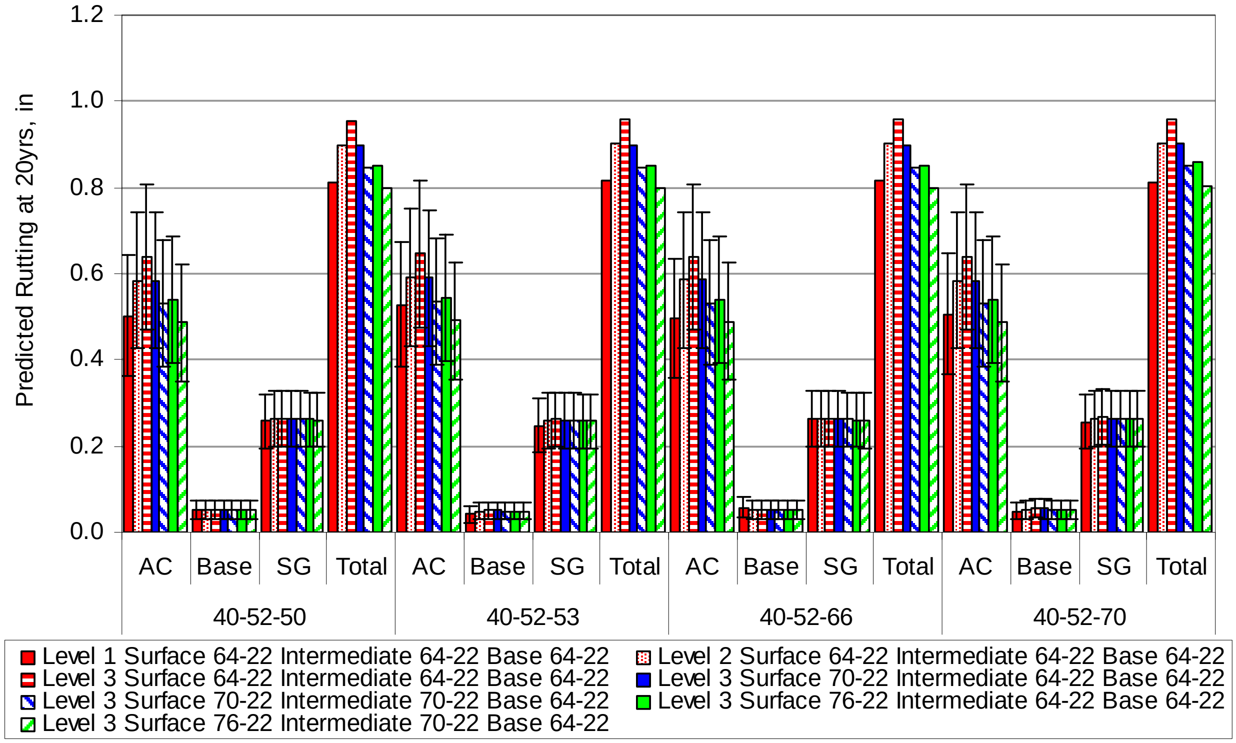
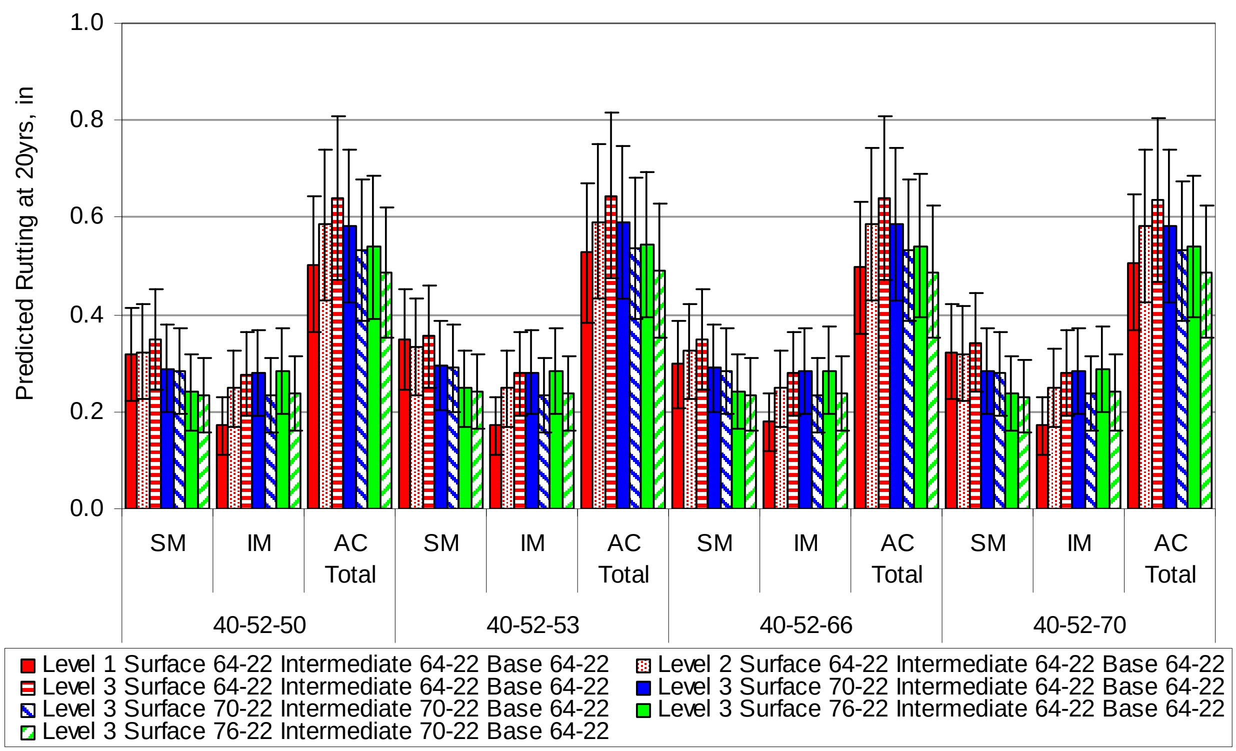


Figure B6. Predicted Rutting Using Surface Mixture 40, Intermediate Mixture 49, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

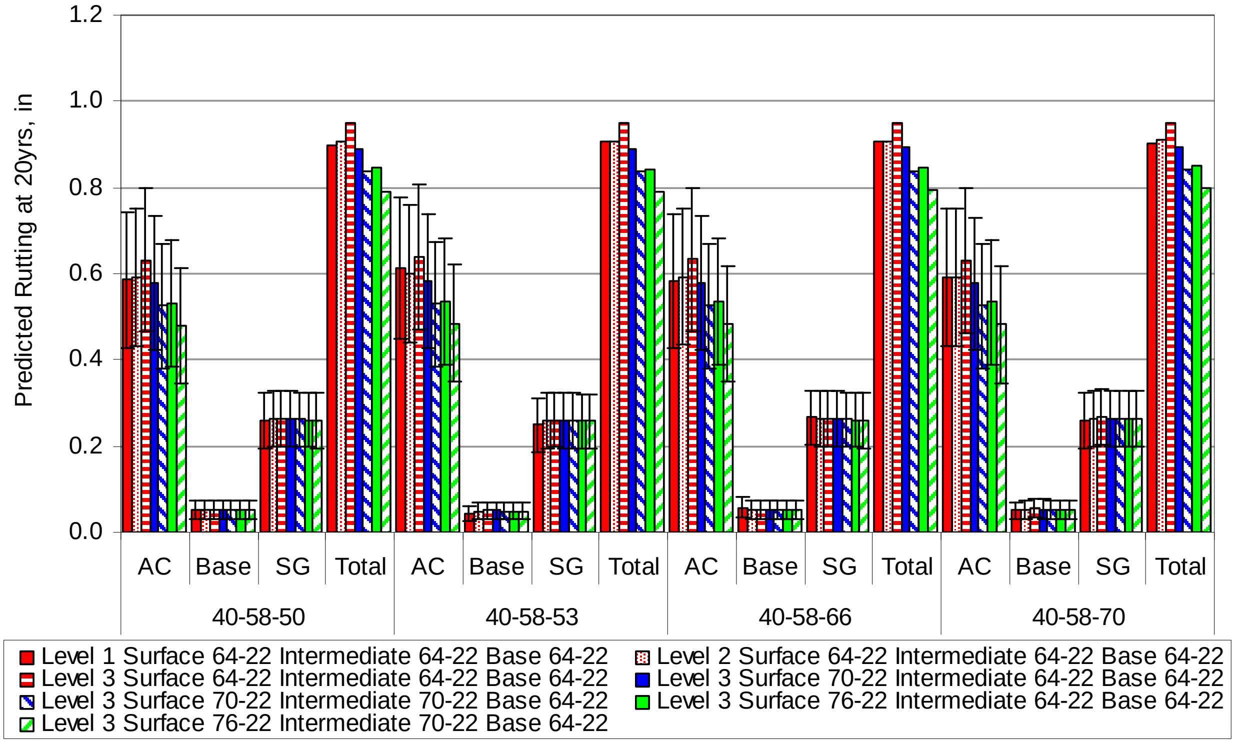


(a)

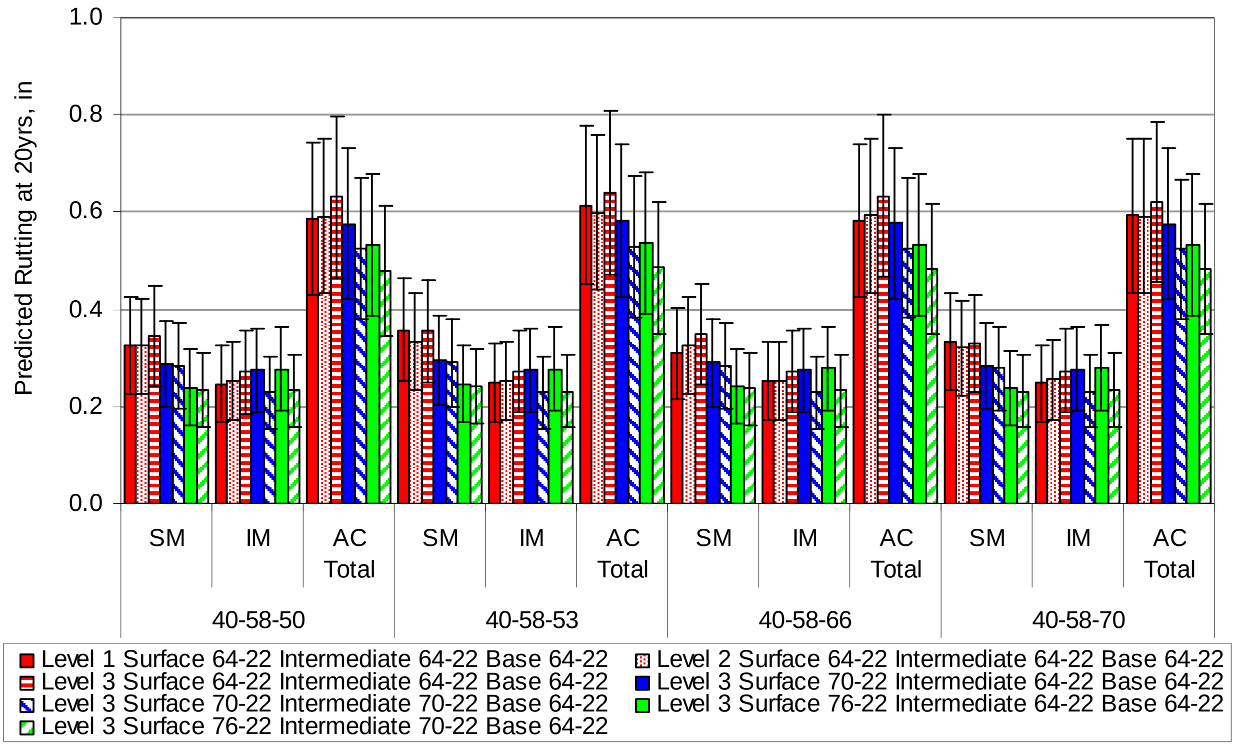


(b)

Figure B7. Predicted Rutting Using Surface Mixture 40, Intermediate Mixture 52, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

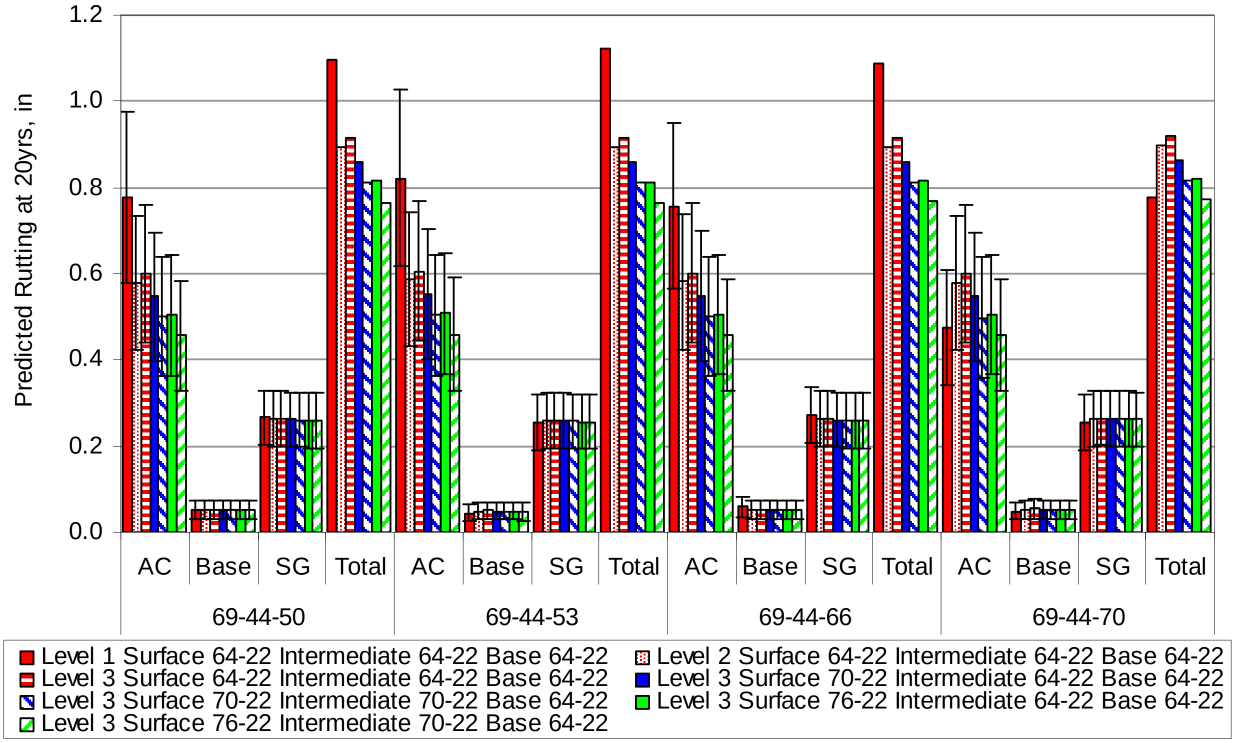


(a)



(b)

Figure B8. Predicted Rutting Using Surface Mixture 40, Intermediate Mixture 58, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)



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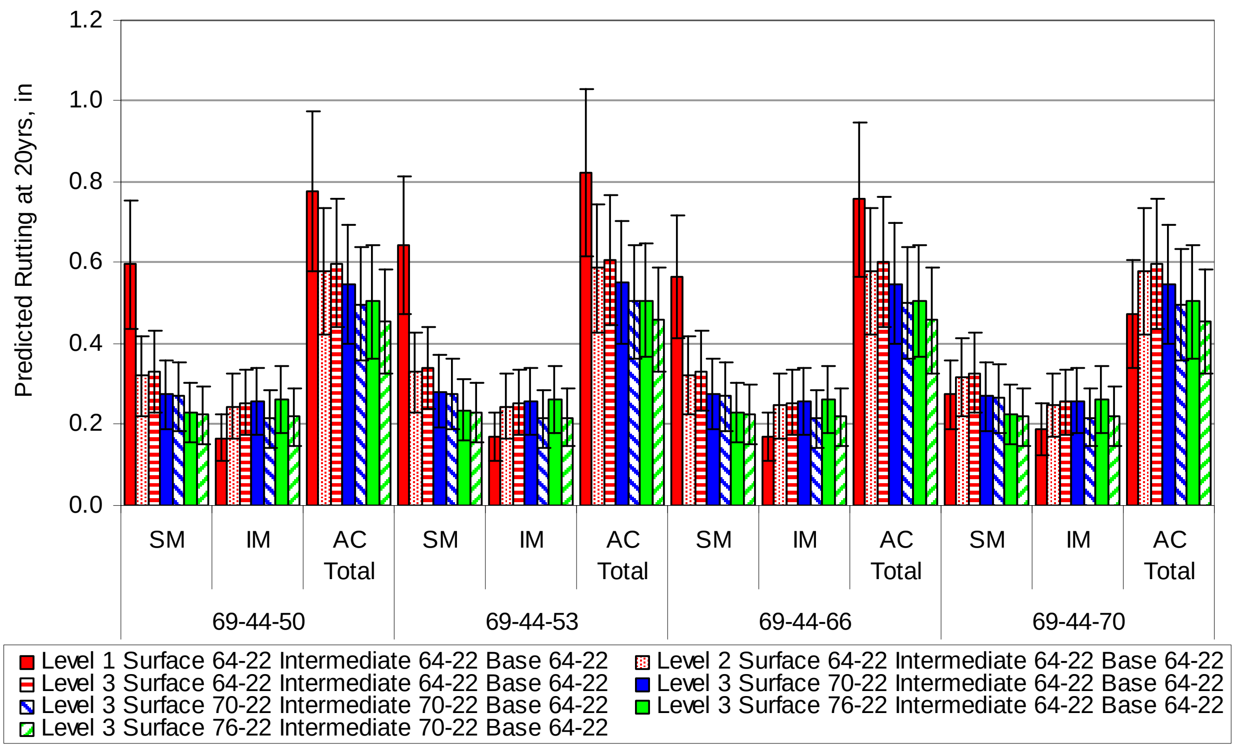
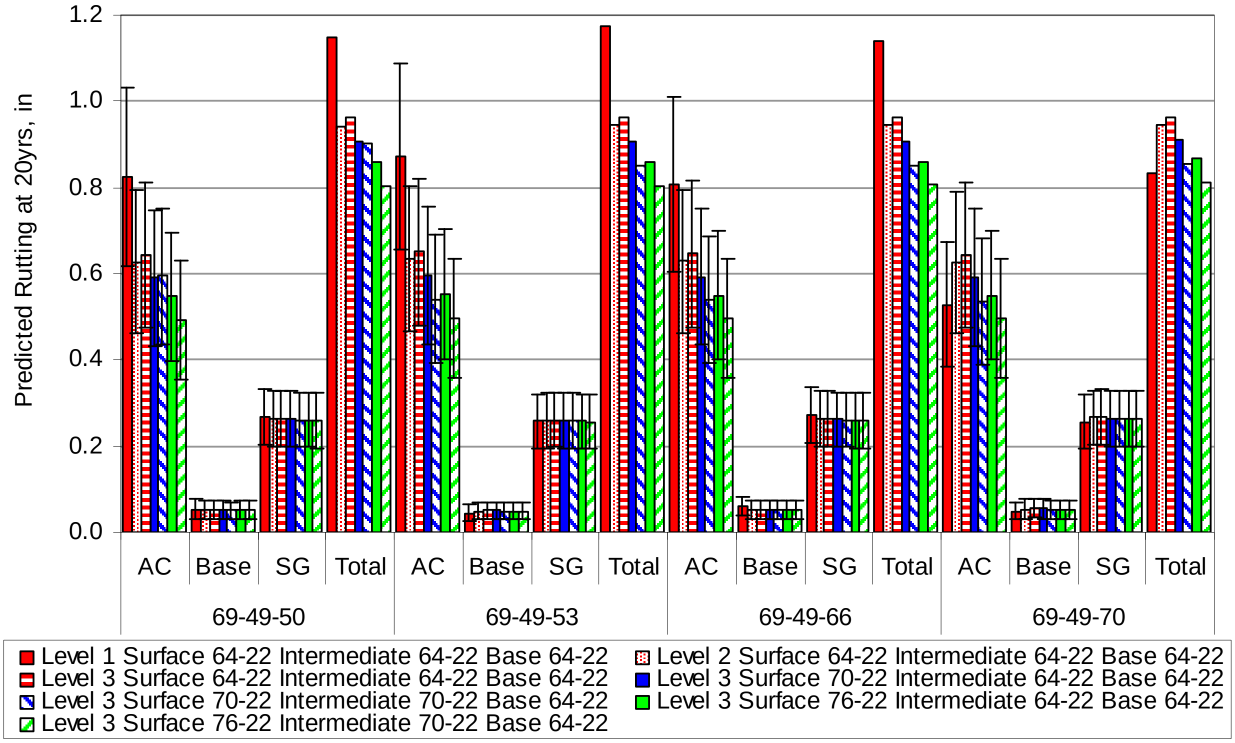
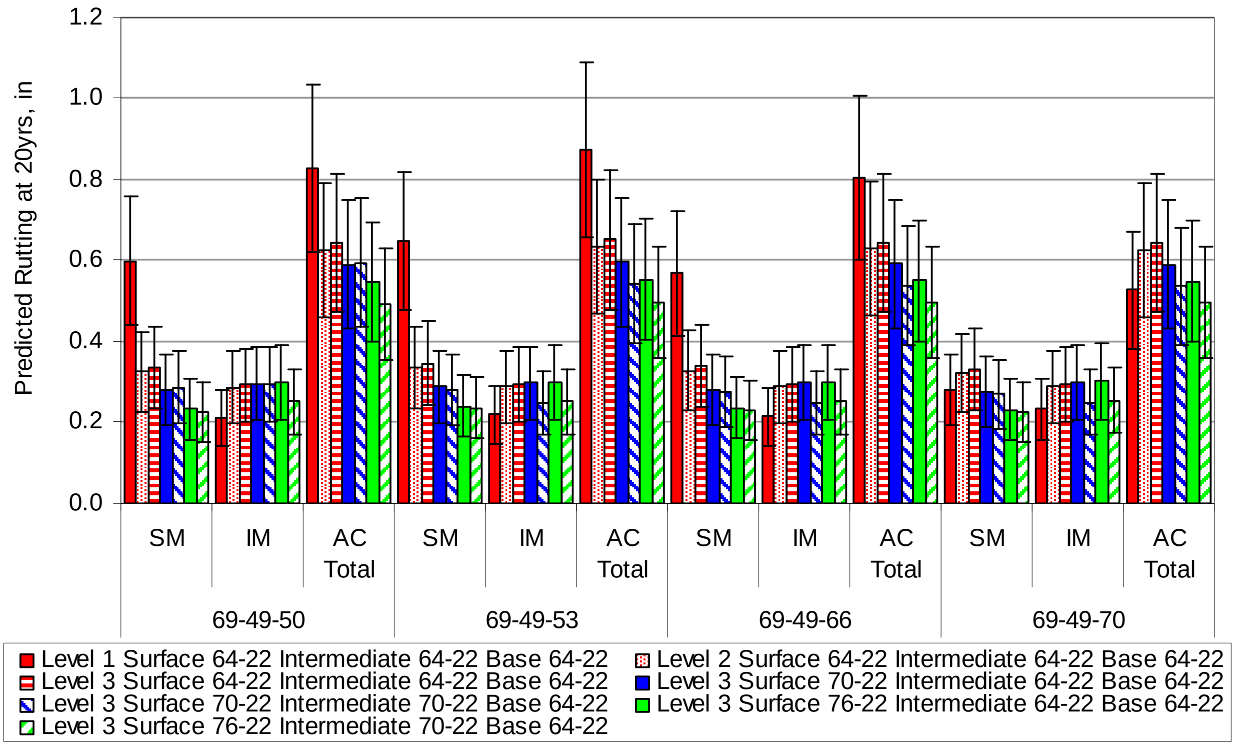


(b)

Figure B9. Predicted Rutting Using Surface Mixture 69, Intermediate Mixture 44, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

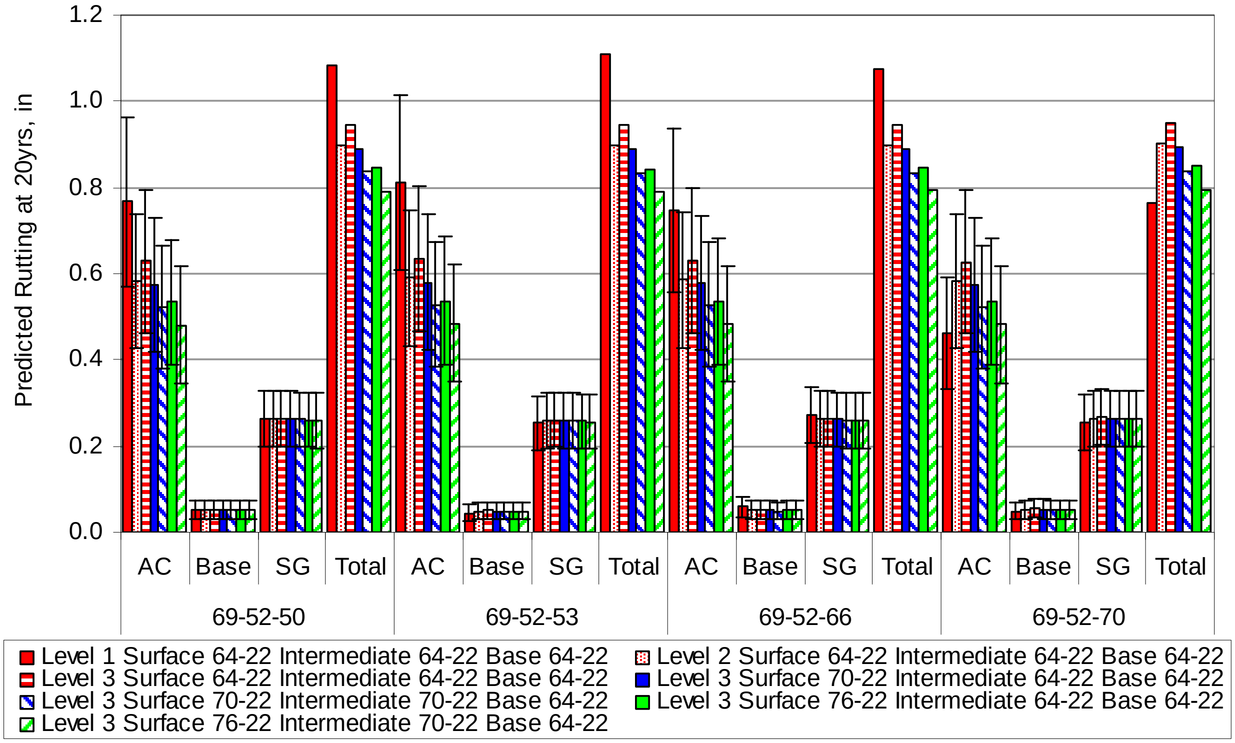


(a)

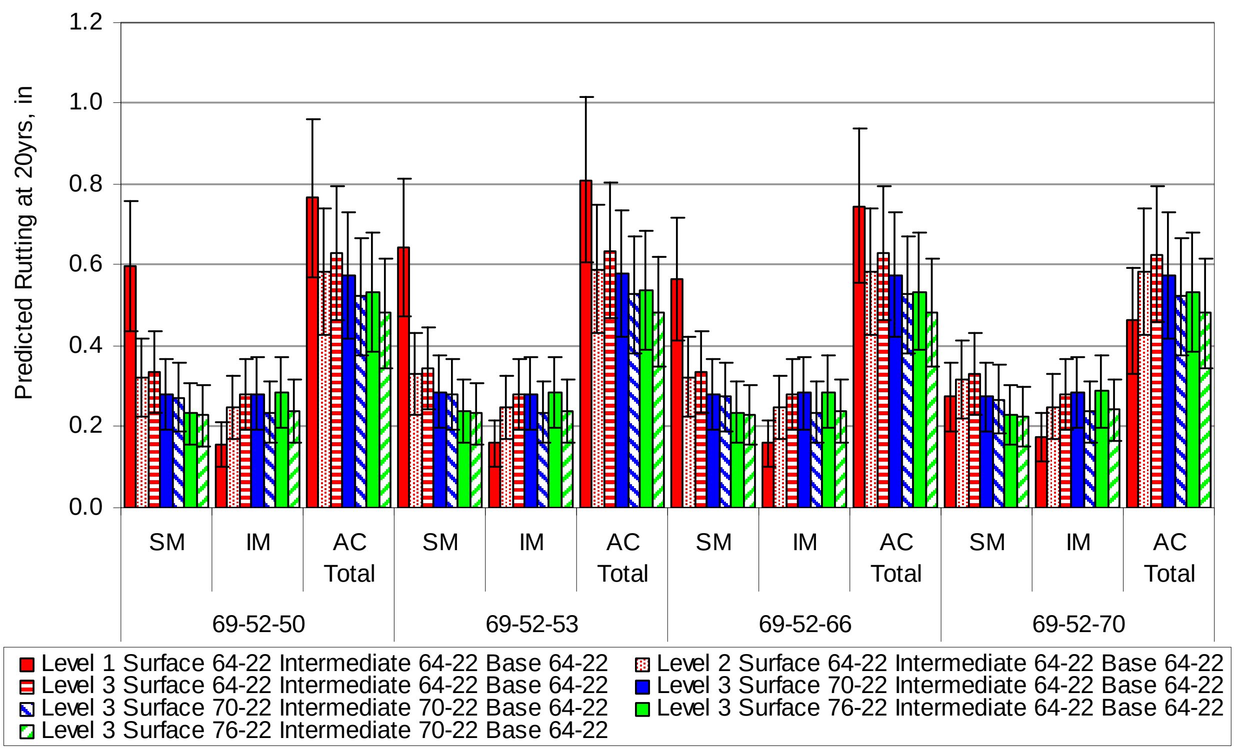


(b)

Figure B10. Predicted Rutting Using Surface Mixture 69, Intermediate Mixture 49, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)

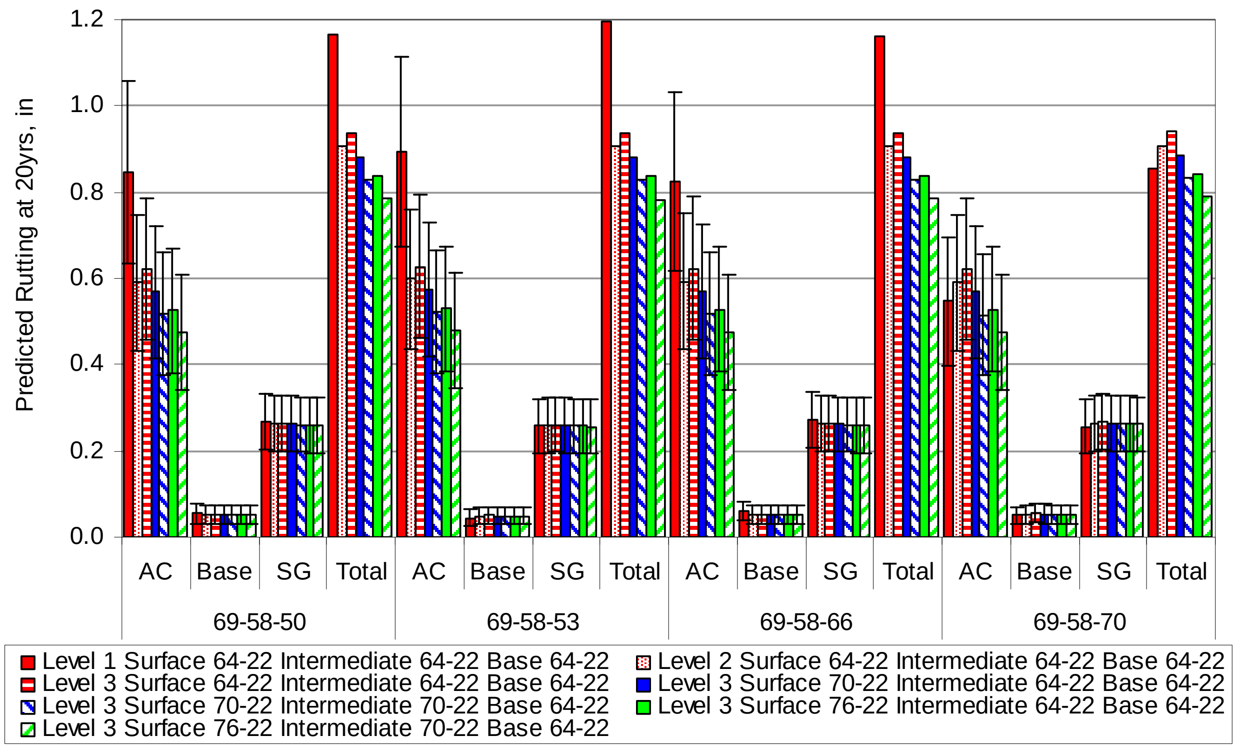


(a)



(b)

Figure B11. Predicted Rutting Using Surface Mixture 69, Intermediate Mixture 52, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)



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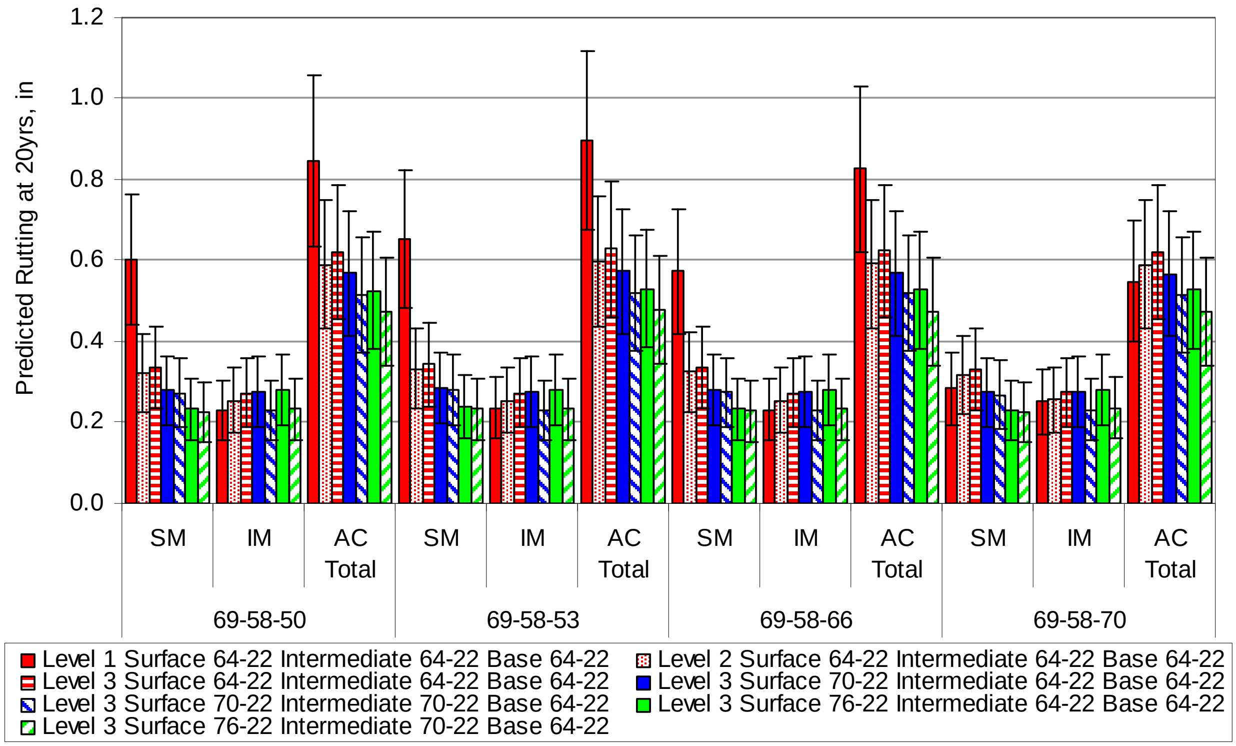

(b)

Figure B12. Predicted Rutting Using Surface Mixture 69, Intermediate Mixture 58, and All Base Layer Combinations in (a) Each Material Layer and Total Predicted Pavement Rutting, and (b) Surface and Intermediate Asphalt Layers and Total Predicted Asphalt Rutting (I-Bars Indicate Standard Error of Prediction)