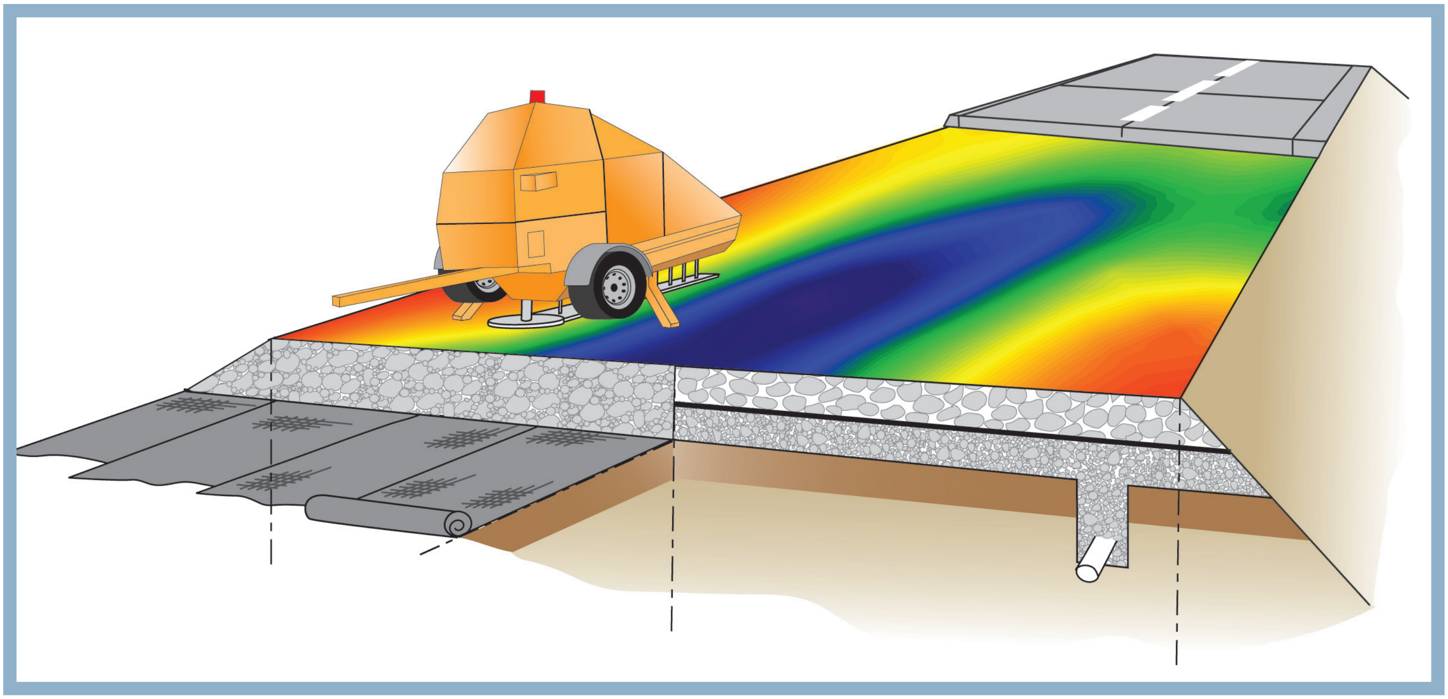
Improving the Foundation Layers for Concrete Pavements

TECHNICAL REPORT:

Mechanistic-Empirical Pavement Design Guide (MEPDG) Sensitivity Analysis



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16. Abstract

The purpose of this Mechanistic-Empirical Pavement Design Guide (MEPDG) analysis was to determine the sensitivity of soil type and stiffness on required slab thickness. This study confirmed previous published work that the MEPDG is not sensitive to subgrade soil type or resilient moduli changes.

The slab thickness varied less than 0.25 in. for a range of soil types and resilient modulus values. Therefore, it does not appear that nonuniformity of support could be directly accounted for in the current MEPDG design method (e.g., implementing a Monte Carlo simulation scheme to assess soil variability).

The most sensitive variables encountered were the traffic level and joint spacing, with a maximum change of 3.75 and 3.0 in., respectively. The effect of climate was also not as critical, requiring only a 0.5 in. change in slab thickness between Des Moines, Iowa and Atlanta, Georgia.

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IMPROVING THE FOUNDATION LAYERS FOR CONCRETE PAVEMENTS: MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE (MEPDG) SENSITIVITY ANALYSIS

Technical Report
April 2014

Research Team Members
Tom Cackler, David J. White, Jeffery R. Roesler, Barry Christopher, Andrew Dawson,
Heath Gieselman, and Pavana Vennapusa

Report Authors
A. S. Brand and Jeffery R. Roesler
University of Illinois

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National Concrete Pavement Technology Center and
Center for Earthworks Engineering Research (CEER)
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103
www.cptechcenter.org and www.ceer.iastate.edu

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CHAPTER 1. INTRODUCTION

Intelligent compaction and compaction monitoring technology have exposed the nonuniform support stiffness that exists beneath concrete and flexible pavements (White et al. 2007, Mooney and Rinehart 2007, Hossain et al. 2006). Subgrade nonuniformity is an important consideration because it can cause stress concentrations that may lead to pavement distresses and premature failure (White et al. 2005).

One current challenge for intelligent compaction is using collected data to assess the positive or negative changes in concrete pavement performance, which can assist in setting rational specification targets for use of the various types of equipment.

The objective of this project was to primarily determine the effects of changes in certain soil type and properties on the required slab thickness using the Mechanistic-Empirical Pavement Design Guide (MEPDG). Version 1.100 of the MEPDG was used to determine the concrete pavement designs in this project (ARA, Inc. 2007).

This study focused on how soil type and resilient modulus in combination with changes in base type, traffic level, climate zone, and slab size affect the final design thickness of the slab.

This initial soil sensitivity analysis with the MEPDG is important to ascertain whether it can be used in conjunction with intelligent compaction data to address nonuniform support conditions under concrete pavements. Target specification limits can only be defined based on the effects that nonuniformity has on concrete pavement performance.

CHAPTER 2. LITERATURE REVIEW

Numerous sensitivity studies have been conducted on the MEPDG program, with several considering its sensitivity to soil and base property changes for jointed plain concrete pavements (JPCP). Table 1 lists a few inputs and their sensitivity on the MEPDG distress outputs.

Table 1. MEPDG literature review sensitivity results

Variable	**Sensitivity**
Base Type - Thickness	None to High*
Traffic (AADTT)	High
Climate	Low to Moderate
Subgrade Soil Type	None
Joint Spacing	Low to High
Subgrade Resilient Modulus	None

*Depends on slab-base interface condition

Both the subgrade soil type and resilient modulus have been reported to be insensitive (Velasquez et al. 2009, Khanum 2005, Kannekanti and Harvey 2005, Haider et al. 2009, Hoerner et al. 2007). Some studies have shown that the base type has a moderate sensitivity for the cracking and faulting models (Haider et al. 2009), while others have demonstrated that the effect is not significant (Velasquez et al. 2009, Khanum 2005, Kannekanti and Harvey 2005). This behavior is likely related to the choice of slab-base interface condition.

Base thickness has been noted to be a sensitive variable in terms of transverse cracking and faulting models (Velasquez et al. 2009). The unbound layer modulus was also found to be sensitive for both the faulting and smoothness models (Guclu and Ceylan 2005, Coree et al. 2005).

As expected, the initial two-way average annual daily truck traffic (AADTT) has been found to be highly significant (Velasquez et al. 2009, Guclu and Ceylan 2005, Hoerner et al. 2007, Oh et al. 2009, Bordelon et al. 2009) and most significant in the fatigue cracking model (Khanum 2005, Kannekanti and Harvey 2005). The climate zone has been shown to have a low to moderate significance (Guclu and Ceylan 2005, Coree et al. 2005, Haider et al. 2009, Hoerner et al. 2007, Johanneck and Khazanovich 2010).

Joint spacing is another input variable with low to moderate significance (Velasquez et al. 2009, Guclu and Ceylan 2005, Hall and Beam 2008, Oh et al. 2009), and others have found joint spacing to be highly significant in the cracking model (Coree et al. 2005, Haider et al. 2009).

These somewhat contradictory findings are consistent with the interaction between climate and slab geometry.

CHAPTER 3. MEPDG EXPERIMENTAL FACTORIAL

Previous studies suggest that the soil type and properties are not sensitive to the final design in the MEPDG. The purpose of this brief analysis is to verify these findings. The input variables explored for this sensitivity analysis are shown in Table 2.

Table 2. Input variables

Variable	Test Values
Base type	Granular (5 million ESAL), Stabilized (100 million ESAL)
Climate	Des Moines, Atlanta
Subgrade soil type	A-1-a (18 ksi), A-3 (15 ksi), A-7-6 (10 ksi)
Joint spacing	15, 12 ft
Subgrade resilient modulus*	A-7-6 (18, 11, 4 ksi)

*Not included in the full factorial

Three soil types were analyzed and, for one soil type, three resilient moduli were tested. Two traffic levels were run with the higher traffic level requiring a stabilized base, while the lower traffic value used a granular base. Two distinct climate zones and two joint spacings were chosen. All fixed input values and assumptions for MEPDG are in the Appendix. The MEPDG was run for each case for a 20-year design life to find the appropriate slab thickness to the nearest 0.25 in., such that transverse cracking did not exceed 20% at 95% reliability. The faulting and IRI values were only reported at the design slab thickness. A total of 28 cases were run with the MEPDG, with the descriptions of each shown in Table 3.

Table 3. Slab thickness, cracking, faulting, and IRI results for each MEPDG case

Case	PCC Thickness (in.)	95% Reliability Transverse Cracking (% slabs cracked) [Target: 20]	95% Reliability Mean Joint Faulting (in.) [Target: 0.120]	95% Reliability Terminal IRI (in./mi) [Target: 172]	Subgrade Soil Type	Joint Spacing	Climate	Base Type
1	8.25	19.7	0.041	140.1	A-1-a (18 ksi)	15 ft	Des Moines, Iowa	Granular (at 5 million ESALs)
2	7.75	18.5	0.023	123.9	A-3 (15 ksi)			
3	8.00	19.1	0.079	306.4	A-7-6 (10 ksi)			
4	7.00	18.0	0.023	133.4	A-1-a	12 ft		
5	6.75	15.8	0.023	123.1	A-3			
6	7.00	19.2	0.047	295.0	A-7-6			
7	8.50	20.0	0.098	172.7	A-1-a	15 ft	Atlanta, Georgia	
8	8.25	17.7	0.023	122.8	A-3			
9	8.25	18.3	0.072	302.4	A-7-6			
10	7.25	14.8	0.023	130.3	A-1-a	12 ft		
11	7.00	15.6	0.023	122.7	A-3			
12	7.25	14.6	0.049	292.8	A-7-6			
13	11.50	18.1	0.105	174.2	A-1-a	15 ft	Des Moines, Iowa	Stabilized (at 100 million ESALs)
14	11.50	18.0	0.107	167.5	A-3			
15	11.25	18.0	0.124	327.5	A-7-6			
16	9.00	15.5	0.132	205.6	A-1-a	12 ft		
17	9.00	15.0	0.108	180.0	A-3			
18	9.00	17.0	0.143	352.8	A-7-6			
19	12.00	18.5	0.107	175.8	A-1-a	15 ft	Atlanta, Georgia	
20	12.00	17.8	0.107	167.0	A-3			
21	11.75	18.9	0.133	332.4	A-7-6			
22	9.00	19.6	0.132	209.2	A-1-a	12 ft		
23	9.00	18.6	0.115	188.1	A-3			
24	9.25	14.7	0.137	347.3	A-7-6			
25	11.75	17.3	0.087	163.0	A-1-a	15 ft	Des Moines, Iowa	Granular (100 million)
26	8.00	19.9	0.112	323.8	A-7-6 (18 ksi)			Granular (5 million)
27	8.00	19.1	0.084	308.9	A-7-6 (11 ksi)			
28	8.25	16.8	0.041	287.4	A-7-6 (4 ksi)			

CHAPTER 4. MEPDG SENSITIVITY RESULTS

Results for the granular base (lower traffic level) are shown in Figure 1 (cases 1 through 12).

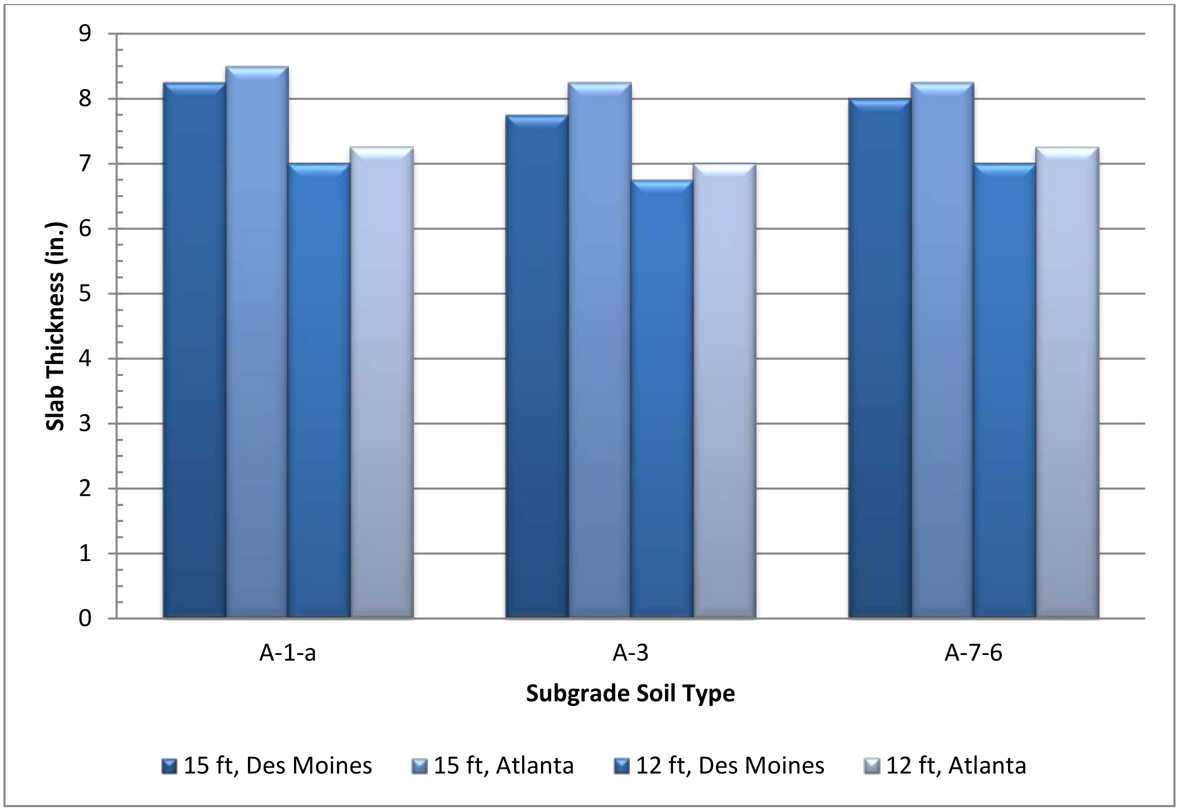


Figure 1. Effect of soil type and joint spacing on a granular base for Des Moines and Atlanta climates

For all subgrade soil and climate types, the design slab thickness decreased either 1 or 1.25 in. as the joint spacing was decreased from 15 to 12 ft. The Atlanta, Georgia climate requires a thicker slab in all cases. The soil type changes resulted in between a 0.25 and 0.50 in. thickness change when all other parameters were fixed. The A-3 soil resulted in the thinnest slab thickness, which likely represents the effect of a moderate soil stiffness, balancing the load and curling stresses.

Figure 2 demonstrates the effects of soil type on a stabilized base (cases 13 through 24).

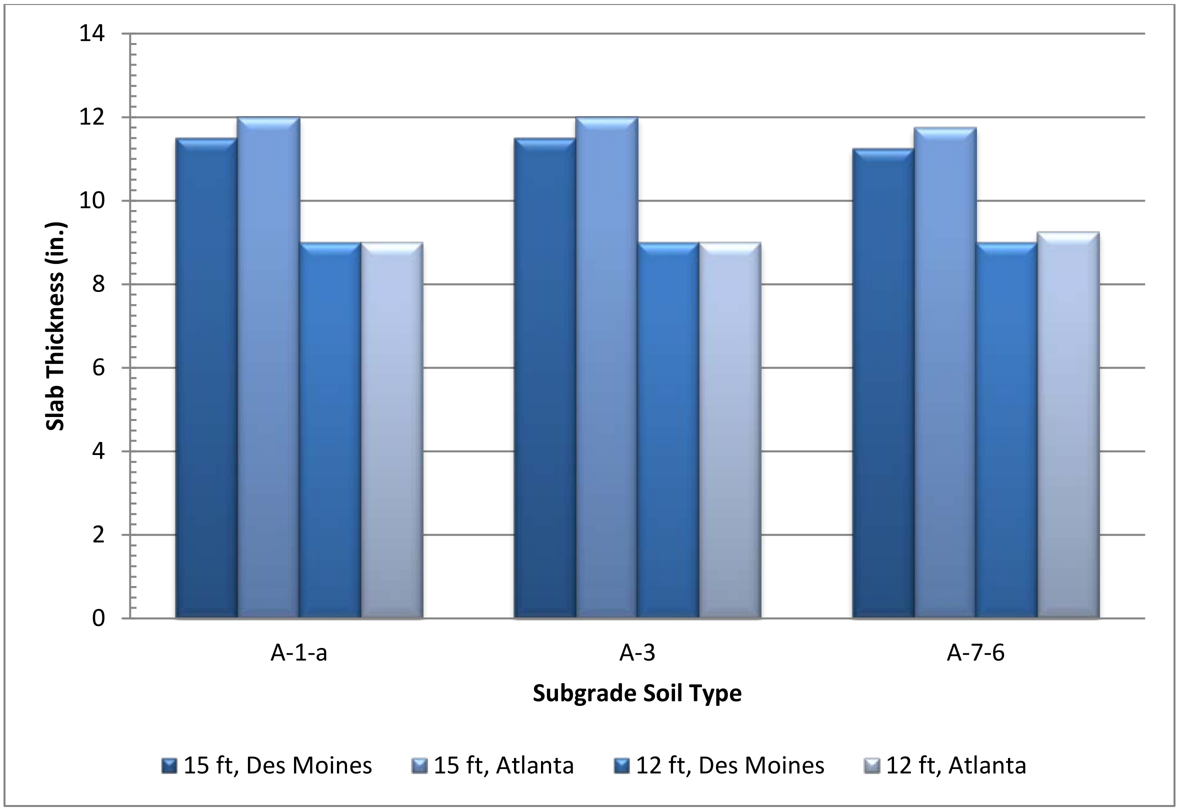


Figure 2. Effect of soil type and joint spacing on a stabilized base for Des Moines and Atlanta climates

For this higher traffic volume (100 million equivalent single axle loads/ESALs), the design slab thickness is much more sensitive: the slab thickness requirements increase 2.25 to 3.00 in. for a joint spacing increase from 15 to 12 ft. The slabs in Atlanta require between 0.00 and 0.50 in. greater thickness than in Des Moines, Iowa. Interestingly, the soil type was less sensitive for the higher traffic volume, varying a maximum of only 0.25 in. for the three soil types.

The effect of traffic level on the required slab thickness (cases 1 through 6 and 13 through 18), shown in Figure 3, is consistent with previous findings.

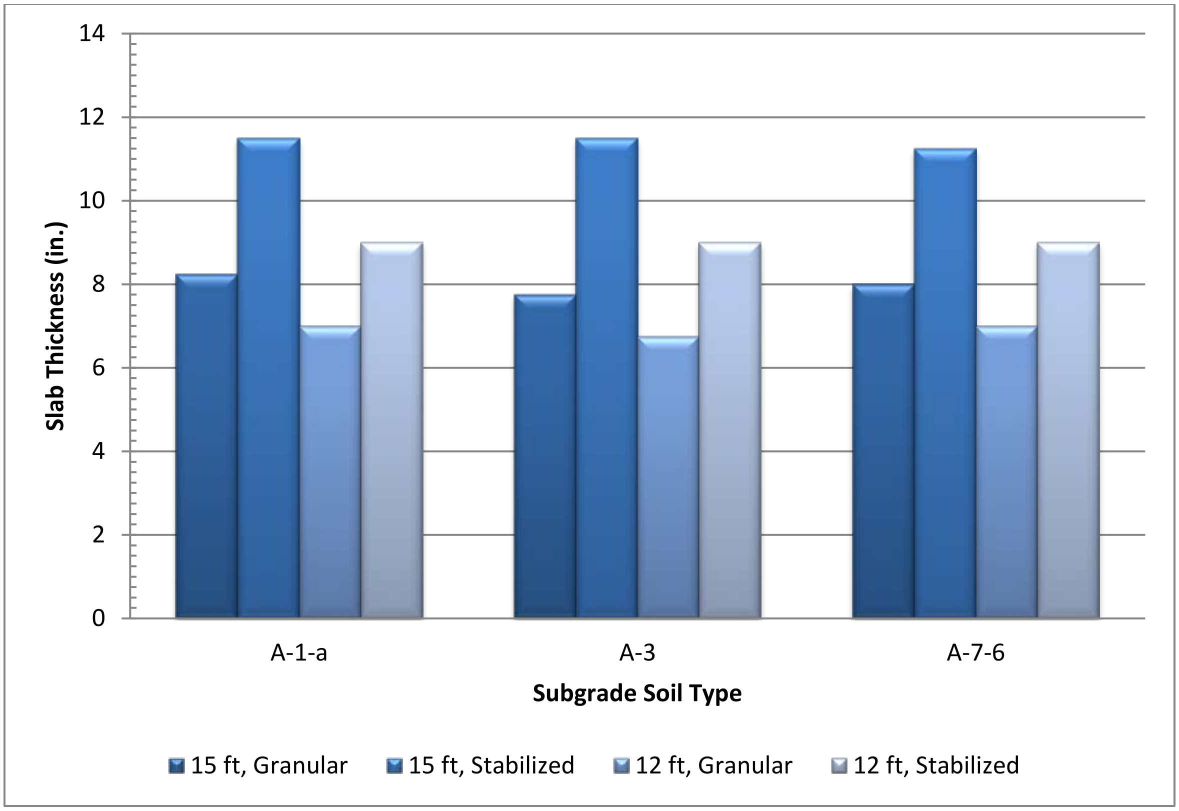
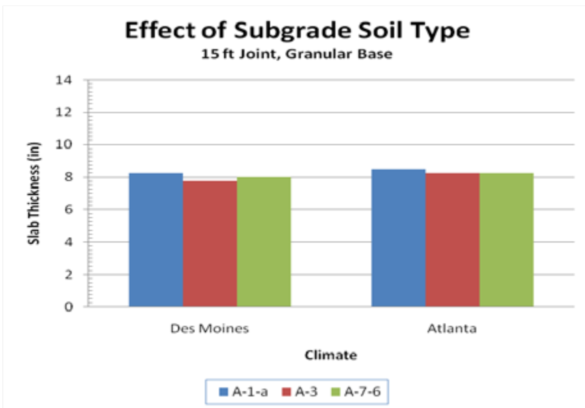


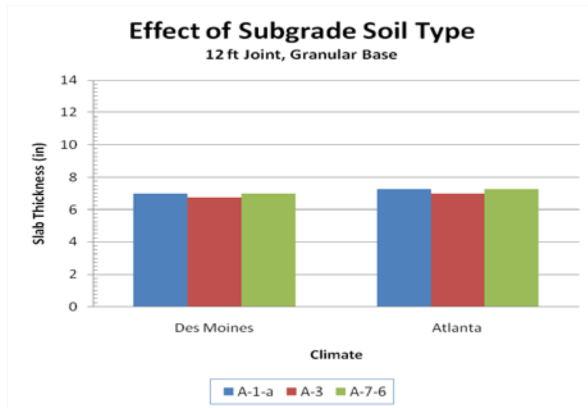
Figure 3. Effect of traffic volume on the design slab thickness

The 15 ft joint spacing designs have a greater thickness increase relative to the 12 ft joint spacing cases. The effect of base type cannot be determined from this analysis, except by comparing cases 19 and 25. At 100 million ESALs, the granular versus stabilized design only required a 0.25 in. thickness increase for a no slab-base friction condition.

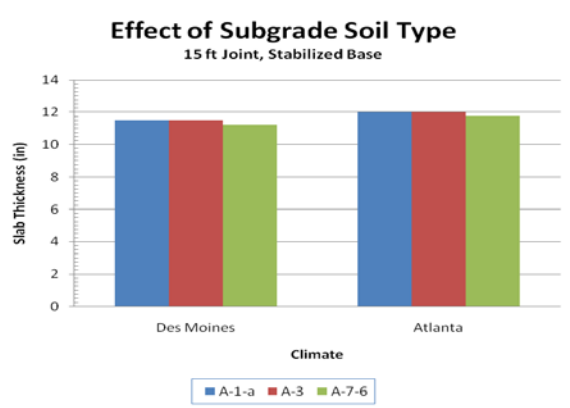
The effect of the subgrade soil type is further explored in Figure 4.



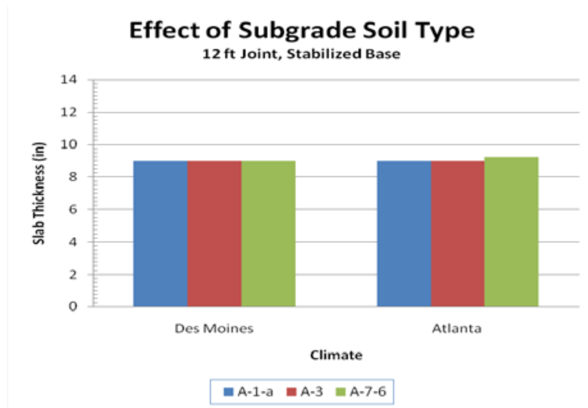
(a)



(b)



(c)



(d)

Figure 4. Effect of subgrade soil type for different climates, slab sizes, and traffic levels

The change in subgrade soil type does not greatly affect the required slab thickness. The greatest slab thickness difference occurred between cases 1 and 2, where the difference was 0.50 in. In all other cases, the greatest difference was only 0.25 in. The soil insensitivity was consistent across climate zones, traffic level, and slab sizes.

The effect of the subgrade resilient modulus is shown in Figure 5.

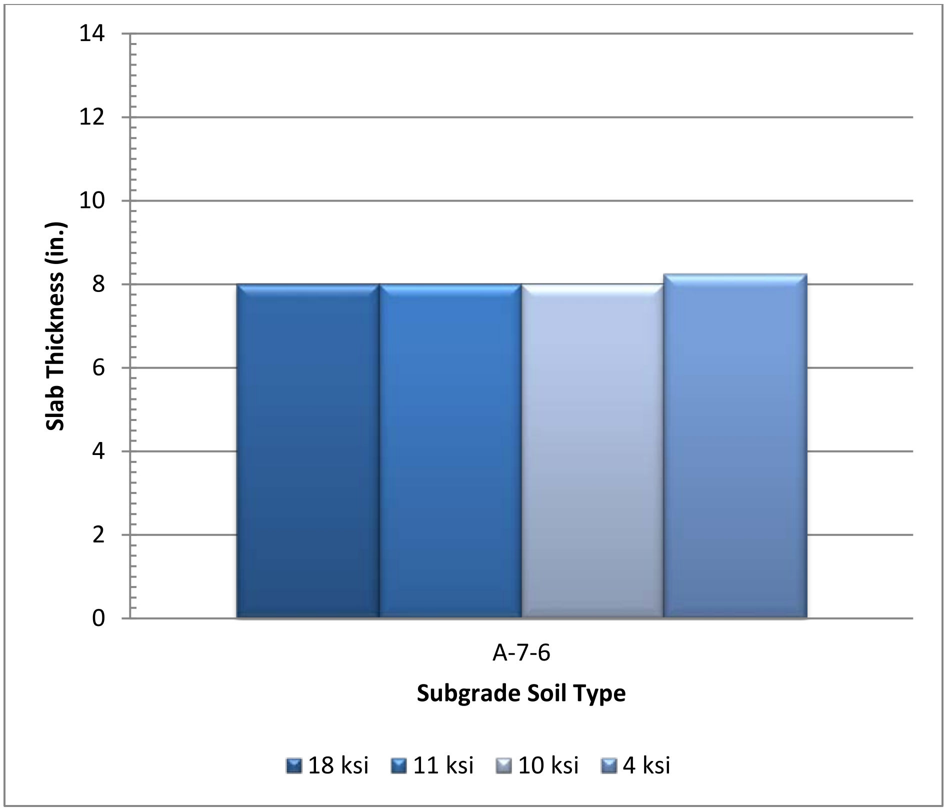


Figure 5. Effect of subgrade resilient modulus on slab thickness for Des Moines, 15 ft slab size, and 5 million ESALs

An A-7-6 subgrade soil type was tested at three different resilient moduli: 18, 11, and 4 ksi (cases 26 through 28). The change in soil stiffness from 18 to 4 ksi resulted in only a 0.25 in. increase in slab thickness. Note, in the main MEPDG runs (cases 1 through 24), the A-7-6 soil had a modulus of 10 ksi, which is also shown in Figure 5.

CHAPTER 5. SUMMARY

The purpose of the MEPDG analysis was to determine the sensitivity of soil type and stiffness on the required slab thickness. This study confirmed previous published work that the MEPDG is not sensitive to subgrade soil type or resilient moduli changes.

The slab thickness varied less than 0.25 in. for a range of soil types and resilient modulus values. Therefore, it does not appear that nonuniformity of support could be directly accounted for in the current MEPDG design method (e.g., implementing a Monte Carlo simulation scheme to assess soil variability).

The most sensitive variables encountered were the traffic level and joint spacing, with a maximum change of 3.75 and 3.00 in., respectively. The effect of climate was also not as critical, requiring only a 0.5 in. change in slab thickness between Des Moines, Iowa, and Atlanta, Georgia.

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APPENDIX: MEPDG INPUT VALUES

This appendix is provided to include all of the input values into MEPDG. Table 4 shows the input values into MEPDG. The subsequent Tables 5 through 8 are supplemental to inputs listed in Table 4.

Table 4. MEPDG input values

General Information		
	Design Life	20 years
	Construction Month	September
	Traffic Open Month	October
	Pavement Type	JPCP
Analysis Parameters		
	Initial IRI	63 in/mi
	Terminal IRI	172 in/mi
	Transverse Cracking	20%
	Mean Joint Faulting	0.12 in
	Reliability	95%
Traffic		
	Initial Two-way AADTT	**Variable**
	Number of Lanes in Design Direction	2
	Percent of Trucks in Design Direction	50.0%
	Percent of Trucks in Design Lane	95.0%
	Operational Speed	60 mph
	Traffic Growth	No growth
Traffic Volume Adjustment Factors		
	Monthly Adjustment	Default MAF (see Table 5)
	Vehicle Class Distribution	Default Distribution (see Table 6)
	Hourly Distribution	See Table 7

Table 4. MEPDG input values (continued)

Axle Load Distribution Factors		
	Axle Load Distribution	Level 3 Default
General Traffic Inputs		
	Mean Wheel Location (inches from the lane marking)	18.0 in.
	Traffic Wander Standard Deviation	10.0 in.
	Design Lane Width	12.0 ft.
	Number of Axles/Truck	See Table 8
	Average Axle Width	8.5 ft.
	Dual Tire Spacing	12.0 in.
	Tire Pressure	120 psi
	Tandem Axle Spacing	51.6 in.
	Tridem Axle Spacing	49.2 in.
	Quad Axle Spacing	49.2 in.
	Average Axle Spacing	Short (12 ft), Medium (15 ft), Long (18 ft)
	Percent of Trucks	Short (33.0%), Medium (33.0%), Long (34.0%)
Climate		
	Location	**Variable**
	Depth of Water Table	6.0 ft
Structure and Design Features		
	Surface Short-wave Absorptivity	0.85
	Permanent Curl/Warp Effective Temperature Difference	-10°F
	Joint Spacing	**Variable**
	Sealant Type	Other
	Doweled Transverse Joints	Yes
	Dowel Diameter	1.5 in.
	Dowel Bar Spacing	12.0 in.
	PCC-Base Interface	Zero Friction Contact
	Erodibility Index	3

Table 4. MEPDG input values (continued)

Layers		
	Layer 1 PCC	PCC
	Layer 1 Thickness	**Variable**
	Layer 2 Base	**Variable**
	Layer 2 Thickness	6.0 in.
	Layer 3 Subgrade	**Variable**
	Layer 2 Thickness	Semi-Infinite (for unbound base); 12 in. (for stabilized base)
	Layer 4 Subgrade (Only for stabilized bases)	**Variable**
	Layer 2 Thickness	Semi-Infinite
PCC Material Properties		
	Unit Weight	150 pcf
	Poisson's Ratio	0.20
	Coefficient of Thermal Expansion	5.5×10^{-6} °F
	Thermal Conductivity	1.25 BTU/hr-ft-°F
	Heat Capacity	0.28 BTU/lb-°F
	Cement Type	Type I
	Cementitious Material Content	600 lb/yd^3
	Aggregate Type	Limestone
	Reversible Shrinkage	50%
	Time to Develop 50% of Ultimate Shrinkage	35 days
	Curing Method	Curing Compound
	28-day PCC Modulus of Rupture	650 psi
Granular Base Layer Properties (Cases 1-12, 25-28)		
	Unbound Material	Crushed stone
	Poisson's Ratio	0.35
	Coefficient of Lateral Pressure	0.5
	Modulus	30,000 psi
	ICM	Default

Table 4. MEPDG input values (continued)

Stabilized Base Layer Properties (Cases 13-24)		
	Material Type	Cement Stabilized
	Poisson's Ratio	0.2
	Elastic/Resilient Modulus	2,000,000 psi
	Thermal Conductivity	1.25 BTU/hr-ft-°F
	Heat Capacity	0.28 BTU/lb-°F
Subgrade Unbound Layer Properties		
	Unbound Material	**Variable**
	Poisson's Ratio	0.35
	Coefficient of Lateral Pressure	0.5
	Modulus	**Variable**
	ICM	Default

Table 5. Level 3 default MAF

Month	Vehicle Class									
	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
January	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
February	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
March	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
April	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
May	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
June	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
July	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
August	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
September	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
October	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
November	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
December	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 6. Level 3 default AADTT distribution by vehicle class

Class 4	1.3%
Class 5	8.5%
Class 6	2.8%
Class 7	0.3%
Class 8	7.6%
Class 9	74.0%
Class 10	1.2%
Class 11	3.4%
Class 12	0.6%
Class 13	0.3%

Table 7. Hourly truck traffic distribution

Midnight	2.3%	Noon	5.9%
1:00 am	2.3%	1:00 pm	5.9%
2:00 am	2.3%	2:00 pm	5.9%
3:00 am	2.3%	3:00 pm	5.9%
4:00 am	2.3%	4:00 pm	4.6%
5:00 am	2.3%	5:00 pm	4.6%
6:00 am	5.0%	6:00 pm	4.6%
7:00 am	5.0%	7:00 pm	4.6%
8:00 am	5.0%	8:00 pm	3.1%
9:00 am	5.0%	9:00 pm	3.1%
10:00 am	5.9%	10:00 pm	3.1%
11:00 am	5.9%	11:00 pm	3.1%

Table 8. Number of axles per truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0.00	0.00
Class 5	2.00	0.00	0.00	0.00
Class 6	1.02	0.99	0.00	0.00
Class 7	1.00	0.26	0.83	0.00
Class 8	2.38	0.67	0.00	0.00
Class 9	1.13	1.93	0.00	0.00
Class 10	1.19	1.09	0.89	0.00
Class 11	4.29	0.26	0.06	0.00
Class 12	3.52	1.14	0.06	0.00
Class 13	2.15	2.13	0.35	0.00