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ORIGINAL RESEARCH PAPER

Evaluation of the Sensitivity of the MEPDG to Bottom-Up Fatigue Cracking in South Carolina

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Abstract
The objective of the study was to evaluate the sensitivity of different input variables on the flexible pavement design thickness of high-speed, high-traffic routes in South Carolina using the Mechanistic-Empirical Pavement Design Guide (MEPDG) by means of the AASHTOware Pavement ME design software. A combination of MEPDG input levels (Levels 1, 2, and 3) were used for pavement analysis based on the availability of data. The variables considered in this investigation included two-way average annual daily truck traffic (AADTT), asphalt mix type, climate station, subgrade type and resilient modulus, and aggregate base thickness. This study mainly focused on the bottom-up fatigue cracking, and individual pavement designs were evaluated to determine the asphalt concrete (AC) thickness for which the total bottom-up cracking was equal to 2% lane area after a 20-year design period. The results indicated that the asphalt mix type did not have significant impact on the pavement thickness. One of the five climate stations evaluated resulted in significantly thicker pavements than the others. Subgrade type, as well as resilient modulus, had a significant effect on the pavement thickness. Finally, pavements were more sensitive to total truck traffic changes at lower AADTT values and then became somewhat less sensitive when exposed to the highest levels of traffic. The results of this study could potentially be used to develop a preliminary asphalt thickness design catalog for interstate routes in South Carolina.

Keywords Mechanistic-Empirical Pavement Design Guide (MEPDG) · Sensitivity analysis · Pavement design · Flexible pavement

1 Introduction

In 2008, the Mechanistic-Empirical Pavement Design Guide (MEPDG) was officially introduced by the American Association of State Highway and Transportation Officials (AASHTO). The MEPDG uses engineering mechanics concepts to calculate pavement responses such as stresses, strains, and deflections resulting from traffic loading. It also uses the empirical distress transfer functions that are nationally calibrated using design inputs and data available from the Long-Term Pavement Performance (LTPP) database [1]. The main advantages of mechanistic–empirical (ME) design over empirical design are that it can be used for new pavement design and existing pavement rehabilitation [2, 3]; it allows changes in load type and material characterization; and it gives more reliable pavement performance prediction and accounts for the environmental and aging effects on materials [4].

Following the adoption of the MEPDG by AASHTO, many agencies including Arizona, Colorado, Georgia, Indiana, Missouri, Utah, and Virginia have transitioned to using the MEPDG method and other states such as Maine, Michigan, Mississippi, Nevada, and South Carolina are in the process of transitioning [5, 6]. Therefore, until the process is complete, the South Carolina Department of Transportation (SCDOT) will continue to use a version of the 1972

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edition of the AASHTO Guidelines for Pavement Design [6, 7]. While this method may have served the SCDOT well, these older procedures were not developed with consideration of the high traffic levels and new materials that we see today [6]. This could lead to over- or underestimating the pavement design needs, and the resulting economic impacts.

New technologies and site-specific conditions can be modeled in an ME framework to provide cost-effective pavement design solutions [8]. However, the MEPDG requires local calibration for implementation, since the global (i.e., national) calibration used data from a wide range of geographic areas with significant differences in materials, climate, and construction practices. Without local calibration, the procedure may not be accurate for local conditions, such as those specific to South Carolina [9].

During the MEPDG calibration process, it can be beneficial to conduct an extensive sensitivity analysis to understand the relative sensitivity of models used in MEPDG to the available data related to the local traffic, climate, and materials. Further, a sensitivity analysis study will help the designers to focus on the inputs having the most effect on desired pavement performance [10].

The MEPDG considers various distresses including longitudinal cracking, fatigue cracking, rutting, and thermal cracking. However, the scope of this study focused on bottom-up fatigue cracking, which, in South Carolina, is considered as a deep structural distress. These cracks generally initiate at the bottom of the asphalt layer and spread to the surface under repeated load application. The bottom-up fatigue cracking (also known as alligator cracking) is expressed as the percent lane area in MEPDG.

1.1 Problem Statement

The South Carolina Department of Transportation (SCDOT) is in the second phase of calibrating the MEPDG to South Carolina conditions. During this calibration process, the SCDOT is interested in developing a thickness design catalog for high priority flexible pavements using the MEPDG. Calibration is a lengthy process, so to move forward with the development of a preliminary design catalog, it was determined that a sensitivity analysis should be completed to better understand how different variables influence pavement design using the MEPDG in South Carolina.

1.2 Objectives and Scope

This study aimed to evaluate the sensitivity of specific variables on the design thickness of high-volume asphalt pavements (e.g., interstate routes) in South Carolina using the AASHTOWare Pavement ME version 5.2.2. The design variables considered in the analysis included average annual daily truck traffic (AADTT), aggregate base course thickness, asphalt mix type, subgrade soil type and resilient modulus, and climate station. This study focused on the pavement thickness for which the bottom-up fatigue cracking distress was limited to 2% lane area using the nationally calibrated coefficients with a 95% reliability as recommended by AASHTO for interstate routes. The results of this analysis are intended to eventually be used to develop an asphalt pavement design catalog for interstates and other high-volume routes in South Carolina.

1.3 Review of Related Studies

The MEPDG requires more than 100 inputs related to traffic, environmental conditions, materials, and climate to calculate pavement distress estimates over the specified design life. Several agencies and institutes throughout the USA have conducted sensitivity analysis studies related to the MEPDG. Some of the sensitivity analysis research and findings that are closely related to the current study are summarized herein.

A sensitivity analysis of flexible pavement by Solanki et al. evaluated the influence of input parameters, namely, climate, traffic characteristics, and modulus values of chemically stabilized subgrade soil on pavement performance using the MEPDG software for selected pavement sections [11]. The study revealed that alligator cracking showed to be more sensitive toward the climate, modulus of the chemically stabilized subgrade soil layer, and traffic level.

Ceylan et al. conducted a similar sensitivity study to determine which pavement design inputs significantly affected pavement distresses for flexible pavements in Iowa [12]. The study evaluated 20 critical inputs related to material properties, traffic, and climate for a design life of 20 years and a design reliability of 50%. The results revealed that alligator cracking was moderately sensitive to AADTT, very sensitive to base thickness, and not at all sensitive to climate (two stations considered).

Sauber et al. conducted a sensitivity analysis using three Specific Pavement Study (SPS) sections in New Jersey to identify the effects of using Level 3 traffic data compared to using Level 1 traffic data in the MEPDG [13]. The results revealed significant differences when Level 1 data were used compared to Level 3.

Freeman et al. conducted an extensive sensitivity analysis for different input variables for the Texas DOT (TxDOT) [14]. After determining the most sensitive variable, a statistical design was developed to understand the effect of varying more than one variable at a time. In addition to the sensitivity study, initial input material parameters and regional calibration values were established using the material information and performance data available in the TxDOT database.

Schwartz et al. completed a global sensitivity analysis using five types of flexible pavement under five climatic conditions and three levels of traffic [15]. The design inputs evaluated in the analyses included traffic volume, layer thicknesses, properties of materials, groundwater depth, and geometric parameters (e.g., lane width). This study used a normalized sensitivity index (NSI), which is “the percentage change in the predicted distress relative to the design limit caused by a percentage change in the design input”. The results from the study indicated that the sensitivity of design inputs for the bound surface layer was consistently significant for all pavement types and stresses.

Witczak and El-Basyouny conducted a sensitivity analysis to predict the influence of design inputs on fatigue cracking [16]. The results showed that the alligator cracking rate was small at low to medium stiffness levels of the asphalt mix compared to the higher stiffness mix. Also, a higher subgrade modulus resulted in less alligator cracking. Further, they noted that increasing the air void content in the asphalt mix may increase fatigue cracking.

Baus and Stires conducted a study to gather information about the new MEPDG to provide preliminary implementation recommendations to the SCDOT in 2010 [17]. This sensitivity analysis was carried out to become familiar with the software and input sensitivity using the then available version of the software. That study also provided guidelines for establishing priorities for new or alternate input data collection methodologies needed to implement the MEPDG in South Carolina.

These studies were based on specific inputs and scenarios considered for the particular studies. However, it is important to carry out an independent study using the available local data for the selected region as sensitivity of inputs varies from region to region. Additionally, most of these studies were done using the older version of the Pavement ME design software hence verification of the input sensitivity using the current design models in the software is an important step prior to the usage in local calibration process.

2 Research Methodology

The MEPDG sensitivity analysis was conducted using the Pavement ME software following the process illustrated in Fig. 1 with the input levels listed in Table 1 and variables listed in Table 2. A combination of Level 1 (site-specific), Level 2 (state-specific), and Level 3 (national/default) MEPDG inputs were used in this study. This was done because Level 1 inputs were not available for all input parameters during the time of this study. Default values were considered for inputs that are not mentioned in Table 1. It should also be noted that the transfer functions embedded in the software for predicting the magnitude of distress have several coefficients that have a significant influence on the level of calculated distress [18]. The MEPDG has not yet been calibrated for South Carolina, so this study was

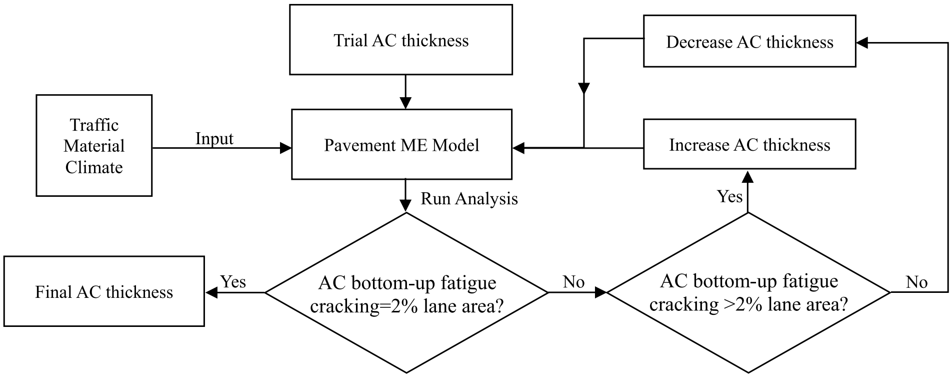


Fig. 1 Flowchart showing the research methodology used in this study

Table 1 MEPDG input level used in the study

Traffic input	AADTT, traffic load spectra		Level 2
Climate input	MERRA climate station		Level 1
Material input	AC layer properties	Air voids (%), effective binder content (%), percent asphalt content by weight of mix (%), asphalt binder, and binder type (superpave performance grade) dynamic modulus, unit weight, pcf (kN/m^3)	Level 1
	Aggregate base layer	Resilient modulus, psi (MPa)	Level 2
	Subgrade layer	Resilient modulus, psi (MPa), soil type	Level 2

Table 2 MEPDG sensitivity analysis variables

Variable	Values
AADTT (two-way)	6000–30,000 (increments of 4000)
Subgrade type	A-2-4 A-7-6
Subgrade resilient modulus (M_R)	6 ksi (41 MPa) 10 ksi (69 MPa) 14 ksi (97 MPa)
Aggregate base thickness ($M_R = 18$ ksi (124.1 MPa))	0 in (0 cm) 8 in (20 cm)
Asphalt mix type	Surface A, B, and C Intermediate B and C Base A
Climate station	Abbeville, SC Hamer, SC Greenville, SC Goose Creek, SC Lexington, SC

conducted using the default coefficients in the software (also referred to as global or national calibration factors).

2.1 Study Variables

2.1.1 Traffic

The average annual daily truck traffic (AADTT) and traffic load spectra are critical traffic input variables affecting the performance of asphalt pavements. Seven sets of two-way AADTT were used in this study ranging from 6000 to 30,000 in increments of 4000. The MEPDG does not use the Equivalent Single Axle Load (ESAL) method for traffic data input, such as the current method of SCDOT pavement design [7]. Instead, the MEPDG provides an alternative to use weigh-in-motion (WIM) data and other site-specific inputs to generate axle load spectra. Also, this study was conducted on asphalt pavement designs for rural interstate routes in South Carolina. Therefore, the vehicle load spectra used in this study (Table 3) was based on the rural interstate distribution from the PerRoad 4.4 design software [19]. This traffic load spectra was chosen because it is similar to the road group "O" of the SCDOT design guide and WIM data for South Carolina was not available for this study. A 95% reliability was selected as recommended by AASHTO for interstate routes, because interstate route designs require more stringent design criteria when compared to secondary roads [20]. Other traffic-related factors considered in this analysis included:

- Design period: 20 years.
- Number of lanes: four total, two in each direction.
- Directional distribution: 50% of two-way traffic in each direction.
- Lane distribution: 100% of traffic in design lane.
- Traffic growth rate: 2% annually.
- Design speed: 60 mph.

2.1.2 Pavement Structure and Material Properties

Two general pavement structures reflecting typical pavement design practice in South Carolina were evaluated in this study as shown in Fig. 2 and described as:

Type 1: asphalt with aggregate base having a thickness of 8 inches (20 cm).
Type 2: full-depth asphalt (no aggregate base).

This study evaluated the influence of six different asphalt mix types commonly used for higher volume pavements in South Carolina, as summarized in Table 4. The Level 1 material properties used in the MEPDG analysis were determined from the evaluation of the different mix types in the laboratory and are summarized in Table 4. The dynamic modulus (|E^*|) is an important parameter for design of flexible pavement using the MEPDG performance model, and it also has a direct influence on fatigue cracking [21].

Table 3 Traffic load spectra

Vehicle class	AADTT %	Single axle	Tandem axle	Tridem axle	Quad axle
Class 4	1.2	1.62	0.39	0.00	0
Class 5	9.4	2.00	0.00	0.00	0
Class 6	3.3	1.02	0.99	0.00	0
Class 7	0.5	1.00	0.26	0.83	0
Class 8	7.4	2.38	0.67	0.00	0
Class 9	68.9	1.13	1.93	0.00	0
Class 10	1.2	1.19	1.09	0.89	0
Class 11	6.1	4.29	0.26	0.06	0
Class 12	0.8	3.52	1.14	0.06	0
Class 13	1.2	2.15	2.13	0.35	0

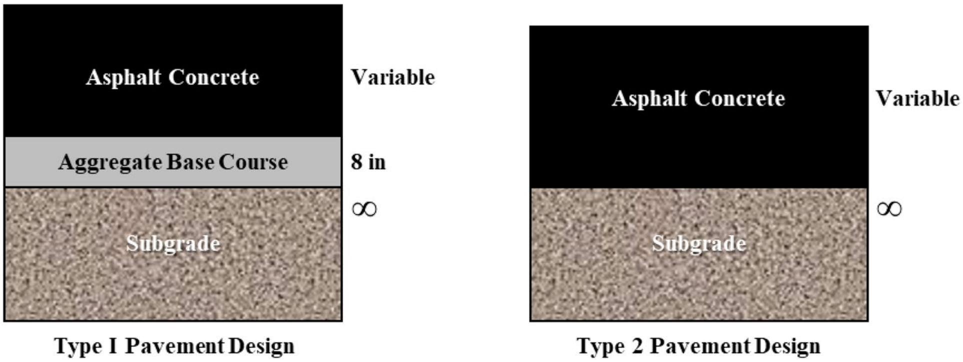


Fig. 2 Two typical pavement sections included in this study. (1 inch=2.54cm)

The dynamic modulus master curves of the asphalt mixes included in this study are given in Fig. 3.

For the Type 1 pavement structure, an 8 in (20 cm) thick layer of crushed graded aggregate base (GAB) was used as representative of the material typically used in South Carolina. A resilient modulus (M_R) of 18 ksi (124 MPa) was selected based on the measured resilient modulus values in South Carolina [22] and not based on default MEPDG values. The other default values for an A-1-a crushed stone base material are given in Table 5. This study was limited to a representative GAB base material for flexible pavements in South Carolina. However, a future study could include different types of base materials such as cement or other stabilized bases and recycled PCC.

2.1.3 Subgrade Soil Type

The South Carolina DOT classifies subgrade soil into two groups across the state designated as Group A and Group B, which are separated by a geographical fall line that runs through the middle of the state, as shown in Fig. 4 [23].

Group A is located northwest of the fall line in the Blue Ridge and Piedmont regions. Group A soils are micaceous clayey silts and micaceous sandy silt, clays, and silty soils. This group is classified as either ML or MH and typically have a liquid limit (LL) greater than 30 as per the USCS classifications. These soils are typically A-5 to A-7 soils per the AASHTO classification.

Group B is located south and east of the fall line in the coastal plains region. Group B soils are unconsolidated sand, clay, gravel, marl, cemented sand, limestone that vary based

Table 4 Characteristics of asphalt mixes included in this study

	Mix type					
	Surface A	Surface B	Surface C	Intermediate B	Intermediate C	Base A
Route type/traffic volume	Interstate	AADT ≥ 5000	AADT < 5000	AADT ≥ 5000	AADT < 5000	AADT ≥ 5000
Sieve Size % passing						
1 in (25.4 mm)	100	100	100	100	100	100
$^3/_4$ in (19.1 mm)	100	100	100	99	99	97
$^1/_2$ in (12.7 mm)	97	99	99	91	91	78
$^3/_8$ in (9.5 mm)	84	93	92	81	82	62
No. 4	53	69	65	57	57	44
No. 8	31	50	49	47	40	34
No. 30	17	25	24	21	20	18
No. 100	8.0	9.4	8.3	8.1	7.4	7.3
No. 200	4.0	5.3	4.7	4.8	4.24	4.3
Binder grade	PG 76-22	PG 64-22	PG 64-22	PG 64-22	PG 64-22	PG 64-22
Binder content (% weight)	5.3	5.2	5.0	4.7	4.5	4.5
Binder content (% volume)	10.9	12.1	12.3	11.1	11.3	9.7
Aged binder (%)	11.3	12.8	15.7	15.7	18.0	20.9
G_{mm}	2.44	2.43	2.43	2.42	2.46	2.48
Air voids (%)	7.3	7.1	7.0	7.1	6.6	7.1

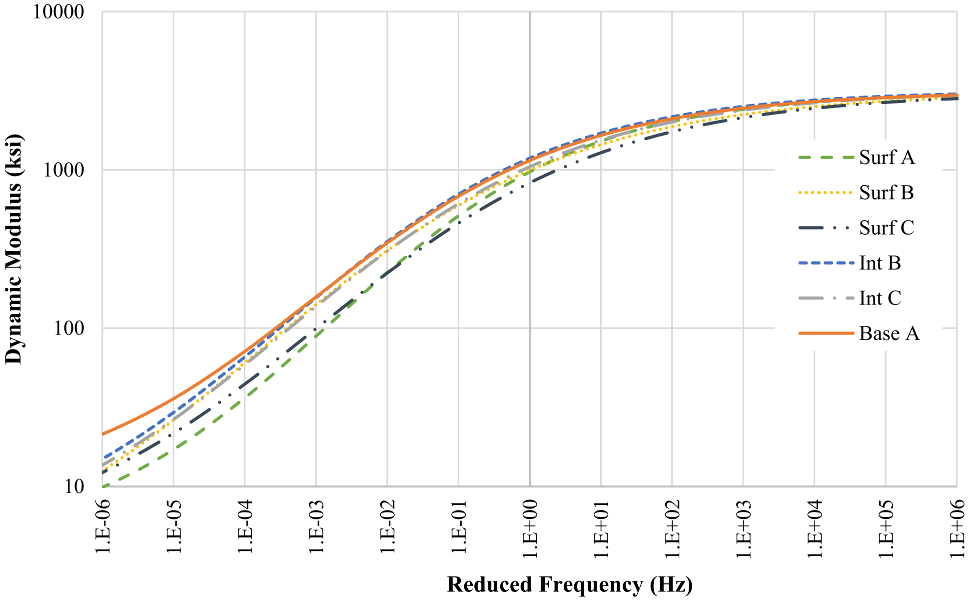


Fig. 3 Dynamic modulus master curves for asphalt mixes included in this study. (1 ksi=6.89 MPa)

Table 5 Characteristics of soil and base material (crushed stone) included in this study

	A-2-4	A-7-6	Crushed stone
Sieve size	Percent passing		
$3^1/_2$ in (88.9 mm)	99.6	99.9	97.6
2 in (50.8 mm)	99.0	99.6	91.6
$1^1/_2$ in (38.1 mm)	98.5	99.3	85.8
1 in (25.4 mm)	97.2	98.8	78.8
$^3/_4$ in (19.1 mm)	95.9	98.3	72.7
$^1/_2$ in (12.7 mm)	93.5	97.5	63.1
$^3/_8$ in (9.5 mm)	91.6	96.9	57.2
No. 4	87.2	94.9	44.7
No. 10	82.5	93.0	33.8
No. 40	67.2	88.8	20.0
No. 80	42.3	84.9	12.9
No. 200	22.4	79.1	8.7
Liquid limit	14	51	6
Plasticity index	2	30	1

on location. Based on the AASHTO classification, Group B soils are A-1 to A-4 [24].

Two types of soils were used in this study to represent the two soil groups described: A-7-6 soil (Group A) and A-2-4 soil (Group B). For each soil type, three values of resilient modulus were included in the analysis (6 ksi (41 MPa), 10 ksi (69 MPa), and 14 ksi (96 MPa)) to span the range of subgrade strength values typically encountered in the state. This range of resilient modulus was different from default MEPDG values, but was based on test results of soils in South Carolina [6]. The other default values from Pavement ME for each specific soil type used in the analysis are shown in Table 5.

2.1.4 Climate Stations

Pavement ME includes 25 Modern Era Retrospective-Analysis and Research Applications (MERRA) climate stations in South Carolina, as shown in Fig. 5 along with climate station IDs. A preliminary study was conducted to compare the results of all 25 climate stations to determine which climate stations to include in this sensitivity analysis study. Of the 25 stations, 5 representative climate stations were selected based on the results of the preliminary evaluation that revealed many climate stations within South Carolina showed similar results. The geographic and climate data summary of the five representative stations selected for this study are summarized in Table 6.

2.2 Analysis Method

In this study, sensitivity analyses were conducted to determine a design asphalt thickness for each combination of variables included in Table 1 based on the bottom-up fatigue cracking results. Pavement ME was used to estimate the distress values for a given asphalt thickness, as illustrated in the example in Fig. 6. The design asphalt thickness was determined as the thickness at which the bottom-up fatigue cracking first reaches 2% lane area. While the threshold value recommended for use in judging the acceptability of the trial design for bottom-up fatigue cracking is 10% of the lane area for interstate routes [1], the thickness corresponding to 2% lane area was considered for this analysis based

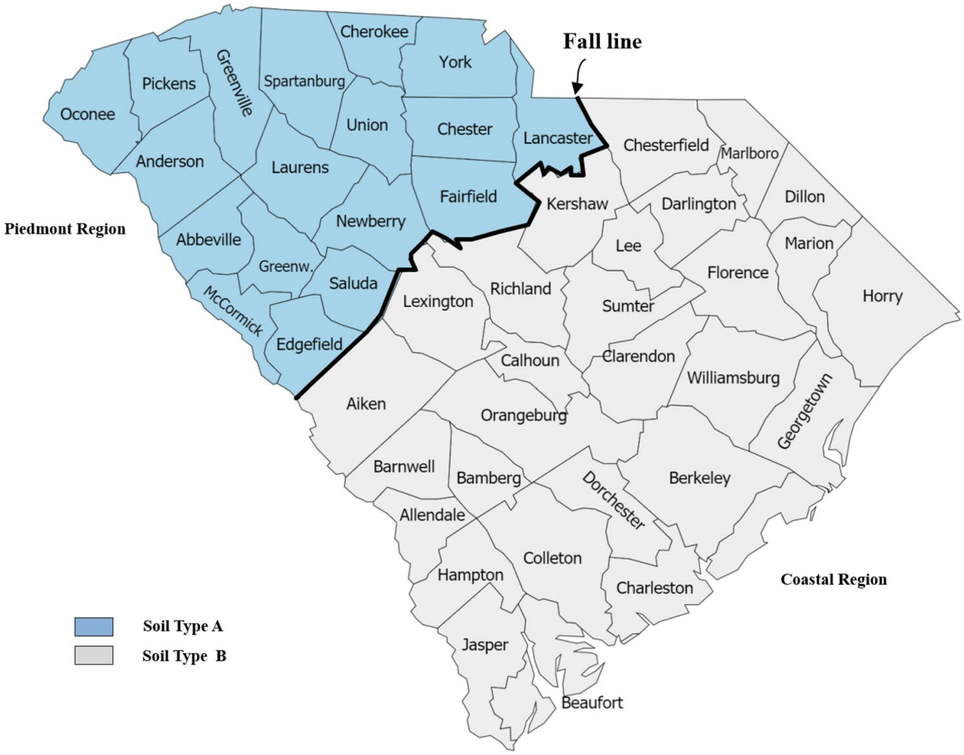


Fig. 4 Soil classifications in South Carolina

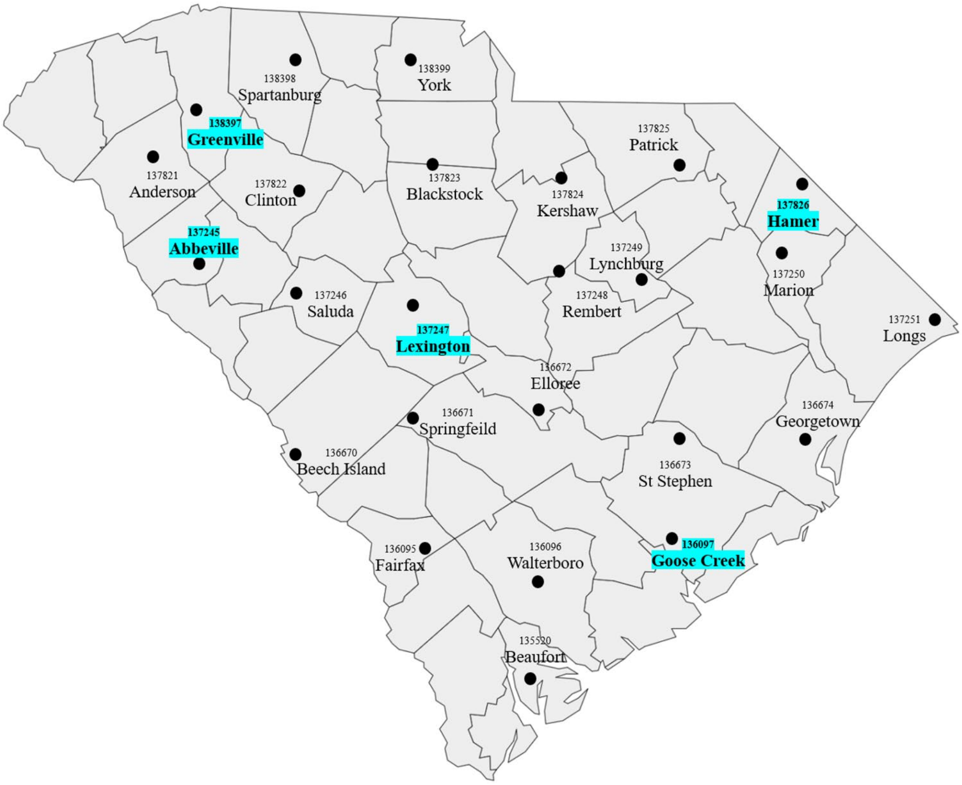


Fig. 5 Climate stations in Pavement ME software for South Carolina; all available climate stations and climate stations selected for this study (highlighted)

Table 6 Details of the five representative South Carolina climate stations included in this study

	Abbeville	Hamer	Lexington	Goose Creek	Greenville
Climate Station ID	137,245	137,826	137,247	136,097	138,397
Longitude (decimals degree)	−82.37	−79.32	−81.03	−80.03	−82.39
Latitude (decimal degree)	34.17	34.47	34.00	32.99	34.85
Elevation, ft (m)	595.31 (181.45)	140.36 (42.78)	297.36 (90.64)	49.13 (14.97)	979.85 (298.66)
Mean annual air temperature, °F (°C)	62.4 (16.9)	62.4 (16.9)	62.8 (17.1)	65.9 (18.8)	57.8 (14.3)
Mean annual precipitation, in (cm)	47.6 (120.9)	49.4 (125.5)	46.6 (118.4)	51.6 (131.1)	57.3 (145.5)
Freezing Index, °F-days (°C-days)	19.6 (−6.9)	31.8 (–0.1)	21.8 (−5.7)	4.6 (−15.2)	70.5 (21.4)
Average annual number of freeze/thaw cycles	42.1	43.2	39.9	15.2	63.3
Number of wet days	288.8	289.4	280.2	303.7	289.0

Depth of the water table is assumed at 10 ft (30.5m) for all stations

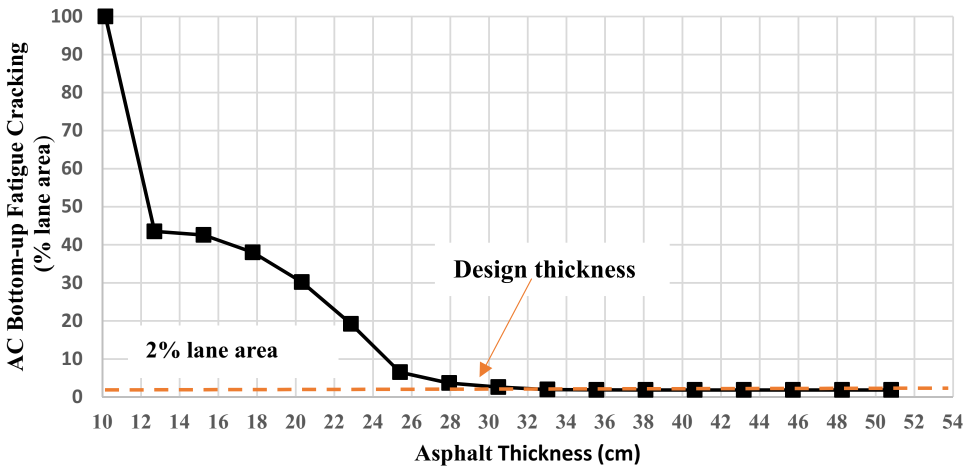


Fig. 6 Sensitivity analysis example (1 inch =2.54 cm)

on SCDOT experience and practice. Also, in the Phase 1 calibration sensitivity analysis, using the global coefficient underestimated the value of bottom-up fatigue cracking with 50% reliability [6], and hence a conservative threshold value of 2% lane area for 95% reliability was chosen. Additionally, this approximately corresponds to the thickness at which the pavement is no longer sensitive to distress when using the global calibration factors. For example, increasing an extra inch of asphalt thickness from 11.5 to 12.5 in (29 to 32 cm) does not significantly change the value of fatigue cracking in the example shown in Fig. 6.

3 Results and Discussion

The effect of each variable selected in the study is discussed separately below: asphalt mix type, a climate station, soil type and resilient modulus, and AADTT.

3.1 Effect of Asphalt Mix Type

The influence of the asphalt mix type was evaluated by conducting the sensitivity analysis using the six asphalt mix types having the properties summarized in Table 4 and Fig. 3. A preliminary analysis comparing all six mix types was only conducted for the Lexington, SC climate station. Figure 7 shows a comparison of the aggregated average required asphalt thickness for each mix type. The statistical analysis of variance test (ANOVA) at a significance

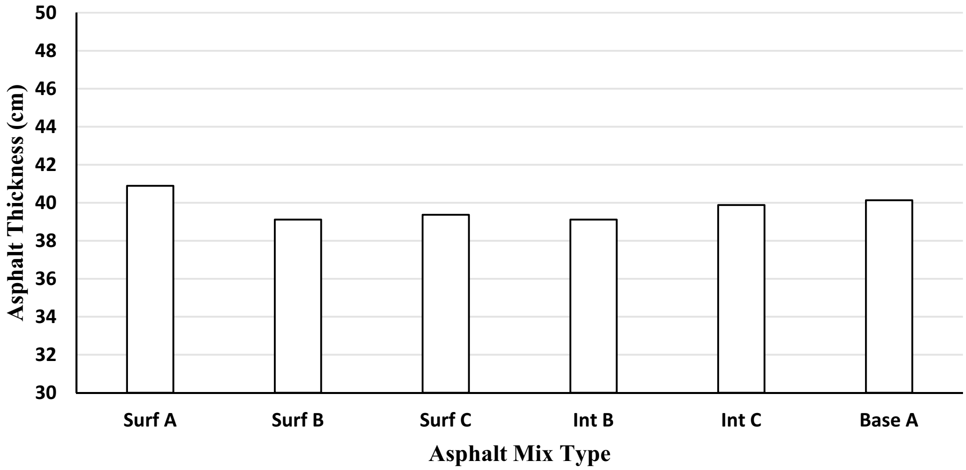


Fig. 7 Comparison of average asphalt thickness by mix type for the Lexington, SC climate station. (1 inch = 2.54 cm)

level of 95% (alpha = 0.5) indicates that there is no significant difference on the mean thickness of the asphalt layer for different mix used in the study (*F* ratio = 1.6, *p* value = 0.17). This reflects the findings from previous work by Nagarajan using the same mix types [25]. Based on these findings, a single mix type (Surface A) was used for subsequent analyses conducted in this study, which would result in slightly conservative designs to compensate for the use of global calibration factors.

3.2 Effect of Climate Station

The effect of climate station was evaluated using five climate stations selected from different geographical regions across the state of South Carolina: upstate (Abbeville and Greenville), midlands (Lexington), and coastal/Pee Dee (Hamer and Goose Creek) (Fig. 5 and Table 5). The results in Fig. 8 show that the Abbeville climate station resulted in a thicker asphalt layer compared to the other climate stations. The statistical analysis of variance test (ANOVA) at a significance level of 95% indicates that there is significant difference on the mean thickness of asphalt layer for different climate stations used in the study (*F* ratio = 34.19, *p* value < 0.0001). Comparison of each pair of climate station was done using the Student's *t* test at a 95% level of significance. The results of the statistical analysis are represented in the figure with the use of letters at the bottom of the bar. Treatments sharing common letters are not statistically different from each other. Abbeville station showed a thickness of about 2–3 in (5–8 cm) extra compared to other stations.

3.3 Effect of Soil Type and Resilient Modulus

As noted previously, two subgrade types, representative of South Carolina soils (A-2-4 and A-7-6), were compared to evaluate the influence of subgrade type on the required asphalt thickness as determined using the MEPDG. For each subgrade type, three resilient modulus (M_R) values were evaluated to represent the strength of pavement subgrades in the state (6 ksi (41 MPa), 10 ksi (69 MPa), and

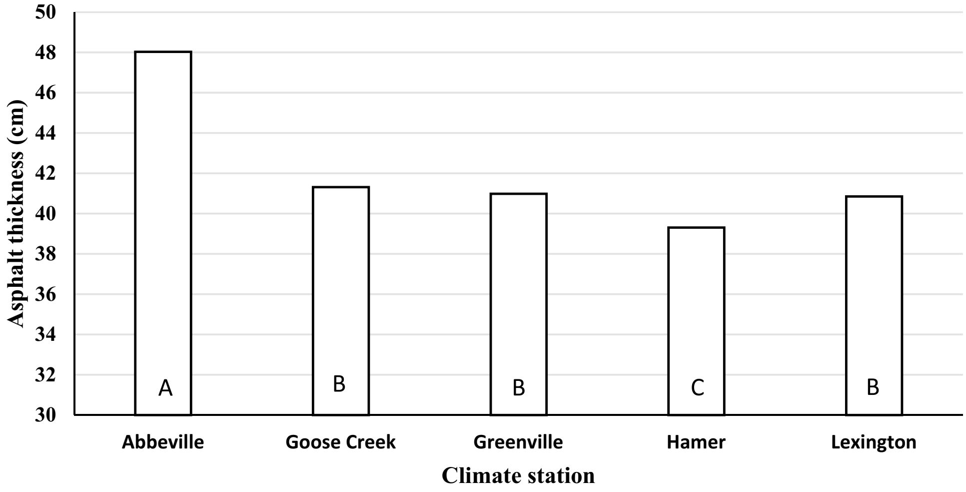


Fig. 8 Comparison of average asphalt thickness by climate station

14 ksi (96 MPa)). The results in Figs. 9, 10, 11, 12, 13 and 14 show that there is a clear effect of subgrade type for the two soils included in this study as the A-2-4 soil type required less asphalt thickness than the A-7-6 soil by 1–2 in (2.5–5 cm) when both soils have the same resilient modulus. The results also show that the two soils can result in a similar asphalt thickness if the resilient modulus of the A-7-6 soil is about 4 ksi (28 Mpa) greater than the

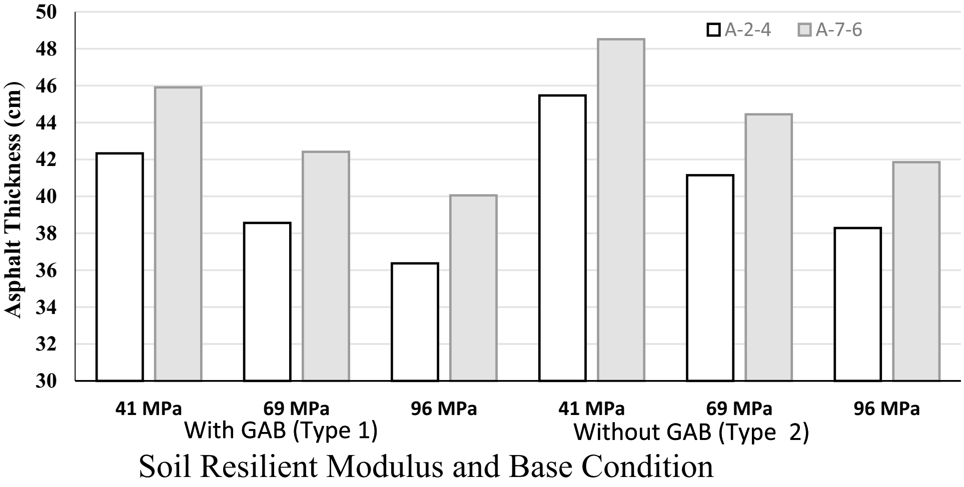


Fig. 9 Comparison of average asphalt thickness by soil type, Resilient Modulus, and Base Condition. (1 inch=2.54 cm, 1 ksi=6.86 MPa)

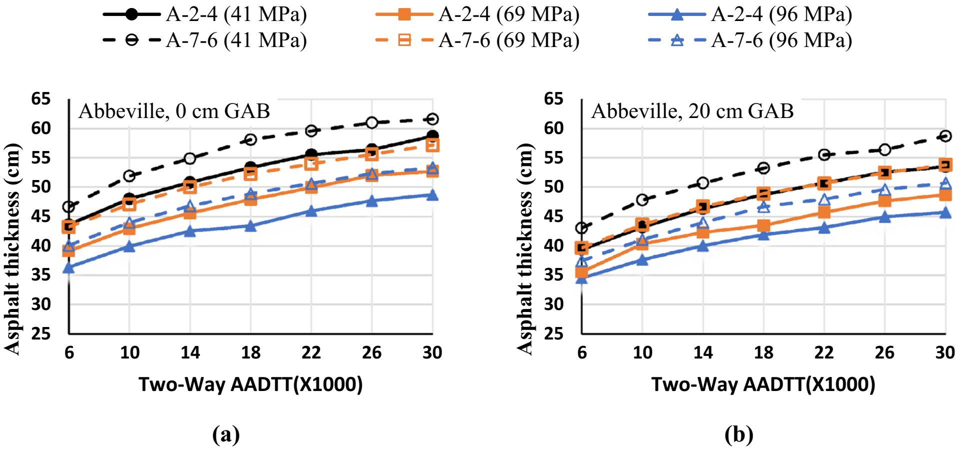


Fig. 10 Comparison of the relationship between AADTT (two-way) and asphalt thickness based on subgrade type (and resilient modulus) for the Abbeville climate station (**a**) with no graded aggregate base (GAB) and (**b**) with 8 in (20 cm) of GAB. (1 inch=2.54 cm)

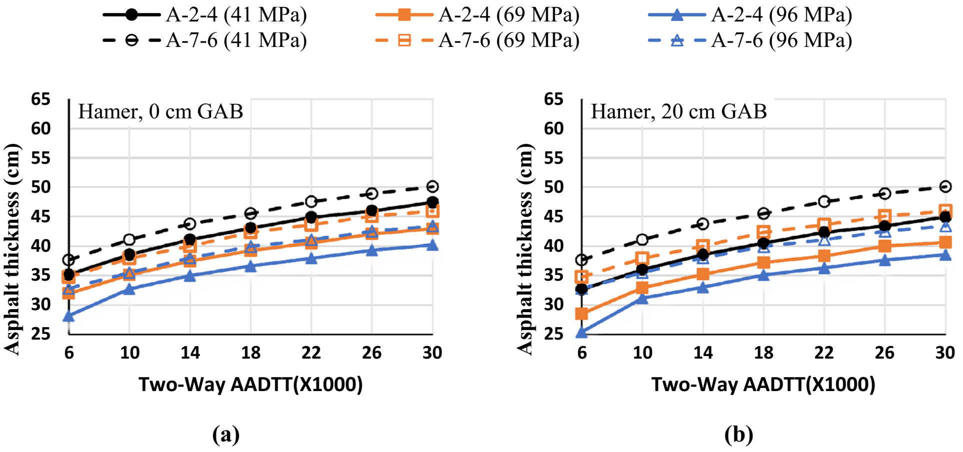
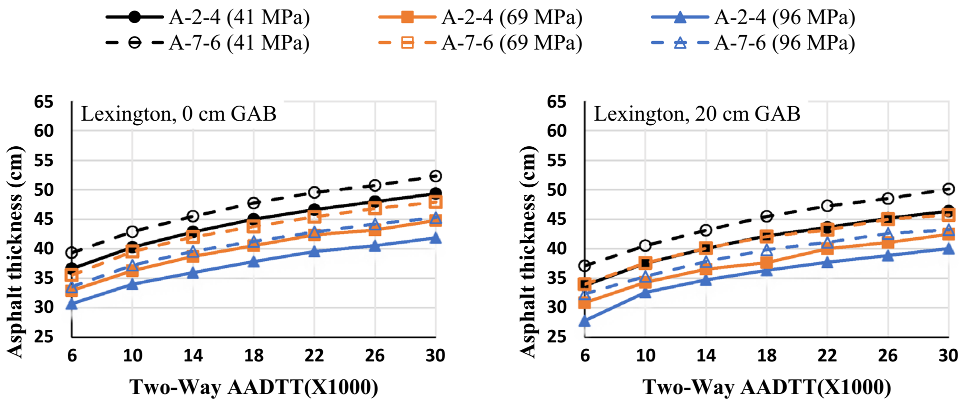


Fig. 11 Comparison of the relationship between AADTT (two-way) and asphalt thickness based on subgrade type (and resilient modulus) for the Hamer climate station (**a**) with no graded aggregate base (GAB) and (**b**) with 8 in (20 cm) of GAB. (1 inch=2.54 cm)

A-2-4 soil. The aggregated differences between soil types were slightly greater when the pavement section included an 8 in (20 cm) layer of a graded aggregate base (GAB).

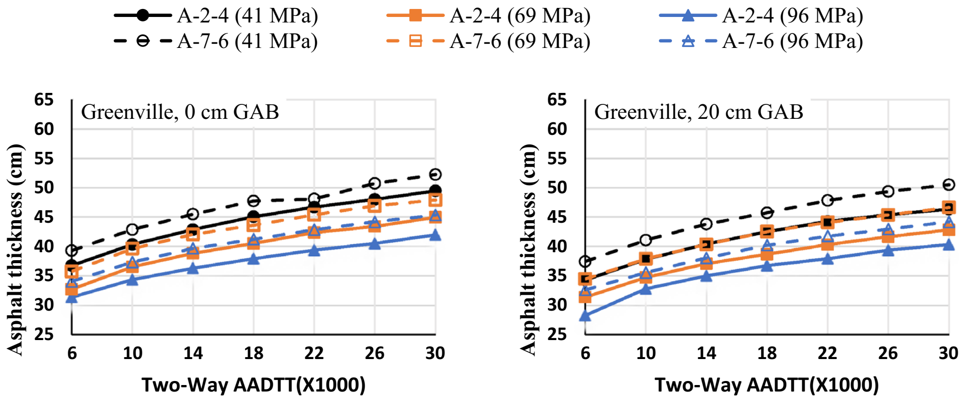
3.4 Effect of AADTT

The results in Figs. 10, 11, 12, 13 and 14 also show the influence of traffic on the required asphalt thickness. As would be expected, the higher volumes of traffic required a thicker pavement section or stronger subgrade to meet the given performance criteria. The pavement design (asphalt thickness),



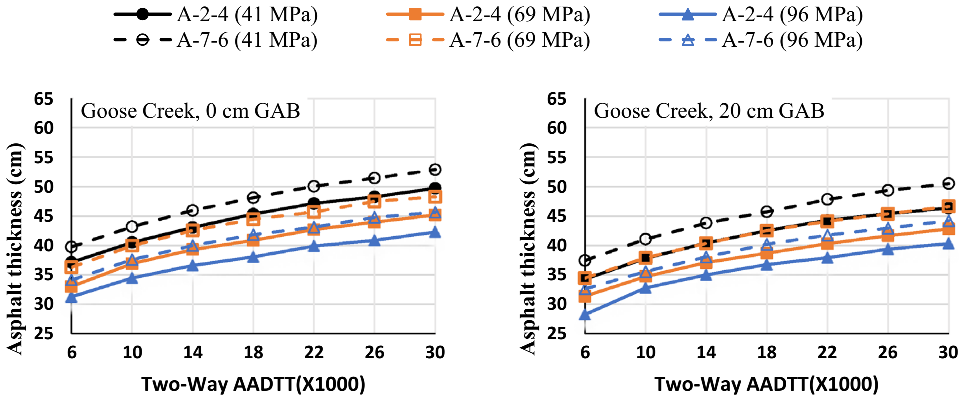
(a) (b)

Fig. 12 Comparison of the relationship between AADTT (two-way) and asphalt thickness based on subgrade type (and resilient modulus) for the Lexington climate station (**a**) with no graded aggregate base (GAB) and (**b**) with 8 in (20 cm) of GAB. (1 inch=2.54 cm)



(a) (b)

Fig. 13 Comparison of the relationship between AADTT (two-way) and asphalt thickness based on subgrade type (and resilient modulus) for the Greenville climate station (**a**) with no graded aggregate base (GAB) and (**b**) with 8 in (20 cm) of GAB. (1 inch=2.54 cm)



(a) (b)

Fig. 14 Comparison of the relationship between AADTT (two-way) and asphalt thickness based on subgrade type (and resilient modulus) for the Goose Creek climate station (**a**) with no graded aggregate base (GAB) and (**b**) with 8 in (20 cm) of GAB. (1 inch=2.54 cm)

Table 7 Distress value for MEPDG sensitivity analysis

Performance criteria	Distress value range		Threshold value
	Type 1	Type 2	
Terminal IRI, in/mile (m/km)	145–149 (2.29–2.35)	148–153 (2.34–2.41)	172 (2.71)
Permanent deformation- total pavement (in)	0.35–0.43 (0.89–1.09)	0.33–0.51 (0.84–1.30)	0.75 (1.91)
AC thermal cracking, ft/mile (m/km)	565–567 (107.01–107.39)	565–566 (107.01–107.20)	1000 (189.39)
AC top-down fatigue cracking, ft/mile (m/km)	332–443 (62.88–83.90)	329–412 (62.31–78.03)	2000 (378.79)
Permanent deformation- AC only, in (cm)	0.11–0.16 (0.27–0.41)	0.10–0.17 (0.25–0.43)	0.25 (0.64)

and thereby pavement performance, was more sensitive to changes in traffic at lower traffic volumes and became less sensitive at the higher traffic volumes.

The terminal international roughness coefficient (IRI), permanent deformation (total and AC only), AC thermal cracking, and AC top-down cracking distress values corresponding to AC bottom-up fatigue cracking of 2% lane area are given in the Table 7 along with the threshold criteria used in the study. All the distresses were checked at a reliability of 95%. As the results show, the distress range values are well within the threshold values for the input range and parameters used in the study.

4 Conclusions

This study investigated the sensitivity of multiple variables on the design asphalt thickness based on the MEPDG (Pavement ME) with global calibration factors and South Carolina specific traffic, materials, and climate input data. The results of the sensitivity analysis can be used to develop a preliminary asphalt pavement design catalog for interstate routes in South Carolina. Based on the results of this study, the following conclusions were drawn.

- The asphalt mix type did not have a significant influence on the asphalt pavement thickness as determined through the sensitivity analysis. This also indicates that when using the MEPDG to design pavements in the future, it will likely be sufficient to have single input data for a limited number of representative asphalt mix types. For example, it may be sufficient to have a single generic input for surface mixes, intermediate mixes and base mixes.
- The climate station had a significant influence on the pavement thickness as the Abbeville climate station that represented the surrounding region generally resulted in asphalt thicknesses that were approximately 2 in. thicker than other stations representing the majority of the state. The preliminary evaluation to select the five stations used in this study also pointed to this finding.
- The type of subgrade had a significant influence on the pavement design by about 1–2 in (2–5 cm). The A-7-6 soil resulted in pavement thickness approximately 1–2 in (2.5–5 cm) greater than pavements designed on top of the A-2-4 soil having the same resilient modulus. This is also in alignment with the current SCDOT pavement design guidelines that uses two types of soils as shown in Fig. 4: Piedmont region soil (representative of the A-7-6 subgrade) and coastal plains region soil (representative of the A-2-4 soil) [7].
- In addition to the soil type, the subgrade resilient modulus also had an effect on the pavement design. The stronger the soil (higher the resilient modulus), the thinner was the required pavement section. The results show that the differences in soil type may be overcome by increasing the resilient modulus of the A-7-6 soil by about 4 ksi (28 MPa), which will result in a pavement thickness that is approximately equal to a A-2-4 soil with a resilient modulus value that is about 4 ksi (28 MPa) lower. This factor is important to consider when designing a pavement as strengthening the subgrade could potentially be more cost-effective than adding more asphalt thickness.
- The addition of an 8 in (20 cm) thick layer of a graded aggregate base (GAB) resulted in an approximately 1–2 in (2.5–5 cm) thinner asphalt layer when all other factors remained the same. This is somewhat in alignment with the SCDOT's current empirical design method, where the asphalt mix furthest from the surface (i.e., asphalt base course) is assigned a structural layer coefficient that is 1.9 times that of the GAB.
- The traffic volume followed the expected trend of increasing pavement thickness with AADTT. The sensitivity of the pavement to traffic, however, decreased as the two-way AADTT increased from 6000 to 30,000.
- The terminal IRI, permanent deformation (total and AC only), AC thermal cracking, AC top-down cracking values corresponding to AC bottom-up fatigue cracking of

2% lane area are well within the threshold values for the input range and parameters used in the study.

This study provides a comprehensive evaluation on the sensitivity of design inputs on AC layer thickness. In addition to understanding how selected inputs affect design thickness, the results or findings of this study can be utilized to improve pavement designs and to prioritize data acquisition of level 1 design inputs. The authors acknowledge that there are some limitations to this study. The pavement layer thicknesses obtained in this paper are based on the nationally calibrated models and inputs related to South Carolina conditions. Therefore, the sensitivity analysis results may be different for different regions hence this study should be done for individual regions with site-specific inputs.

5 Future Study and Recommendation

The study can be updated with locally calibrated model and more site-specific inputs, then a catalog can be developed using the similar methodology which can save cost and time of the designer for preliminary design and proof checking of design.

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Data availability The article contains most of the relevant data for the analysis and results.

Declarations

Competing Interest The authors declare that they have no financial or proprietary interest that could have appeared to influence the work reported in this research paper.

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