MINNESOTA DEPARTMENT OF TRANSPORTATION

RESEARCH

2007-23

Adaptation of the 2002 Guide for the Design of Minnesota Low-Volume Portland Cement Concrete Pavements

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Technical Report Documentation Page

1. Report No. MN/RC-2007-23	2.	3. Recipients Accession No.
4. Title and Subtitle Adaptation of the 2002 Guide for the Design of Minnesota Low-Volume Portland Cement Concrete Pavements		5. Report Date June 2007
		6.
7. Author(s) Iliya Yut, Shariq Husein, Carly Turgeon, and Lev Khazanovich		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Minnesota Department of Civil Engineering 500 Pillsbury Dr. S.E. Minneapolis, MN 55455		10. Project/Task/Work Unit No.
		11. Contract (C) or Grant (G) No. (c) 81655 (wo) 85
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/PDF/200723.pdf		

16. Abstract (Limit: 200 words)

A new Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as the 2002 Design Guide, was recently proposed in the United States. The development of such a procedure was conducted by the National Cooperative Highway Research Program (NCHRP) under sponsorship by the AASHTO. The Design Guide is a significant innovation in the way pavement design is performed.

A comprehensive evaluation of the MEPDG performance predictions was conducted. It was found that the faulting model produced acceptable predictions, while the cracking model had to be adjusted. The cracking model was re-calibrated using the design and performance data for 65 pavement sections located in Minnesota, Iowa, Wisconsin, and Illinois. A prototype of the catalog of recommended design features for Minnesota low volume PCC pavements was developed using the MEPDG version 0.910. The catalog offers a variety of feasible design alternatives (PCC and base thickness, joint spacing and PCC slab width, edge support type, and dowel diameter) for a given combination of site conditions (traffic, location, and subgrade type). It is recognized, however, that version 0.910 is not the final version of the MEPDG. Therefore, the catalog should be updated after the MEPDG software is finalized.

17. Document Analysis/Descriptors pavement design, concrete pavements, mechanistic-empirical, design catalog, transverse cracking, joint faulting, calibration		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 158	22. Price

Adaptation of the 2002 Guide for the Design of Minnesota Low-Volume Portland Cement Concrete Pavements

Final Report

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June 2007

Published by:

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Executive Summary

A new Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as the 2002 Design Guide, was recently proposed in the United States. The development of such a procedure was conducted by the National Cooperative Highway Research Program (NCHRP) under sponsorship by the American Association of State Highway and Transportation Officials (AASHTO). The Design Guide is a significant innovation in the way pavement design is performed: design inputs include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria and many others.

The mechanistic-empirical performance prediction models in the MEPDG were calibrated using nationwide pavement performance data. Although MnROAD performance data were actively used in calibration, it was necessary to perform calibrations against a wider range of Minnesota variables to achieve a practical procedure. It was also necessary to evaluate the performance of in-service pavements to establish reasonable distress threshold criteria for use in the Guide.

This study had the following objectives:

- Evaluate MEPDG default inputs
- Evaluate prediction capabilities of the MEPDG
- Recalibrate, if necessary, the MEPDG performance prediction models
- Develop a prototype design catalog for Minnesota low volume concrete roads

A comprehensive evaluation of the MEPDG performance predictions was conducted. It was found that the faulting model produced acceptable predictions, while the cracking model had to be adjusted. The cracking model was re-calibrated using the design and performance data for 65 pavement sections located in Minnesota, Iowa, Wisconsin, and Illinois.

A prototype of the catalog of recommended design features for Minnesota low volume PCC pavements was developed using the MEPDG version 0.910. The catalog offers a variety of feasible design alternatives (PCC and base thickness, joint spacing and PCC slab width, edge support type, and dowel diameter) for a given combination of site conditions (traffic, location, and subgrade type). Selection of the most economical design alternative may depend on local experience, available materials (PCC aggregates), available construction equipment, and other factors. It is recognized, however, that version 0.910 is not the final version of the MEPDG. Therefore, the catalog should be updated after the MEPDG software is finalized.

Chapter 1

Introduction

A new Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as the 2002 Design Guide, was recently proposed in the United States (1). The development of such a procedure was conducted by the National Cooperative Highway Research Program (NCHRP) under sponsorship by the American Association of State Highway and Transportation Officials (AASHTO). The Design Guide is a significant innovation in the way pavement design is performed—design inputs include traffic (full load spectra for single, tandem, tridem, and quad axles), material and subgrade characterization, climatic factors, performance criteria and many others. The catalog gives the designer the flexibility to consider different design features and materials for the prevailing site conditions. Evaluation of this procedure is still underway, but many state transportation agencies have already begun adaptation and local calibration of this procedure.

Although the main focus of the MEPDG is design of high-volume roads, it also provides recommendations for the rational design of pavements for low-volume roads. As a part of the NCHRP 1-37A study, the design guidelines for low-volume concrete pavements were developed and presented in the form of a design catalog. The catalog has the following features:

- The traffic levels are 50,000, 250,000, and 750,000 trucks/buses in the design lane for the entire pavement design life of 20 years.
- Environmental conditions are of the US northern climate region (northern Illinois/Indiana area) and southern climate region (Atlanta, Georgia area).
- Five qualitative levels of subgrade soil modulus include very good, good, fair, poor, and very poor. 8 ft and 40 ft are assumed for ground water table levels in wet and dry regions, respectively.
- The performance criteria or the maximum allowable distress indicators and smoothness for the PCC low-volume roads are
    - Joint faulting: 0.15 in
    - Cracking: 45% slabs
    - IRI: 200 in/mile.
- Designs are based on a level of reliability of 50 or 75 percent.

The advantage of the NCHRP 1-37A catalog is that it provides a highly informative and practical guide on the details of design recommendations developed using the MEPDG. The catalog, however, has significant drawbacks:

- The catalog was developed using one of the earliest versions of the MEPDG software. During the course of the NCHRP 1-37A and the follow-up NCHRP 1-40D studies the MEPDG software was substantially revised and the catalog does not correspond to the latest version of the MEPDG software.

- The mechanistic-empirical performance prediction models in the MEPDG were calibrated using nationwide pavement performance data. Although MnROAD performance data were actively used in calibration, it is necessary to perform calibrations against a wider range of Minnesota variables to achieve a practical procedure. It is also necessary to evaluate the performance of in-service pavements to establish reasonable distress threshold criteria for use in the Guide.

Therefore, it is desirable to re-evaluate the catalog and refine it for Minnesota conditions. To achieve these objectives, the Minnesota Department of Transportation (MnDOT) and the Local Road Research Board (LRRB) initiated a study "Adaptation of Mechanistic – Empirical 2002 Guide for Design of Minnesota Low-Volume PCC Pavements." The objective of the study was improvement of design guidelines for Minnesota low-volume PCC pavements by adapting the latest mechanistic-empirical design procedure and calibrating it for local conditions. To achieve this objective, the following activities had to be executed:

- Evaluate MEPDG default inputs

- Evaluate prediction capabilities of the MEPDG

- If necessary, re-calibrate the MEPDG performance models for Minnesota conditions.

- Develop a prototype design catalog for Minnesota low volume concrete roads

This report documents the activities performed under this study.

Chapter 2

Evaluation of Typical MEPDG Inputs

2.1 Introduction

This chapter evaluates typical inputs of the MEPDG for Minnesota low-volume concrete roads, such as climate, traffic, subgrade and materials. It also presents recommendations for default values of these parameters. Since one of the main objectives of this study is to develop a design catalog for Minnesota low-volume concrete roads using the MEPDG software, the MEPDG inputs were divided into two groups:

- Design Catalog Parameters –The parameters that are candidates for inclusion in the list of input parameters of the catalog.
- Default Values – Remaining MEPDG inputs that will be assumed the same for all Minnesota low-volume Portland cement concrete (PCC, hereafter) pavements.

Throughout this chapter, sample screen-shots from the MEPDG software illustrate the source of the parameters that are described in each group. A detailed discussion of the parameters included in each group is presented below.

2.2 Design Catalog Parameters

This group of parameters was identified as candidates for inclusion in the list of input parameters of the future design catalog. It can be further subdivided into the following subgroups:

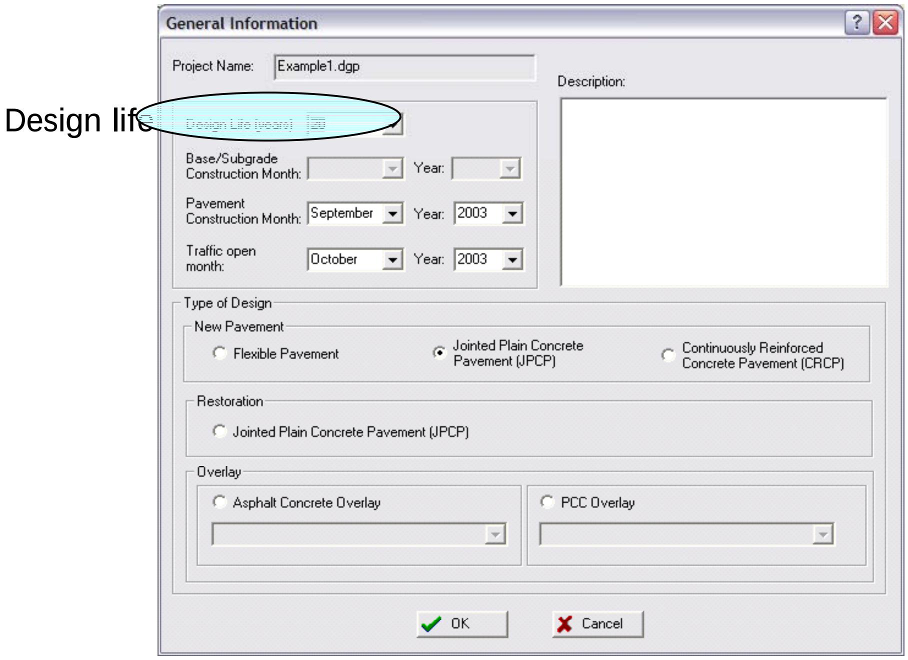
- Design Life and Traffic Level Information
- PCC Slab Design Parameters
- Climatic Parameters
- Performance Criteria

2.2.1 Design Life and Traffic Level Information

These inputs include basic information on pavement design life (for example, 20 or 40 years) and AADTT (Average Annual Daily Truck Traffic). These parameters are presented in figures 2.1 and 2.2, respectively.

The MEPDG defines pavement design life as the length of time for which a pavement structure is being designed, including the time from construction until major programmed rehabilitation. Although the expected life of low volume concrete pavements is between 30 and 50 years, only one level of expected design life, 20 years, is considered in this study. For a design period longer than 20 years the MEPDG performance predictions are governed primarily by the cumulative traffic regardless of the number of years in which the traffic is accumulated.

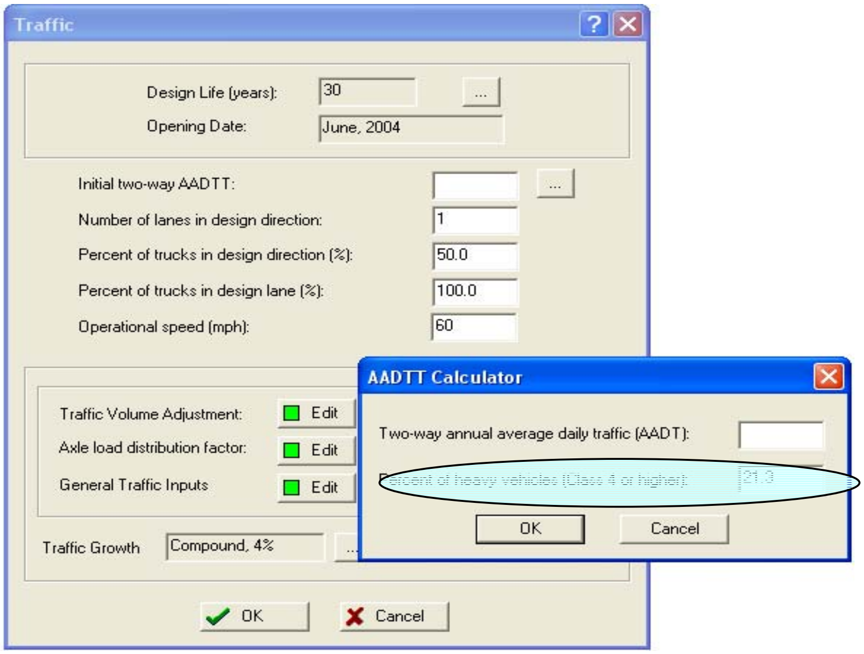
AADTT is the estimate of typical truck traffic on a road segment per day for all days of the week over the period of a year. It is a product of the average annual daily traffic (AADT) and the percentage of heavy trucks.



Project Name: Example1.dgp
Design Life (years) 20
Base/Subgrade Construction Month: Year:
Pavement Construction Month: September Year: 2003
Traffic open month: October Year: 2003
○ Flexible Pavement
● Jointed Plain Concrete Pavement (JPCP)
○ Continuously Reinforced Concrete Pavement (CRCP)
○ Jointed Plain Concrete Pavement (JPCP)
○ Asphalt Concrete Overlay
○ PCC Overlay

Figure 2.1. General information: design life (2).

Traffic information



Traffic

Design Life (years): 30

Opening Date: June, 2004

Initial two-way AADTT:

Number of lanes in design direction: 1

Percent of trucks in design direction (%): 50.0

Percent of trucks in design lane (%): 100.0

Operational speed (mph): 60

Traffic Volume Adjustment: 🟩 Edit

Axle load distribution factor: 🟩 Edit

General Traffic Inputs 🟩 Edit

Traffic Growth: Compound, 4%

AADTT Calculator

Two-way annual average daily traffic (AADT):

Percent of heavy vehicles (Class 4 or higher): 21.0

Figure 2.2. Traffic information: percent of heavy vehicles (2).

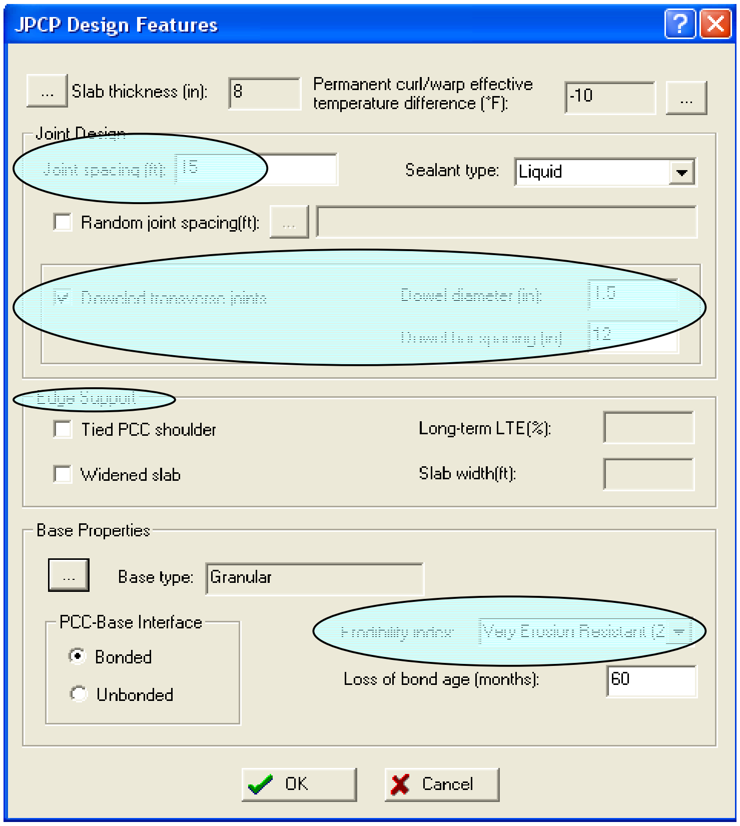
As discussed in the next chapter, a typical Minnesota low-volume PCC pavement experiences traffic levels ranging from 350 to 35,000 vehicles per day. Typically, 5 percent of total traffic consists of heavy vehicles, but in some cases these vehicles make up as much as 12 percent. In the design catalog, the traffic levels of 50,000, 250,000, and 750,000 trucks/buses in the design lane for the entire pavement design life of 20 years are considered.

2.2.2 PCC Slab Design Parameters

The following PCC slab design parameters are considered in the catalog:

- PCC slab thickness
- Joint Design
    - Joint spacing
    - Dowel diameter
    - Base thickness
- Shoulder type and load transfer

It is expected that the PCC slab thickness varies from 6 to 9 inches. PCC joint spacing is either 15 or 20 ft. Both undoweled and doweled joints are considered. The base thickness varies from 6 to 48 in. Three types of shoulder (granular, asphalt, and tied PCC) are considered. The corresponding MEPDG software screen is shown in Figure 2.3.


PCC slab design input

Slab thickness (in): 8

Permanent curl/warp effective temperature difference (°F): -10

Joint Design

Joint spacing (ft): 15

Sealant type: Liquid

☐ Random joint spacing(ft):

☑ Doweled transverse joints

Dowel diameter (in): 1.5

Dowel bar spacing (in): 12

Edge Support

☐ Tied PCC shoulder

Long-term LTE(%):

☐ Widened slab

Slab width(ft):

Base Properties

Base type: Granular

PCC-Base Interface

● Bonded

○ Unbonded

Erodibility index: Very Erosion Resistant (2

Loss of bond age (months): 60

Figure 2.3. PCC slab design parameters/features (*2*).

2.2.3 Climatic Parameters and Regional Information

The MEPDG simulates temperature and moisture profiles in the pavement structure and subgrade over the design life of a pavement using the Enhanced Integrated Climatic Model (EICM). EICM is incorporated into the MEPDG software (*3*). To simplify entering of numerous climatic inputs, such as historic data of precipitation, air temperature, sunshine, etc., the MEPDG software also contains a climatic database, which provides hourly data from 800 weather stations across the United States. 15 of these stations are located in Minnesota. Table 2.1 presents a list of weather stations available with MEPDG software for the Minnesota climate. In this study, the temperature data from four climatic stations in Minnesota (Rochester, Minneapolis, Hibbing, and Redwood Falls) and one in North Dakota

(Grand Forks) were used to evaluate effect of climate on cracking. Those climatic stations represent the following locations:

- Northwest – Grand Forks, ND
- Northeast – Hibbing
- Metro – Minneapolis
- Southwest – Rochester
- Southeast – Redwood Falls

Table 2.1. Minnesota ICM weather station locations and region names. (*2*).

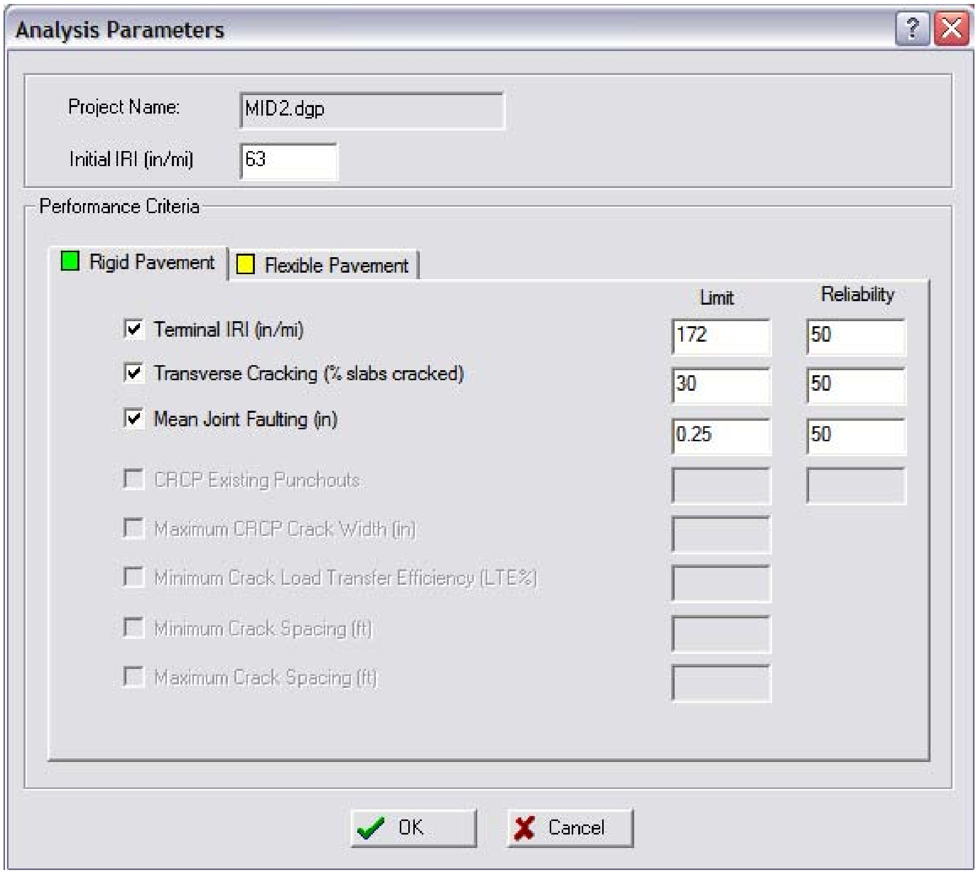
Name	*Station Location*	*Latitude (degrees.minutes)*	*Longitude (degrees.minutes)*	*Elevation (ft)*
Alexandria	Municipal Airport	45.53	-95.23	1421
Baudette	Baudette International Airport	48.44	-94.37	1080
Brainerd	Brainerd-Crow Wing County	46.24	-94.08	1222
Duluth	International Airport	46.50	-92.11	1426
Grand Marais	The Bay of Grand Marais	47.45	-90.2	613
Hibbing	Chisholm-Hibbing Airport	47.23	-92.5	1352
International Falls	Falls International Airport	48.34	-93.24	1182
Minneapolis	Crystal Airport	45.04	-93.21	869
Minneapolis	Flying Cloud Airport	44.50	-93.28	919
Minneapolis-St. Paul	International Airport	44.53	-93.14	817
Park Rapids	Park Rapids	46.54	-95.04	1450
Redwood Falls	Municipal Airport	44.33	-95.05	1021
Rochester	Municipal Airport	43.54	-92.29	1323
St. Cloud	Municipal Airport	45.32	-94.03	1021
St. Paul	Downtown Holman Field	44.56	-93.03	708

2.2.4 Performance Criteria

In this study the critical levels of transverse joint faulting and transverse PCC slab cracking after which the pavement condition should be considered inadequate are defined. The following critical values were suggested by the CPAM (Concrete Paving Association of Minnesota) and the Minnesota Department of Transportation:

- Mean transverse joint faulting: 0.25 in.
- Transverse cracking: 30 percent of slabs

The input screen for these parameters is shown in Figure 2.4.



Project Name: MID2.dgp

Initial IRI (in/mi) 63

	Limit	Reliability
☑ Terminal IRI (in/mi)	172	50
☑ Transverse Cracking (% slabs cracked)	30	50
☑ Mean Joint Faulting (in)	0.25	50
☐ CRCP Existing Punchouts		
☐ Maximum CRCP Crack Width (in)		
☐ Minimum Crack Load Transfer Efficiency (LTE%)		
☐ Minimum Crack Spacing (ft)		
☐ Maximum Crack Spacing (ft)		

Figure 2.4. Performance criteria: mean joint faulting and transverse cracking (*2*).

2.3 Default Input Values

This category contains remaining MEPDG inputs that will be assumed the same for all Minnesota low-volume PCC pavements. This includes information about the following two main groups of parameters:

- Traffic inputs
- Material properties

2.3.1 Traffic Inputs

Traffic data is one of the most important input parameters required for the structural design/analysis of pavement structures. Traffic data required by the MEPDG can be divided into the following groups:

- Traffic volume
- Traffic wander
- Configurations of typical axles and trucks

Traffic Volume

The current American Association of State Highway and Transportation Officials (AASHTO) Guide for pavement design uses the equivalent single axle load (ESAL) approach for traffic characterization (5). This concept is not applicable for the MEPDG. The performance prediction models incorporated into the MEPDG require input of the full spectrum (distribution) of single, tandem, tridem, and quad axle loads applied to a pavement structure by the traffic stream for each month of the pavement design life.

Obtaining and entering the large amounts of data associated with the full-axle spectrum, however, would be a very tedious procedure prone to error. The MEPDG recognizes that and provides a more convenient alternative. The Guide software generates the axle spectrum for each month of the pavement design life based on the following data:

- Base year truck traffic volume
- Traffic volume adjustment factors
- Axle load distribution factors

Base Year Traffic Volume

Typical base year truck traffic volume inputs are shown in Figures 2.5 and 2.6. In addition to the AADTT input described in the section Design Catalog Inputs, lane distribution factors and vehicle (truck) operational speed should be provided. The latter is not important for the design of PCC pavements, so an arbitrary input of 30 mi/hour is adopted. The following traffic/lane distribution parameters will be used in this study:

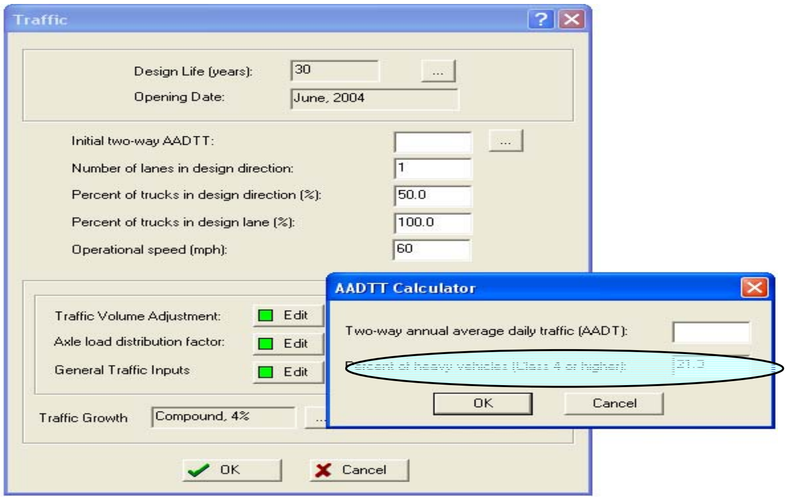
- Number of lanes in design direction: NLD = 1
- Percent of trucks in design direction: PTDD = 50.0%
- Percent of trucks in design lane: PTDL = 100.0%

It should be noted that even if a specific project has traffic/lane distribution parameters; it still can be designed using the results of this study. The software uses AADTT and the traffic/lane distribution factors to predict the total number of heavy vehicles in the design lane in the base, year, TT_b using the following equation:

$$TT_b = \frac{AADTT \cdot 365 \cdot \frac{PTDD}{100} \cdot \frac{PTDL}{100}}{NLD} \qquad (2.1)$$

where TT_b is total number of trucks in the design lane during the first year of the pavement life. NLD is Number of lanes in design direction, PTDD is Percent of trucks in design direction, and PTDL is Percent of trucks in design lane.

Traffic
Information



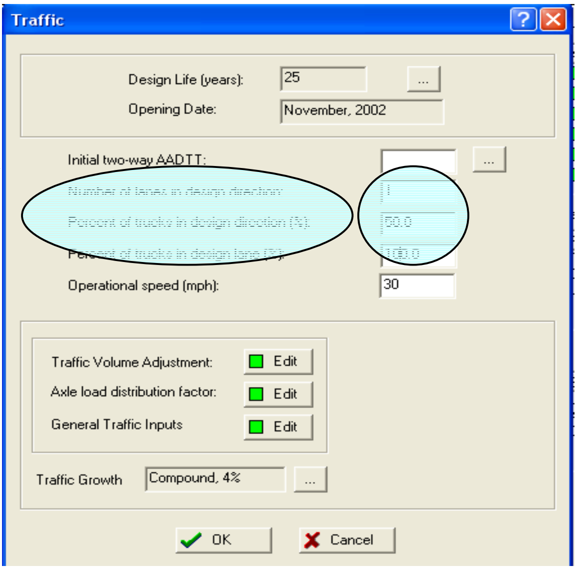
Traffic

Design Life (years): 30
Opening Date: June, 2004
Initial two-way AADTT:
Number of lanes in design direction: 1
Percent of trucks in design direction (%): 50.0
Percent of trucks in design lane (%): 100.0
Operational speed (mph): 60
Traffic Growth: Compound, 4%

AADTT Calculator

Two-way annual average daily traffic (AADT):
Percent of heavy vehicles (Class 4 or higher): 21.3

Figure 2.5. Base-year traffic input (2).



Design Life (years): 25

Opening Date: November, 2002

Initial two-way AADTT:

Number of lanes in design direction: 1

Percent of trucks in design direction (%): 50.0

Percent of trucks in design lane (%): 100.0

Operational speed (mph): 30

Traffic Volume Adjustment: 🟩 Edit

Axle load distribution factor: 🟩 Edit

General Traffic Inputs: 🟩 Edit

Traffic Growth: Compound, 4%

Traffic
information

Figure 2.6. Number of lanes and percent of trucks in design direction (2).

Traffic Volume Adjustment Factors

These inputs enable the MEPDG software to predict the number of each vehicle class passing in every hour of the pavement design life. The traffic volume adjustment factors consist of the following inputs:

- Vehicle class distribution
- Monthly traffic volume adjustment factors
- Hourly truck distribution
- Traffic growth factors

Vehicle class distribution

The current MEPDG requires users to input information about the distribution of truck classes in the design traffic. The truck classes include vehicle classes 4 to 13 as defined by FHWA (*6*). This truck classification is shown in Figure 2.7.

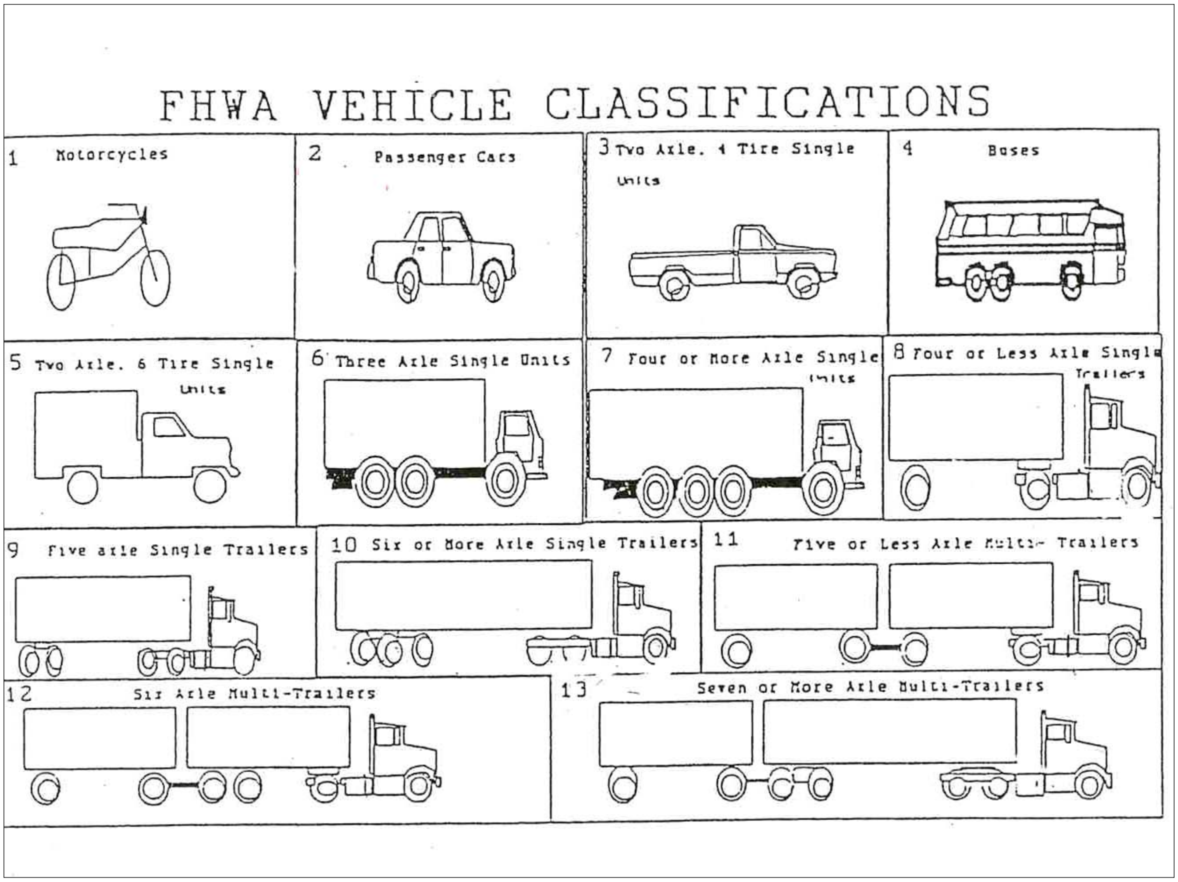


Figure 2.7. Illustrations and definitions of the vehicle classifications by FHWA (6).

In this study, the MEPDG software default information for vehicle classes' distribution is replaced by the distribution that is more representative for Minnesota low-volume roads. The Mn/DOT 1994 Geotechnical and Pavement Manual, Rural CSAH or County Roads, provided a typical traffic composition using Mn/DOT vehicle classification as shown in Table 2.2. This distribution was converted into the MEPDG vehicle class distribution using the following procedure:

- Mn/DOT Vehicle Class No. 1 vehicle traffic is ignored since it corresponds to the FHWA vehicle classes 2 and 3, which are ignored by the MEPDG.

- Percentage of FHWA vehicle classes 11, 12, and 13 are assumed to be the same as in the MEPDG default distribution for the category "Predominately single-trailer trucks with a low percentage of single-unit trucks."

- Mn/DOT vehicle classes 2 through 8 are converted to the FHWA vehicle classes using Table 2.3. The percentage of the AADT is proportionally increased to ensure that the total percentage of the FHWA vehicle classes 4 through 13 is equal to 100 percent.

The results of this conversion are shown in Table 2.4. Table 2.4 also presents the nationwide default vehicle class distribution provided in the MEPDG software. A remarkable similarity in the percentage of the FHWA class 5 vehicles – the most common heavy vehicle type - can be observed. Also, the obtained vehicle distribution might be a slightly better representation of Minnesota traffic conditions for low-volume roads.

Table 2.2. Assumed vehicle distribution [after Mn/DOT 1995, Geotechnical and Pavement Manual, Rural CSAH or County Roads, Table 4-4.2 (*9*)]

Mn/DOT Vehicle Class No.	**Vehicle Type**	**Percent of AADT**
1	Cars and Pickups	94.1%
2	2 Axle, 6 Tire-Single Unit	2.6%
3	3+ Axle - Single Unit	1.7%
4	3 Axle Semi	0.0%
5	4 Axle Semi	0.1%
6	5+ Axle Semi	0.5%
7	Bus/Truck Trailers	1.0%
8	Twin Trailers	0.0%

Table 2.3. Comparison between Mn/DOT (Table 2.2) and FHWA vehicle class distributions.

MN/DOT VEHICLE CLASS NO.	**FHWA VEHICLE CLASS NO.**
1	NA
2	CLASS 5
3	CLASS 6, 7
4	CLASS 8
5	CLASS 8
6	CLASS 9, 10
7	CLASS 4
8	CLASS 11

Table 2.4. Comparison of the default MEPDG and the proposed vehicle class distributions

FHWA Vehicle Class	**MEPDG Default** **Percent of AADTT Distribution (*)**	**Recommended** **Percent of AADTT Distribution**
Class 4	0.8%	10.8%
Class 5	30.8%	28.1%
Class 6	6.9%	18.4%
Class 7	0.1%	18.4%
Class 8	7.8%	1.1%
Class 9	37.5%	5.4%
Class 10	3.7%	5.4%
Class 11	1.2%	1.2%
Class 12	4.5%	4.5%
Class 13	6.7%	6.7%
Total	**100%**	**100%**

* Default MEPDG AADTT distribution for the *Principal Arterials and Others* (with truck traffic classification of 10, percent of buses less than 2, and percent of multi-trailers between 2 and 10).

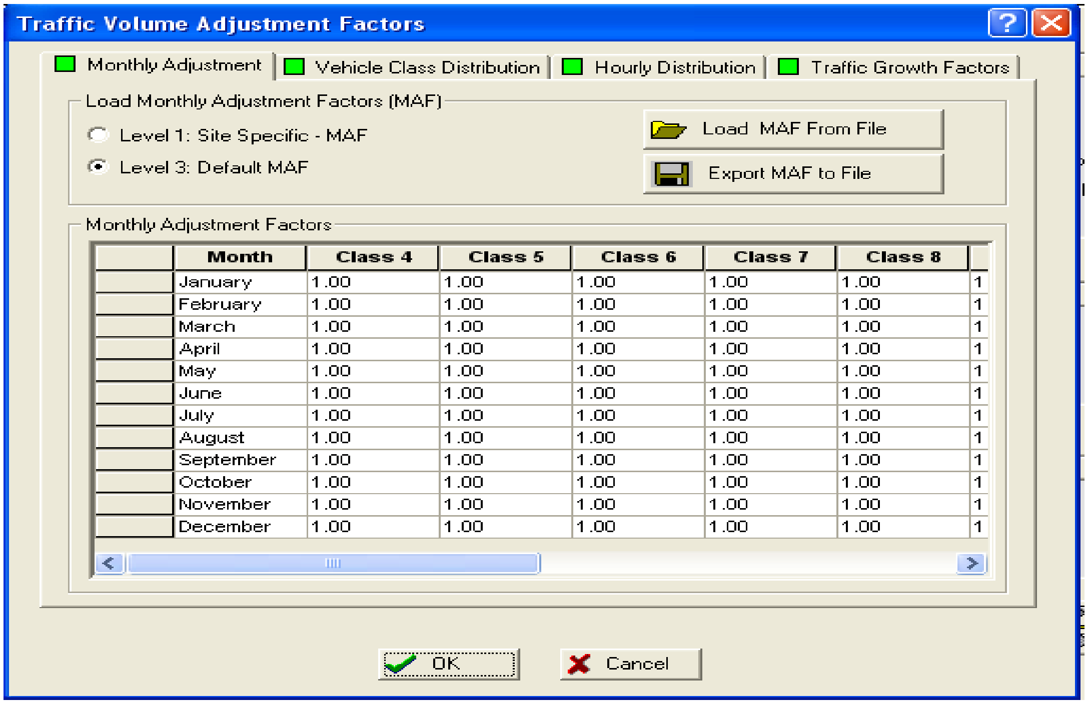
Monthly traffic volume adjustment factors

The MEPDG permits accounting for seasonal variations in the traffic volume through monthly traffic volume adjustment factors. These factors are defined as 12 times the percentage of the annual truck traffic for a particular vehicle class 4 and above (based on FHWA vehicle class distribution as presented in figure 2.10) that occurs in a specific month. The monthly adjustment factors are important for the PCC faulting and cracking predictions because subgrade properties in Minnesota vary by season. The MEPDG software assumes that by default the monthly traffic volume is constant during the entire year, thus the monthly traffic adjustment factors are assumed to be equal to one for every vehicle class in each month. Monthly traffic volume adjustment factors for all the vehicle classes are presented in Figure 2.8, and can be calculated using the equation below:

$$MAF_i = \frac{AADTT_i}{\sum_{i=1}^{12} AADTT_i} * 12 \quad (2.2)$$

where MAF_i represents the monthly adjustment factor for month I and $AADTT_i$ is the AADTT for month i.

It should be noted that the sum of the MAF of all months must equal 12.



Load Monthly Adjustment Factors (MAF)

○ Level 1: Site Specific - MAF
● Level 3: Default MAF

Monthly Adjustment Factors

Month	Class 4	Class 5	Class 6	Class 7	Class 8	
January	1.00	1.00	1.00	1.00	1.00	1
February	1.00	1.00	1.00	1.00	1.00	1
March	1.00	1.00	1.00	1.00	1.00	1
April	1.00	1.00	1.00	1.00	1.00	1
May	1.00	1.00	1.00	1.00	1.00	1
June	1.00	1.00	1.00	1.00	1.00	1
July	1.00	1.00	1.00	1.00	1.00	1
August	1.00	1.00	1.00	1.00	1.00	1
September	1.00	1.00	1.00	1.00	1.00	1
October	1.00	1.00	1.00	1.00	1.00	1
November	1.00	1.00	1.00	1.00	1.00	1
December	1.00	1.00	1.00	1.00	1.00	1

Figure 2.8. Monthly traffic volume adjustment factors (2).

Hourly truck traffic distribution

The hourly distribution factors are the percentages of truck traffic traveling in a given hour relative to the 24-hour period. This percentage is assumed to be the same for all seasons during the pavement design life.

Figure 2.9 presents an hourly truck traffic distribution input screen. Although the MEPDG software provides default hourly distribution factors, these defaults were replaced with a different set of values calculated based on traffic count data obtained from the study "Best Practices for Estimating ESALS on City and County Roads in Minnesota", conducted in May 2002 for Douglas, Kandiyohi, and Olmsted counties. Table 2.5 and Table 2.6 present a list of sites and projects selected for this study along with calculations performed to obtain hourly truck traffic distribution.

Table 2.5. List of sites and projects selected for traffic count data in the study, “Best Practices for Estimating ESALS on City and County Roads in Minnesota” (8).

County Road Study
Week Long Counts- data collected by portable tubes across road
Most counted in 1998 and 1999, some only in one year or the other

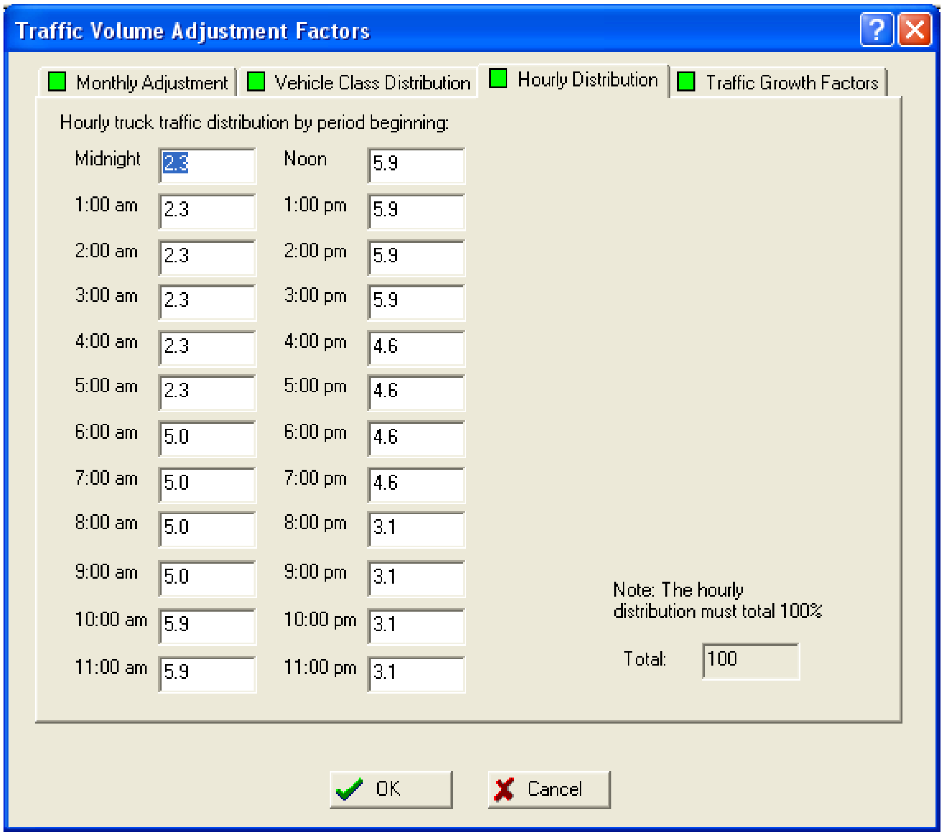
SITE	ROUTE	DESCRIPTION	COUNTY
3001	CSAH 25	S OF CSAH 8	DOUGLAS
3002	CSAH 1	S OF CR 55	DOUGLAS
3003	CSAH 7	N OF CSAH 5	DOUGLAS
3004	CSAH 82	E OF CR 109	DOUGLAS
3005	CSAH 6	N OF CSAH 22	DOUGLAS
3006	CSAH 82	NW OF CSAH 8	DOUGLAS
3007	CSAH 42	N OF TH 29	DOUGLAS
3008	CSAH 5	W OF CSAH 3	DOUGLAS
3009	CSAH 5	E OF CSAH 3	DOUGLAS
3010	CSAH 45	S OF CR 90	DOUGLAS
3011	CSAH 1	S OF TH 7	KANDIYOHI
3012	CSAH 1	N OF TH 7	KANDIYOHI
3013	CSAH 2	N OF TH 7	KANDIYOHI
3014	CSAH 2	N OF TH 12	KANDIYOHI
3015	CSAH 10	E OF CR 95	KANDIYOHI
3016	CSAH 1	N OF CR 89	KANDIYOHI
3017	CSAH 5	N OF TH 7	KANDIYOHI
3018	CSAH 8	S OF CSAH 16	KANDIYOHI
3019	CSAH 4	S OF CSAH 17	KANDIYOHI
3020	CSAH 8	S OF CR 91	KANDIYOHI
3021	CSAH 29	W OF TH 71	KANDIYOHI
3022	CSAH 40	W OF TH 71	KANDIYOHI
3023	CSAH 6	W OF CR 135	OLMSTED
3024	CSAH 6	E OF CSAH 3	OLMSTED
3025	CSAH 3	S OF CSAH 26	OLMSTED
3026	CSAH 5	S OF CSAH 4	OLMSTED
3027	CSAH 12	W OF CSAH 27	OLMSTED
3028	CSAH 7	S OF CSAH 23	OLMSTED
3029	CSAH 7	N OF CR 129	OLMSTED
3030	CSAH 10	S OF CR 142	OLMSTED
3031	CSAH 10	S OF CSAH 9	OLMSTED
3032	CSAH 9	W OF CR 155	OLMSTED
3033	CSAH 9	E OF CR 155	OLMSTED
3034	CSAH 25	W OF CSAH 22	OLMSTED
3035	CSAH 22	0.5 MI S OF CSAH 4	OLMSTED
3036	CSAH 22	0.5 MI N OF CSAH 4	OLMSTED
3038	CSAH 1	N OF CR 101 WB JCT	OLMSTED

Table 2.6. Calculations: Average Percent Hourly Truck Traffic Distribution (8).

		Time →	12:00:00 AM	1:00:00 AM	2:00:00 AM	3:00:00 AM	4:00:00 AM	5:00:00 AM	6:00:00 AM	7:00:00 AM	8:00:00 AM	9:00:00 AM	10:00:00 AM	11:00:00 AM	12:00:00 PM	1:00:00 PM	2:00:00 PM	3:00:00 PM	4:00:00 PM	5:00:00 PM	6:00:00 PM	7:00:00 PM	8:00:00 PM	9:00:00 PM	10:00:00 PM	11:00:00 PM
Douglas	3001	1	0.000	0.000	0.000	0.000	0.000	0.000	3.030	0.000	6.061	9.091	0.000	6.061	3.030	3.030	9.091	15.152	3.030	24.242	9.091	0.000	3.030	3.030	3.030	0.000
Douglas	3001	5	0.000	0.000	0.000	0.000	4.000	0.000	0.000	8.000	8.000	16.000	4.000	0.000	4.000	12.000	0.000	4.000	16.000	4.000	8.000	4.000	0.000	4.000	4.000	0.000
Douglas	3002	1	2.000	0.000	0.000	0.000	0.000	0.000	0.000	4.000	12.000	10.000	6.000	10.000	14.000	12.000	4.000	8.000	6.000	4.000	2.000	2.000	2.000	2.000	0.000	0.000
Douglas	3002	5	0.000	1.587	0.000	0.000	0.000	0.000	1.587	4.762	9.524	7.937	9.524	6.349	9.524	9.524	6.349	7.937	7.937	3.175	0.000	0.000	6.349	3.175	4.762	0.000
Douglas	3003	1	0.296	0.296	0.000	0.000	0.000	0.000	1.479	4.734	6.805	9.763	4.142	9.172	9.172	8.876	9.172	6.805	4.734	4.438	5.917	3.254	2.367	2.663	3.846	2.071
Douglas	3003	5	0.000	0.360	0.000	0.000	0.000	1.799	4.676	4.676	5.036	9.353	8.633	9.353	8.993	10.432	9.353	10.072	3.597	4.317	1.439	2.878	1.799	1.799	0.360	1.079
Douglas	3005	1	1.660	0.000	0.415	0.830	0.000	0.830	1.660	7.054	5.809	5.809	9.959	11.203	5.809	9.959	10.788	7.884	4.979	2.075	2.905	4.564	3.320	0.830	0.415	1.245
Douglas	3005	5	0.339	0.000	0.000	0.339	0.678	1.017	2.712	2.712	6.441	9.831	8.136	9.831	9.492	8.136	7.797	5.085	6.441	8.814	3.729	2.712	3.051	2.034	0.678	0.000
Douglas	3007	1	0.215	0.215	0.215	0.323	0.323	0.538	2.688	6.774	7.097	6.882	9.785	8.065	7.204	8.172	8.065	9.355	6.559	4.624	2.796	2.796	2.366	1.828	1.828	1.290
Douglas	3007	5	0.361	0.434	0.289	0.000	0.361	0.723	2.601	5.564	8.960	7.009	8.237	9.104	8.020	6.214	7.876	6.431	7.370	5.491	3.613	2.962	3.035	2.818	1.806	0.723
Douglas	3008	3	1.130	0.565	0.000	0.565	0.565	0.000	3.390	4.520	6.215	2.825	7.345	15.819	6.215	6.780	9.605	9.040	2.825	5.085	3.955	2.825	2.825	3.390	2.825	1.695
Douglas	3008	7	0.300	0.300	0.000	0.000	0.901	0.601	3.003	3.604	7.508	5.105	8.709	8.408	9.610	7.508	6.006	6.006	11.111	4.204	7.207	2.703	4.204	2.402	0.300	0.300
Douglas	3009	3	1.379	0.690	0.000	0.690	0.000	0.690	0.690	7.586	6.207	4.138	6.897	12.414	9.655	7.586	8.966	6.897	6.897	4.828	1.379	2.069	2.069	4.138	2.069	2.069
Douglas	3009	7	0.000	0.448	0.000	0.000	1.345	0.448	1.794	1.345	8.072	8.969	6.726	10.314	8.969	8.520	5.830	6.726	7.623	5.830	6.278	2.691	4.484	2.242	1.345	0.000
Douglas	3010	1	0.296	0.296	0.791	0.494	2.075	3.063	3.458	6.324	7.905	7.708	7.510	8.004	7.312	6.917	6.621	6.719	8.004	6.126	3.656	2.372	1.383	1.186	1.482	0.296
Douglas	3010	5	1.280	1.280	0.098	0.787	0.787	2.953	2.953	5.807	7.185	7.283	7.283	7.874	6.988	6.693	6.594	7.480	5.906	6.004	5.020	1.969	1.575	1.575	2.461	2.165
Kandiyohi	3011	1	0.000	0.000	0.000	0.424	0.424	0.424	1.271	3.390	6.780	10.169	8.475	9.746	6.356	7.627	11.017	10.169	7.627	7.627	2.542	2.966	0.847	1.271	0.424	0.424
Kandiyohi	3011	5	0.364	0.000	0.364	0.364	0.000	1.818	3.636	7.636	10.182	11.636	10.909	10.909	4.727	6.182	8.000	9.091	6.182	2.909	2.545	0.727	0.727	0.727	0.000	0.364
Kandiyohi	3012	1	0.313	0.313	0.000	0.313	1.254	1.254	3.135	7.524	8.464	9.404	6.583	8.150	6.270	7.210	10.031	7.524	7.524	6.270	3.762	0.940	2.194	0.940	0.313	0.313
Kandiyohi	3012	5	0.270	0.270	0.541	0.000	0.000	0.270	3.243	9.189	8.378	8.378	11.351	6.216	4.054	10.270	7.568	8.108	7.297	4.865	2.973	2.703	1.622	1.892	0.270	0.270
Kandiyohi	3013	1	1.036	1.036	2.073	0.000	1.036	1.554	3.109	5.699	6.736	6.736	5.699	5.181	5.699	4.145	8.290	8.290	6.736	5.699	7.772	3.109	2.591	4.663	1.036	2.073
Kandiyohi	3013	5	2.062	1.031	1.031	2.062	1.546	4.124	3.608	7.216	6.186	7.732	7.216	5.155	5.670	6.186	9.794	5.670	6.186	5.670	1.031	1.031	3.608	2.577	3.093	0.515
Kandiyohi	3015	3	0.000	0.909	0.000	0.455	0.909	2.273	3.636	7.727	5.000	7.727	5.909	8.636	6.364	10.909	5.909	9.091	4.091	4.091	3.636	2.727	5.909	3.636	0.000	0.455
Kandiyohi	3015	7	0.816	0.408	0.816	0.000	0.816	1.224	1.224	4.082	6.531	7.755	8.163	6.531	7.755	4.082	4.898	8.571	7.347	6.531	9.388	6.939	2.041	1.633	1.633	0.816
Kandiyohi	3016	1	0.971	0.971	0.000	0.000	1.942	0.971	1.942	2.913	4.854	8.738	5.825	13.592	7.767	4.854	6.796	8.738	5.825	9.709	5.825	2.913	1.942	0.971	0.000	1.942
Kandiyohi	3016	5	0.741	0.000	0.741	0.000	0.000	1.481	1.481	8.148	11.111	7.407	5.185	4.444	10.370	8.889	2.963	5.926	11.852	5.926	3.704	5.185	1.481	2.963	0.000	0.000
Kandiyohi	3017	1	0.256	0.767	0.767	0.767	0.767	1.023	5.627	5.627	3.325	6.394	5.627	4.859	6.905	8.440	8.951	8.440	10.486	6.138	4.859	3.581	2.558	2.046	1.279	0.512
Kandiyohi	3017	7	0.526	0.789	1.316	1.053	2.105	1.579	4.474	3.421	5.263	4.474	6.316	6.842	7.368	6.053	7.895	8.684	7.632	5.526	5.789	2.632	2.895	3.684	1.579	2.105
Kandiyohi	3018	1	0.865	0.865	0.576	1.729	2.882	4.035	4.035	6.340	5.764	7.493	5.764	6.628	7.205	5.187	8.646	7.493	8.069	3.746	5.187	2.594	2.594	1.441	0.576	0.288
Kandiyohi	3018	5	0.669	1.338	1.338	0.334	4.348	3.679	6.355	6.355	9.030	6.020	7.358	5.017	6.355	8.361	5.686	5.351	7.358	5.351	2.007	1.672	2.341	2.341	1.003	0.334
Kandiyohi	3019	1	0.000	0.562	0.000	0.000	0.562	4.494	10.112	7.865	7.865	8.427	3.933	3.371	6.180	5.056	6.742	6.742	8.989	5.618	5.618	0.562	2.809	2.809	1.124	0.562
Kandiyohi	3019	5	0.000	0.559	0.559	0.000	0.559	0.000	4.469	3.911	4.469	4.469	5.587	7.821	7.821	7.821	5.587	9.497	4.469	6.145	6.704	6.145	5.587	5.587	0.559	1.676
Kandiyohi	3020	1	0.288	0.288	1.441	0.000	0.000	0.865	2.305	5.476	7.493	8.069	10.663	8.646	5.476	6.628	8.069	6.052	5.764	5.187	7.205	3.746	1.729	2.594	0.576	1.441
Kandiyohi	3020	5	0.262	1.309	0.785	0.785	2.618	1.047	4.450	5.236	5.759	9.162	8.377	11.780	5.236	4.188	6.283	6.283	5.236	6.283	4.188	3.403	2.356	1.832	1.309	1.832
Kandiyohi	3021	4	0.000	0.000	0.000	0.000	0.000	1.613	4.032	8.065	5.645	8.871	8.871	8.065	8.065	4.032	8.871	12.097	5.645	4.839	2.419	4.839	0.000	2.419	0.806	0.806
Kandiyohi	3021	8	0.000	0.000	0.000	0.000	0.000	0.000	1.626	4.065	3.252	5.691	9.756	5.691	8.130	8.130	8.130	10.569	4.065	9.756	2.439	6.504	4.065	6.504	1.626	0.000
Kandiyohi	3022	3	0.889	0.667	1.333	0.000	0.667	2.222	4.667	8.667	10.000	7.111	5.556	9.333	5.556	4.444	7.111	7.333	3.111	4.222	3.333	3.778	4.889	2.444	1.111	1.556
Kandiyohi	3022	7	0.803	2.008	0.402	0.000	0.803	2.410	4.016	7.631	4.418	7.229	8.434	5.622	6.827	6.627	7.229	4.618	5.622	6.426	5.221	3.213	3.815	3.414	1.807	1.406
Olmsted	3023	3	0.588	0.000	0.000	0.000	0.588	0.000	3.529	2.941	7.647	4.118	8.235	4.706	11.176	4.706	10.000	14.706	12.941	4.706	4.706	1.176	1.765	1.765	0.000	0.000
Olmsted	3023	7	0.680	0.227	0.227	0.227	0.454	0.907	2.721	4.308	6.122	9.524	8.617	9.070	7.256	6.803	8.844	10.884	9.977	4.989	3.628	2.268	0.907	0.907	0.454	0.000
Olmsted	3024	3	2.062	0.000	1.031	2.062	1.031	5.670	3.093	5.155	5.670	7.216	5.155	6.701	10.825	3.608	4.639	6.186	8.763	5.155	3.608	2.062	3.608	2.062	2.577	2.062
Olmsted	3024	7	1.449	0.000	0.000	0.000	0.483	0.000	1.932	4.831	4.831	5.314	7.246	9.179	8.213	5.797	7.246	7.246	7.246	6.763	5.314	5.314	2.415	3.865	2.415	2.899
Olmsted	3025	1	0.000	2.174	2.174	2.899	1.449	4.348	5.072	4.348	4.348	9.420	7.971	11.594	5.797	5.797	5.797	9.420	2.174	5.797	3.623	1.449	1.449	0.000	2.174	0.725
Olmsted	3025	5	0.000	0.000	0.000	0.000	2.239	7.463	5.224	8.955	14.179	8.209	11.194	8.955	5.224	3.731	2.985	6.716	8.209	1.493	4.478	0.000	0.746	0.000	0.000	0.000
Olmsted	3026	1	0.000	0.000	0.000	0.000	0.000	0.000	3.425	6.849	11.644	6.849	12.329	10.959	3.425	9.589	7.534	6.164	4.795	5.479	4.110	1.370	0.685	1.370	1.370	2.055
Olmsted	3026	5	0.524	0.000	0.000	0.000	1.571	0.000	5.236	6.283	9.424	5.759	8.901	8.377	5.759	7.853	8.377	5.759	9.948	7.330	4.188	3.141	0.000	0.000	1.047	0.524
Olmsted	3027	3	0.750	0.150	0.750	0.450	0.900	1.649	2.849	5.847	6.597	5.247	6.147	5.097	8.696	6.297	7.796	8.696	7.796	7.046	4.498	6.297	2.099	2.249	1.199	0.900
Olmsted	3027	7	0.278	0.278	0.278	0.417	1.113	1.113	5.981	4.868	5.702	6.120	6.259	8.067	6.815	8.067	6.815	7.232	6.259	6.815	6.537	4.033	3.199	2.643	0.834	0.278
Olmsted	3028	1	1.188	2.375	0.713	0.713	1.663	3.325	7.126	6.888	7.601	8.314	8.314	8.076	6.413	4.513	6.413	7.363	5.226	3.800	3.088	2.138	1.663	1.663	0.713	0.713
Olmsted	3028	5	0.480	0.320	0.160	0.480	1.600	3.840	5.120	4.640	8.000	7.200	7.200	8.000	6.240	6.400	5.920	6.400	6.400	5.600	2.880	4.800	1.920	2.560	2.400	1.440
Olmsted	3029	1	0.308	1.846	0.923	0.615	0.923	4.000	9.846	8.615	9.231	7.385	7.077	9.846	7.077	4.923	5.538	6.462	4.923	2.769	3.077	0.923	1.231	0.923	0.615	0.923
Olmsted	3029	5	0.385	0.385	0.000	0.000	0.000	2.692	3.462	4.231	11.538	10.769	9.231	8.846	4.615	5.385	4.615	7.692	6.538	6.154	3.077	3.846	2.692	1.154	2.308	0.385
		AVERAGE	**0.559**	**0.545**	**0.426**	**0.388**	**0.929**	**1.654**	**3.515**	**5.623**	**7.267**	**7.658**	**7.468**	**8.109**	**7.148**	**6.945**	**7.175**	**7.863**	**6.872**	**5.763**	**4.268**	**2.895**	**2.439**	**2.282**	**1.335**	**0.875**

The hourly distribution factors calculated in this study are provided in Table 2.7. Figure 2.10 presents comparison of these factors with the default MEPDG software factors. It can be observed that although these distributions are quite similar, the factors calculated in this study have higher values for the daytime and lower values for the nighttime. This indicates that a greater portion of trucks travel during the daytime on Minnesota low-volume roads, which contradicts what would be predicted by the MEPDG software defaults. It should be noted that the MEPDG traffic defaults are more applicable for interstate highway traffic than for low-volume traffic roads.

Hourly distribution



Hourly truck traffic distribution by period beginning:

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

Note: The hourly distribution must total 100%

Total: 100

Figure 2.9. Hourly traffic distribution (2).

Table 2.7. Calculated MEPDG default hourly truck traffic distribution.

Midnight	1.15%	Noon	7.25%
1:00 AM	1.15%	1:00 PM	7.25%
2:00 AM	1.15%	2:00 PM	7.25%
3:00 AM	1.15%	3:00 PM	7.25%
4:00 AM	1.15%	4:00 PM	5.63%
5:00 AM	1.15%	5:00 PM	5.63%
6:00 AM	1.15%	6:00 PM	5.63%
7:00 AM	7.25%	7:00 PM	1.97%
8:00 AM	7.25%	8:00 PM	1.97%
9:00 AM	7.25%	9:00 PM	1.97%
10:00 AM	7.25%	10:00 PM	1.97%
11:00 AM	7.25%	11:00 PM	1.97%

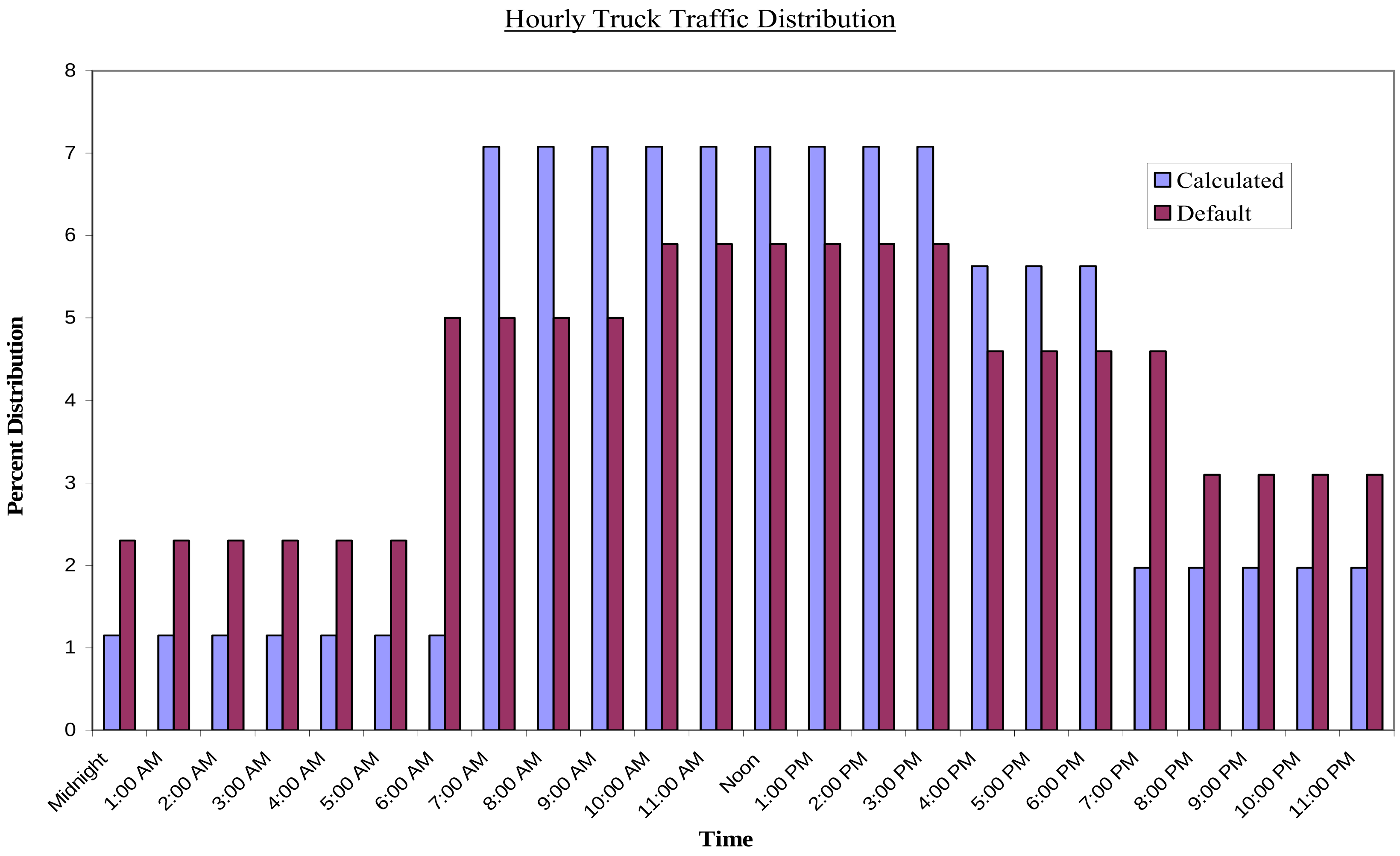


Figure 2.10. Hourly truck traffic distribution based on MEPDG default and calculated total average distribution.

Traffic growth factors

The MEPDG procedure recognizes that the traffic volume is not always constant but may increase or decrease over time. In this study, in accordance with the MEPDG software defaults, it is assumed that the yearly traffic volume increases by four percent of the preceding year's traffic for each truck class.

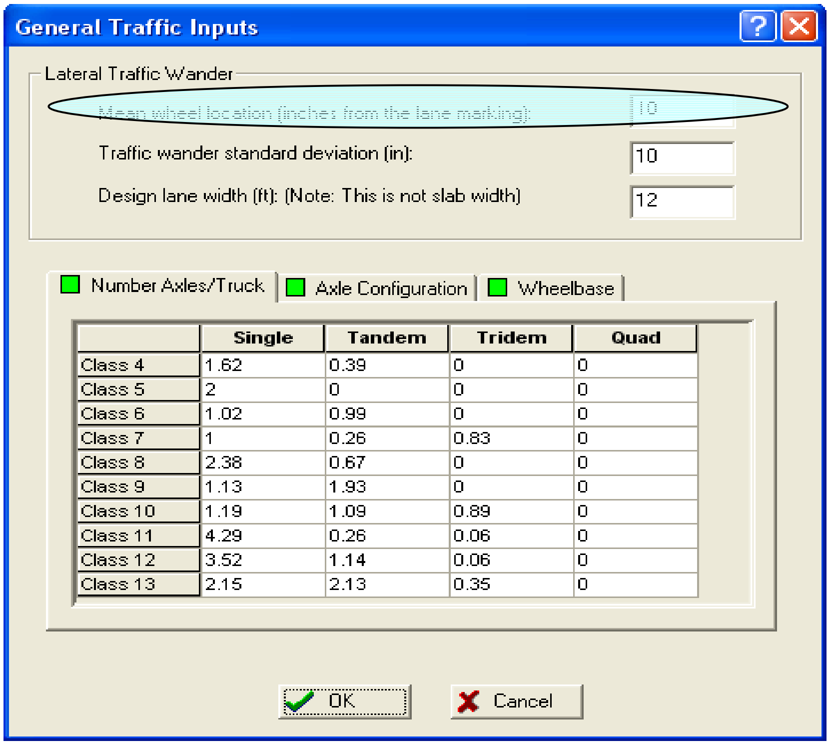
Traffic Wander

In the MEPDG, lateral traffic wander is modeled as normal distribution using mean wheelpath and standard deviation. The mean wheelpath is measured from the paint stripe at the lane-shoulder edge to the outer edge of the wheel. It is used for predicting distress by determining the number of axle load applications over a point. Presented in Figure 2.11 are the default values for the traffic wander parameters:

- Mean wheelpath – 18 in
- Standard deviation – 10 in

These values were used in this study.

General traffic



Lateral Traffic Wander

Mean wheel location (inches from the lane marking): 10

Traffic wander standard deviation (in): 10

Design lane width (ft): (Note: This is not slab width) 12

🟩 Number Axles/Truck | 🟩 Axle Configuration | 🟩 Wheelbase

	Single	Tandem	Tridem	Quad
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

Figure 2.11. Mean wheel location, traffic wander, and axle configuration (2).

Design Lane Width

The design lane width parameter is defined as the distance between the lane markings on both sides of the design lane. The MEPDG default value for design lane width is 12 ft; however, it may or may not be equal to the slab width.

Configurations of typical axles and trucks

The MEPDG default axle load distribution factors, axle configuration, and number of axles per truck are adopted as the traffic characteristics in this study. Under axle configuration a tire pressure of 120 psi is used for both single and dual tires. Axle configuration for typical wheel and axle loads, applied to a roadway, is described through a series of data elements. These data elements can be measured directly in the field and are important due to their sensitivity to wheel locations, axle configuration, and axle type. Typical values for these elements are listed below:

- *Average axle-width* – The average distance between two outside edges of tires on an axle. Typically 8.5 ft is assumed for axle width.

- *Dual tire spacing* – The distance between centers of a dual tire. Typically a value of 12 in. is used.

The wheel base is defined as the spacing between the steering and the first drive axle of the truck-tractors. Default MEPDG values for short, medium, and long average axle spacing are 12 ft, 15 ft, and 18 ft, respectively.

2.3.2 Material Properties

The MEPDG procedure requires providing detailed information for each layer in the pavement structure. The interaction among the materials, climate, traffic, structural response, and performance prediction components is critical for the final acceptance of the design and results. The following information should be provided for the pavement layers:

- Material properties required for computing pavement responses

- Additional materials inputs to the distress/transfer functions

- Additional materials inputs required for climatic modeling

A typical low-volume PCC pavement in Minnesota has the following layers:

- PCC layer

- Granular base layer

- Subgrade

The default properties for each of these layers are provided below.

PCC material properties

This contains several sub-categories, which are briefly discussed as outlined below.

- Unit weight and Poisson's ratio
- Concrete mix properties
- Concrete strength and Modulus of Elasticity
- Thermal properties

Unit weight and Poisson's ratio

PCC unit weight and Poisson's ratio are design inputs required for calculation of PCC curling stresses. The MEPDG default values for unit weight and Poisson's ratio equal to 150 lb/ft^3 and 0.20, respectively, were adopted in this study.

Concrete mix properties

The MEPDG procedure requires providing information related to the PCC mix design. The following typical Mn/DOT PCC mix value will be used in this study:

- Cement type – Type 1
- Cement content (lb/yd^3) – 600 lb/ yd^3
- Water/cement ratio – 0.42
- Aggregate type – limestone or gravel.

Using the American Concrete Institute (ACI) recommendation, the following PCC mix shrinkage properties will be assumed:

- Reversible shrinkage (percentage of ultimate shrinkage) – 50 percent
- Time to develop 50 percent of ultimate shrinkage – 35 days

It is assumed that a curing compound will be used for PCC curing. The PCC zero-stress temperature and PCC ultimate shrinkage at 40 percent relative humidity will be determined using the default MEPDG equations.

Concrete strength and Modulus of Elasticity

The following default value for concrete 28-day modulus of rupture is adopted:

- Modulus of rupture after 28 days – 700 lb/in^2

Thermal properties

Thermal properties include coefficient of thermal expansion, thermal conductivity, and heat capacity. The coefficient of thermal expansion is a key parameter for prediction of PCC stresses and deflections. The thermal conductivity and heat capacity are used for prediction of temperature distribution throughout the concrete slab. The following values are assumed for these parameters:

- PCC coefficient of thermal expansion – 0.0000048 and 0.0000055 in/in/^{o}F for limestone and gravel coarse aggregate, respectively.
- PCC thermal conductivity – 1.25 BTU/hr-ft-^{o}F
- PCC heat capacity – 0.28 BTU/lb-^{o}F

Unbound material properties

The properties for the unbound materials (base and subgrade) can be divided into two groups:

- Strength properties
- ICM materials properties

The MEPDG procedure characterizes strength properties of unbound materials through resilient modulus at the optimum moisture content and the Poisson's ratio. These properties can be obtained from laboratory testing or through correlation with other material properties or material classification. Table 2.8 provides a summary of correlations that MEPDG adopts to estimate modulus from other material properties. Unbound granular materials can be defined using the AASHTO classification system for soil groups A-1 to A-3. Subgrade materials can be defined using both the AASHTO and USC (Unified Soil Classification) systems. Typical resilient modulus correlations to empirical soil properties are also provided in Figure 2.12. In this study, the Mn/DOT soil factor was combined with AASHTO classification using guidelines developed by Skok et al.(8). Table 2.9 provides the recommendations for selection of the subgrade resilient modulus for the optimum moisture content based on the soil classification, Mn/DOT soil factor, or other available properties.

Table 2.8. Summary of correlations of material properties *(1)*.

Strength/Index Property	**Model**	**Comments**	**Test Standard**
CBR	$M_r = 2555(CBR)^{0.64}$	CBR = California Bearing Ratio, percent	AASHTO T193—The California Bearing Ratio
R-value	$M_r = 1155 + 555R$	R = R-value	AASHTO T190—Resistance R-Value and Expansion Pressure of Compacted Soils
AASHTO layer coefficient	$M_r = 30000\left(\frac{a_i}{0.14}\right)$	a_i = AASHTO layer coefficient	AASHTO Guide for the Design of Pavement Structures (1993)
PI and gradation*	$CBR = \frac{75}{1 + 0.728(w \cdot PI)}$	W*PI = P200*PI P200= percent passing No. 200 sieve size PI = plasticity index, percent	AASHTO T27—Sieve Analysis of Coarse and Fine Aggregates AASHTO T90—Determining the Plastic Limit and Plasticity Index of Soils
DCP*	$CBR = \frac{292}{DCP^{1.12}}$	CBR = California Bearing Ratio, percent DCP =DCP index, in/blow	ASTM D6951—Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications

Note: The subgrade strength properties are assumed based on the soil classification.

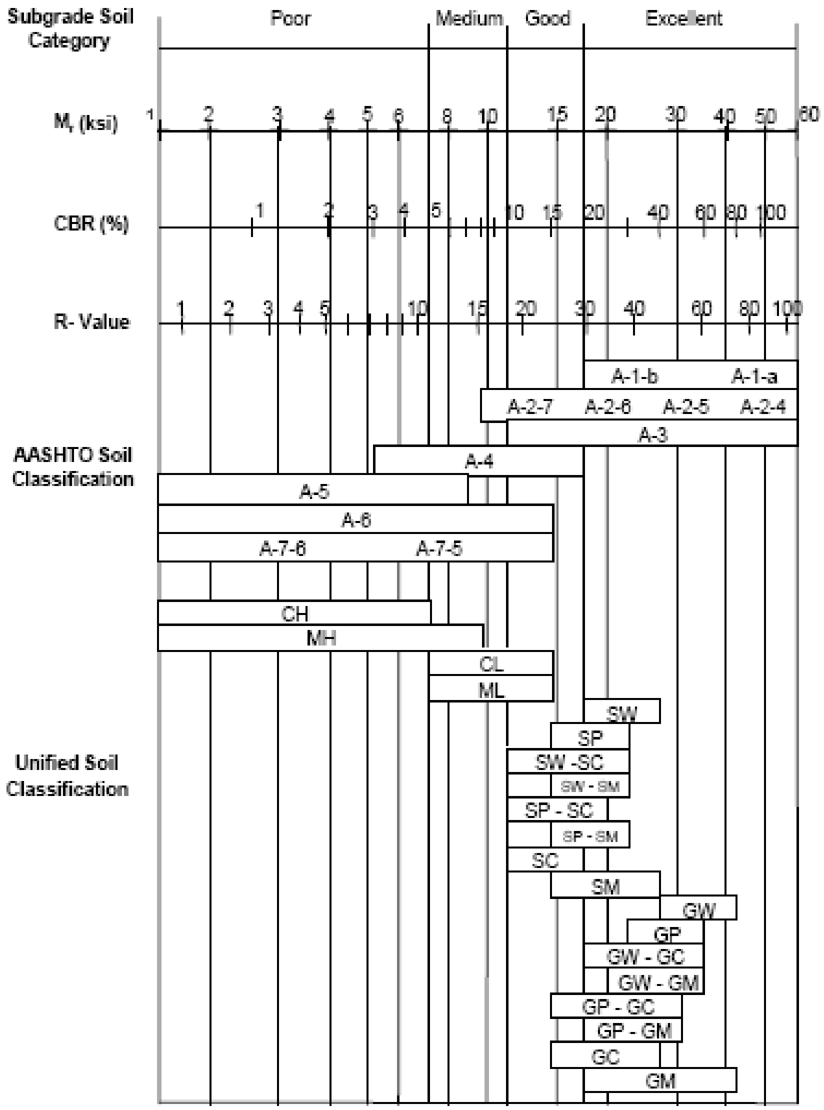


Figure 2.12. Typical Resilient Modulus Correlations to Empirical Soil Properties and Classification Categories. (1)

Table 2.9. Proposed Soil Strength Properties for the Design Catalog

Soil Classification			**Soil Strength Tests / Properties**				
Textural Class	AASHTO	Mn/DOT Soil Factor	R-Value	(240 psi Exudation Pressure)	CBR Percentage	DCP mm/blow	*Modulus (10^3 psi)
			Measured	Estimated	Estimated	Estimated	
Gravel	A-1	50-75	NA	70	21	12	38-40
Sand	A-1, A-3	50-75	NA	70	21	12	38-40 , 29
Loamy Sand	A-2	50-75	46-74	30	6.2	22	24-32
Sandy Loam	A-2, A-4	100-130	17-49	30	4.4	27	24
Loam	A-4	100-130	14-26	15	4.2	27	24
Silt Loam	A-4	100-130	10-40	12	3.9	28	24
Sandy Clay Loam	A-6	100-130	14-27	17	4.5	26	17
Clay Loam	A-6	100-130	13-21	13	4.1	28	17
Silty Clay Loam	A-6	120-130	11-21	10	NA	NA	17
Sandy Clay	A-7	120-130	NA	14	NA	NA	12
Silty Clay	A-7	120-130	NA	8	3.4	30	12
Clay	A-7	120-130	10-17	12	3.9	28	8

(*) From MEPDG defaults (2). Mn/DOT Soil Factor (8)

Soil properties for EICM

The following input parameters are required by the EICM to predict temperature distribution in the PCC layer and moisture distribution in the unbound layers:

- Plasticity index
- The percentage of particles by weight passing the #200 sieve
- The percentage of particles by weight passing the #4 sieve
- The diameter of the sieve, in mm, at which 60 percent by weight of the soil passes through.

Table 2.10 summarizes the default values for these parameters used in the MEPDG Software, which are also adopted for use in this study.

Effective temperature difference

Permanent curl/warp effective temperature difference (^oF) is set to a default value of -10 ^oF.

Drainage

Default MEPDG drainage and infiltration parameters are listed below:

- Infiltration – Minor (10%)
- Drainage path length – 12-ft
- Pavement cross slope – 2%

Erodibility index

The MEPDG default value of 4 for this parameter is considered in this study. Erodibility index values range from 1 to 5. An erodibility index of 1 corresponds with a very erosion-resistant material and of 5 corresponds with a very erodable one. The use of the value of 4 is a conservative definition of erodibility.

Table 2.10. MEPDG default soils properties used for ICM *(2)*.

Soil Classification		**Gradation and Plasticity Index**					**Calculated / Derived Parameters**				
Textural Class	AASHTO	Modulus (psi)	Plasticity Index (PI)	% passing #200 sieve	% Passing # 4 sieve	D60 (mm)	Max. dry unit wt. (pcf)	Specific gravity of Solids (Gs)	Saturated Hydraulic Conductivity (ft/hr)	Optimum water Content (%)	Calculated degree of saturation
	A-1-a	40,000.00	1	3	20	8	122.2	2.66	263	11.1	82
Gravel	A-1-b	38,000.00	1	3	40	2	122.2	2.66	37	11.1	82
	A-2-4	32,000.00	2	20	80	0.1	121.9	2.68	0.000866	11.7	83.9
⇣	A-2-5	28,000.00	2	20	80	0.1	121.9	2.68	0.000866	11.7	83.9
	A-2-6	26,000.00	15	20	95	0.1	117.5	2.71	1.73E-05	13.9	85.9
Loamy Sand	A-2-7	24,000.00	15	20	90	0.1	117.5	2.71	1.73E-05	13.9	85.9
Sand	A-3	29,000.00	0	10	80	0.2	126	2.65	0.0223	9.2	78
	A-4	24,000.00	3	60	90	0.05	119.4	2.7	2.22E-05	13	85.4
⇣	A-5	20,000.00	1	80	90	0.05	121.1	2.69	2.10E-05	12.1	84.5
	A-6	17,000.00	25	80	95	0.01	100.8	2.75	6.52E-07	22.6	88.5
Clay	A-7-5	12,000.00	30	85	99	0.01	97.1	2.75	2.53E-07	24.8	88.9
	A-7-6	8,000.00	40	90	99	0.01	91.3	2.77	4.86E-08	28.8	89.4

Chapter 3

Determination of Typical Design Features of Minnesota Low-Volume Concrete Roads

3.1 Introduction

This chapter presents the results of determination of typical design features of Minnesota low-volume Portland Cement Concrete (PCC) pavements. The agencies that actively build low-volume PCC pavements were contacted for information to determine typical design features of Minnesota low-volume PCC pavements. Information collected from these agencies is summarized below.

3.2 Survey of Agencies

With the help from the Concrete Paving Association of Minnesota (CPAM), the following agencies were identified as actively constructing and maintaining low-volume PCC pavements:

- City of Owatonna – Department of Transportation
- Waseca County – Highway Department
- Ramsey County – Highway Department
- Olmsted County – Highway Department
- City of Moorhead – Department of Transportation
- City of E. Grand Forks – Consulting Engineers: Floan-Sanders, Inc.
- City of White Bear Lake – Department of Transportation
- City of Rochester – Department of Transportation
- Minnesota Department of Transportation (Mn/DOT)

These nine agencies (three counties, five cities, and Mn/DOT) were contacted for design and performance information on low-volume PCC pavements. Figure 3.1 presents locations of these counties and cities. It shows that the contacted cities and counties represent southern, central, and northwestern regions of Minnesota. The northeastern part of the state is not represented because concrete pavements are not typical for this region. The agencies were asked to provide information on their typical design solutions, including PCC thickness, base type and thickness, PCC joint spacing, PCC strength requirements, etc. A sample of a questionnaire sent to the agencies is provided in Figure 3.2.

Table 3.1 presents status of the request, contact persons, and locations of the agencies. Eight out of nine agencies responded to the survey, with seven of them providing detailed information. A brief summary of the agencies' responses is presented in Table 3.2. One can observe that low-volume PCC pavements in Minnesota are designed to carry average daily traffic (ADT) from several hundred to almost 35,000 vehicles per day. The reported PCC thicknesses vary from 6 in. to 9 in. All the agencies follow PCC design compressive strength requirement of 3900 psi, as recommended by the Minnesota DOT.

Base and subgrade properties do not vary much around the state, but different agencies follow different base design thickness. It is found that subgrade soil type is mostly pure clay or clay loam. Typical bases are either of class 2 or class 5 material (materials classification based on Mn/DOT Grading and Base Manual, Specification 3138), and base design thickness varies from 2 in to 8 in.

PCC joint spacing varies from 10 ft to 16 ft, and agencies use both skewed and perpendicular transverse joints. Although most of the agencies do not use dowels, the cities of Rochester and Moorhead reported using 1.25-in. dowels.

A variety of shoulder types were reported. While Waseca County uses aggregate shoulders, the city of Moorhead uses tied PCC shoulders. Drainage designs also vary from agency to agency. Drainage types mentioned in table 3.2 are storm sewer, curb and gutter, perforated pipes, and drain tiles.

The details of the design practices reported by the cities and counties are presented below.

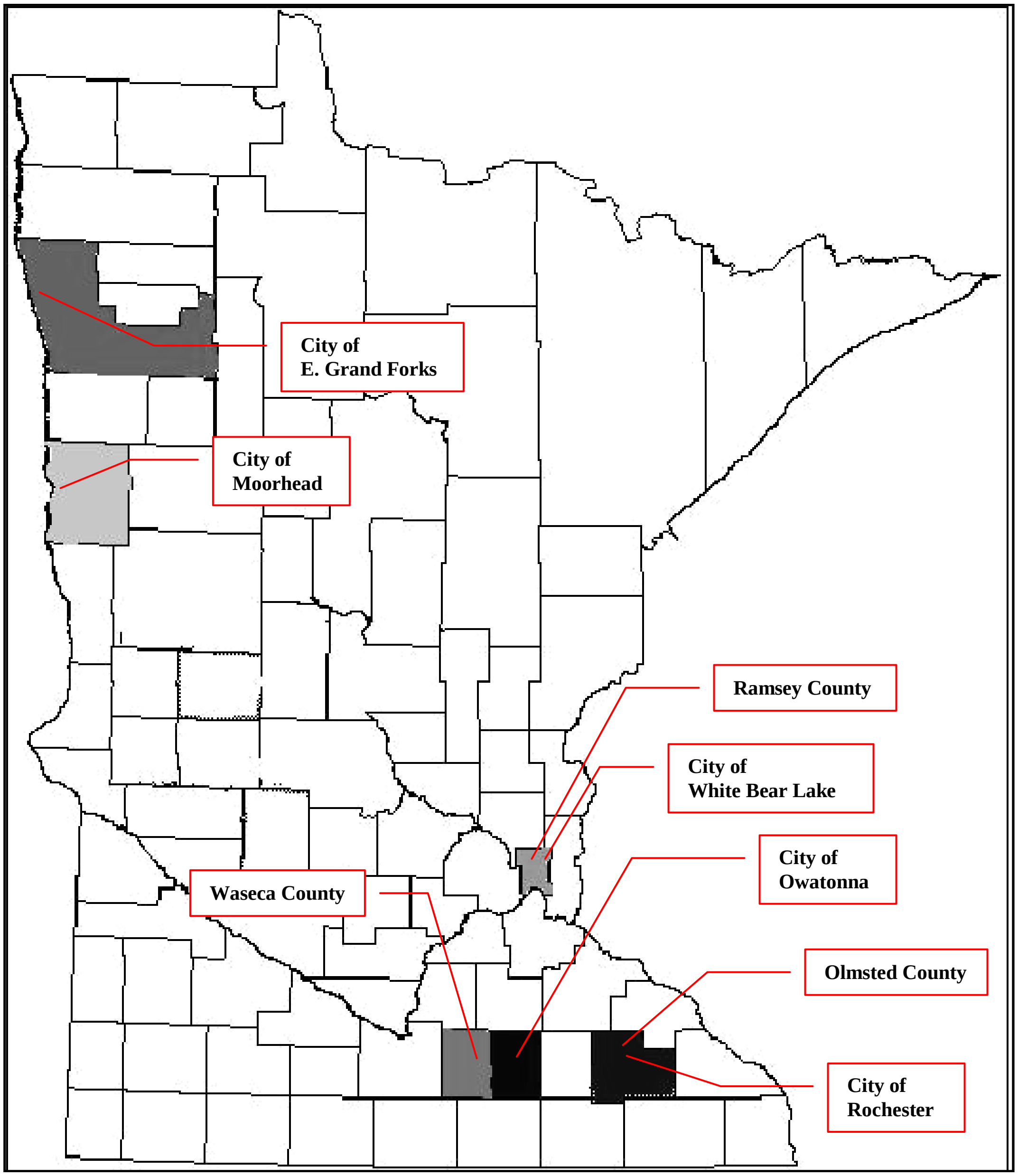
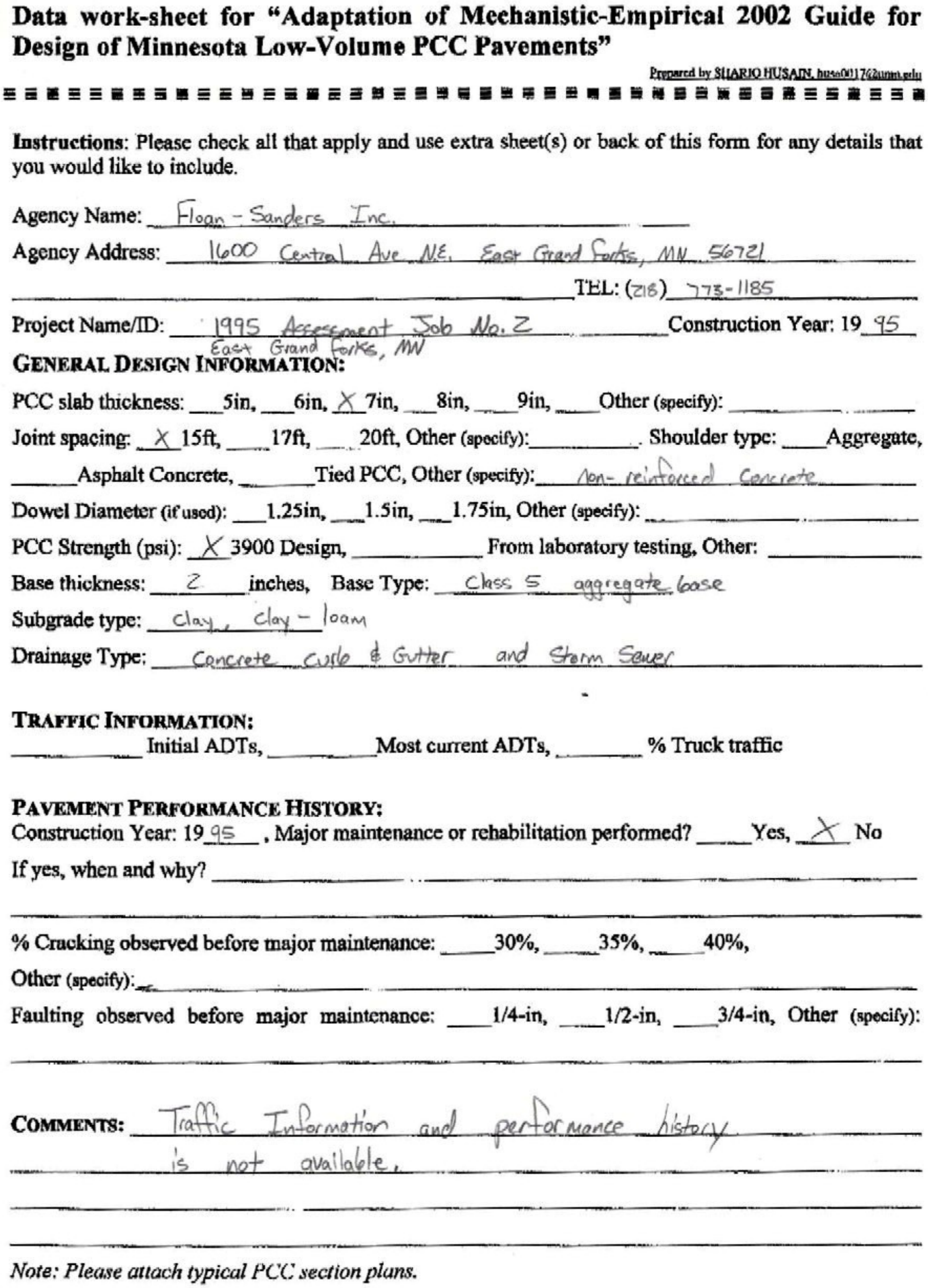


Figure 3.1. Locations of local and county transportation/highway agencies contacted



Data work-sheet for "Adaptation of Mechanistic-Empirical 2002 Guide for Design of Minnesota Low-Volume PCC Pavements"

Prepared by SHARIQ HUSAIN, husa0017@umn.edu

Instructions: Please check all that apply and use extra sheet(s) or back of this form for any details that you would like to include.

Agency Name: Floan - Sanders Inc.

Agency Address: 1600 Central Ave NE. East Grand Forks, MN 56721

TEL: (218) 773-1185

Project Name/ID: 1995 Assessment Job No. 2 East Grand Forks, MN Construction Year: 19 95

GENERAL DESIGN INFORMATION:

PCC slab thickness: ___5in, ___6in, [✓ 7in], ___8in, ___9in, ___Other (specify): ___

Joint spacing: [✓ 15ft], ___17ft, ___20ft, Other (specify):___. Shoulder type: ___Aggregate, ___Asphalt Concrete, ___Tied PCC, Other (specify): Non-reinforced Concrete

Dowel Diameter (if used): ___1.25in, ___1.5in, ___1.75in, Other (specify): ___

PCC Strength (psi): [✓ 3900 Design], ___ From laboratory testing, Other: ___

Base thickness: 2 inches, Base Type: Class 5 aggregate base

Subgrade type: clay, clay - loam

Drainage Type: Concrete curb & Gutter and Storm Sewer

TRAFFIC INFORMATION:

___ Initial ADTs, ___Most current ADTs, ___ % Truck traffic

PAVEMENT PERFORMANCE HISTORY:

Construction Year: 19 95, Major maintenance or rehabilitation performed? ___Yes, [✓ No]

If yes, when and why? ___

% Cracking observed before major maintenance: ___30%, ___35%, ___40%,

Other (specify): ___

Faulting observed before major maintenance: ___1/4-in, ___1/2-in, ___3/4-in, Other (specify): ___

COMMENTS: Traffic Information and performance history is not available.

Note: Please attach typical PCC section plans.

Figure 3.2. Sample of Minnesota low-volume road survey questionnaire

Table 3.1. Summary of Requests for Information.

Agency	**District**	**Contact person**	**Status of the request**
City of Owatonna – Department of Transportation	6	Jeff Johnson (City Engineer)	Completed
Waseca County – Highway Department	7	Jeff Blue (County Engineer)	Completed
Ramsey County – Highway Department	Metro Area	Kathy Jaschke (Public Works Dept.)	Completed
Olmsted County – Highway Department	6	Curt Bolles (Construction Supervisor)	Not responded
City of Moorhead – Department of Transportation	4	Clair Hanson (Public Works Dept.)	Completed
City of E. Grand Forks – Consulting Engineers: Floan-Sanders, Inc.	2	Tom Stenseth	Completed
City of White Bear Lake – Department of Transportation	Metro Area	Mark Burch (City Engineer)	Do not maintain pavement design data
City of Rochester – Department of Transportation	6	Russ Kelm (Design Engineer)	Completed
MN Department of Transportation (Office of Materials - Maplewood)	Metro Area	Tom Burnham (Research Engineer)	Completed

Table 3.2. Summary of design parameters in current practice by local agencies

Agency Name	PCC Slab Thickness (in)	PCC Design Strength (psi)	Base Properties	Subgrade Type	Drainage Type and Conditions	Joint Spacing	Shoulder Type	Traffic (ADT)	Performance Criteria
City of Owatonna	8	3,900	6" (class 2)	Clay	Perforated Pipes	16-ft (max) (doweled)	no shoulder (curb & gutter)	1,950	Crack: 30% Fault : NA
Waseca County	6 to 8, 8-6-8, 9-7-9	3,900	4-6 in (class 5)	Clay, Clay-Loam	NA	15-ft effective; 13-16-14-17 ft (skewed & un-doweled)	Class 2 & 3 type AGG or crushed bituminous asphalt	350 to 2,550	Crack:30%-40%
City of Moorhead	8 and 9	3,900	6" & 8" (class 5)	Clay	4" & 6" drain tiles	15-ft (max) (doweled-1.25-in)	Tied PCC, curb & gutter	11,500 & 14,500	Crack: 40%
City of E. Grand Forks	7	3900	2" & 5" (Class 5)	Clay, Clay-Loam	Storm sewer, curb & gutter	10 to 15-ft (un-doweled)	PCC	3,600	Crack: NA
City of Rochester	8.5	3,900 (average field strength is 5,300)	5" (Class 2)	12-in (select granular borrow modified)	NA	12-ft (doweled-1.25-in)	Tied PCC	9,820 & 18,640	Engineering judgment/field visits
Ramsey County	7.5, 8, and 9	3,900	4" & 5" (Class 5, 6, and 7)	6-in & 2-ft (granular material)	Storm sewer	15-ft (effective) & 20-ft (doweled-1.25-in)	Tied PCC	3,850 to 34,600	Crack: < 30% Fault : < 0.25-in Engineering judgment/ overlays
Mn/DOT	7 and 7.5	3,900	2",3" & 5" (Class 5)	Clay, Clay-Loam	NA	15-ft & 27-ft (doweled - 1 to 1.25 in)	AGG & bituminous asphalt	1,400 to 8,200	Engineering judgment/field visits

3.3 Design Practices of Individual Agencies

This section presents design practices of the individual agencies that responded to the questionnaire.

3.3.1 City of Owatonna

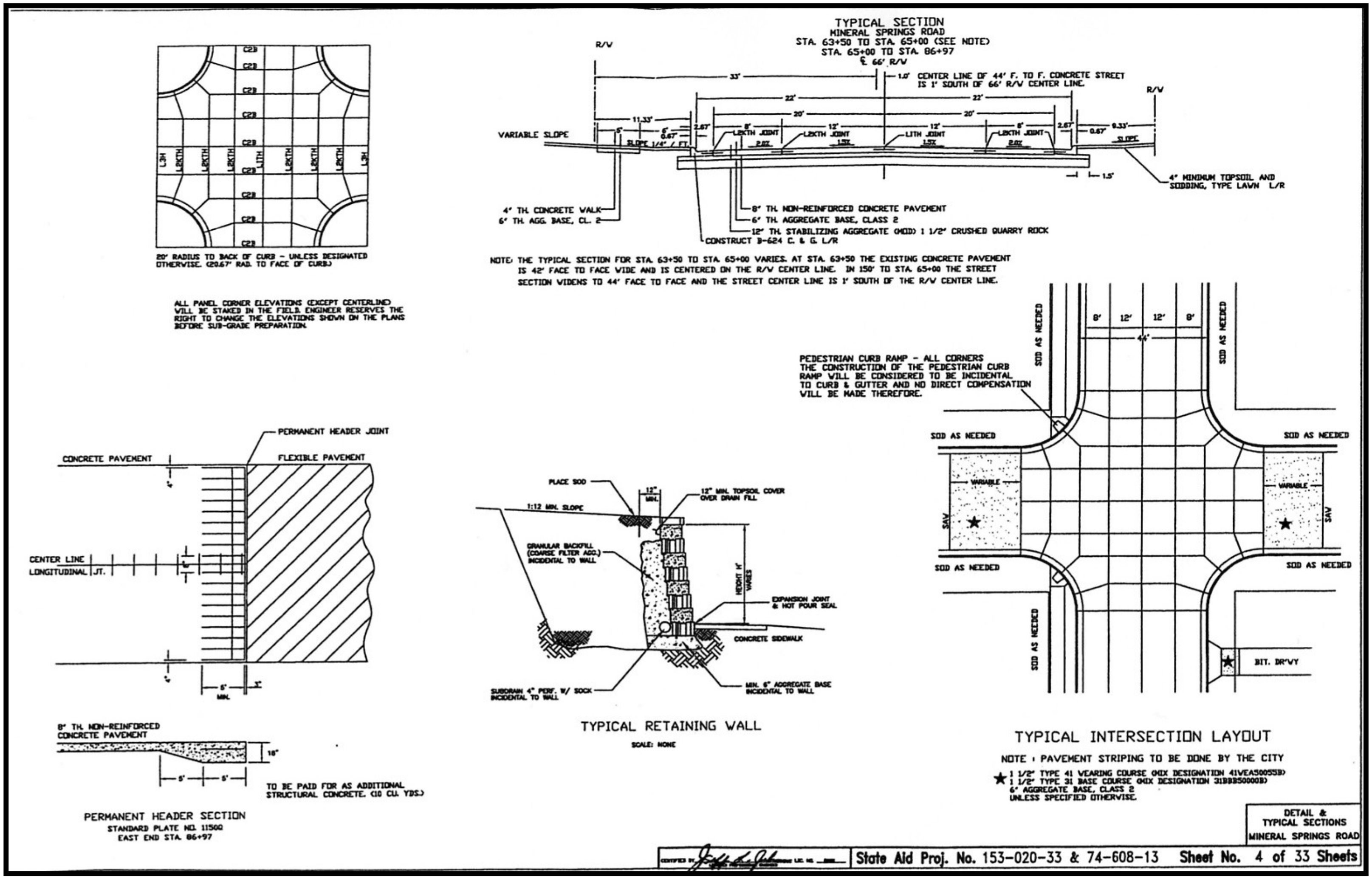
The city of Owatonna is located in the southeast climatic zone of Minnesota, approximately 67 miles south of Minneapolis near interstate highway I-35. In 2003 the city of Owatonna had more than 27 miles of concrete pavements. A typical PCC pavement in Owatonna is 8 in. thick, doweled, and has a 6-in base layer of Class 2 aggregate on top of 12-in of stabilizing aggregate over a clay subgrade. The joint spacing does not exceed 16 ft. The pavements do not have dedicated shoulders, but PCC curbs and gutters serve as tied PCC shoulder. Perforated pipes are used for drainage.

The PCC mixes are designed to satisfy Mn/DOT specifications, including a design compressive strength of 3900 psi. Figure 3.3 presents a typical low-volume road construction plan. It shows a typical pavement cross-section and an intersection layout.

A properly constructed PCC pavement is expected to serve for up to 50 years in the city of Owatonna without any major rehabilitation. Pavement maintenance and rehabilitation tasks are based upon engineering judgments and are performed as needed. Although no strict guidelines are available, cracking of more than 30 percent of PCC slabs constitutes the end of the performance period and triggers major rehabilitation or reconstruction. Faulting is not a major problem in Owatonna, except on truck routes.

3.3.2 Waseca County

Waseca County is also located in the southeast climatic zone of Minnesota, west of Owatonna, and approximately 79 miles south of Minneapolis near interstate highway I-35. From 1975 to 2001, more than 50 miles (25 projects) of concrete roads were constructed in Waseca County. The pavements are undoweled and, in most cases, PCC thickness varies with respect to traffic volume and ranges from 6 in. to 8 in. In some other cases, the PCC slab thickness varies from the pavement edge to the pavement center line, typically 8”-6”-8” or 9”-7”-9”. The pavements have 4 in. to 6 in. of class 5 aggregate base on top of clay or clay-loam subgrade. Pavements constructed on the County State Aid Highway (CSAH) in 1975-1976 used a 20-ft skewed, undoweled joint spacing. Concrete pavements placed from 1980 to 2000 used a 15-ft effective skewed, undoweled random joint spacing (13’, 16’, 14’, and 17’). The pavements have 3 in. to 5 ½ in. class 2 and 3 type aggregate shoulders or crushed salvaged bituminous pavement.


TYPICAL SECTION
MINERAL SPRINGS ROAD
STA. 63+50 TO STA. 65+00 (SEE NOTE)
STA. 65+00 TO STA. 86+97
℄ 66' R/W

CENTER LINE OF 44' F. TO F. CONCRETE STREET IS 1' SOUTH OF 66' R/W CENTER LINE.

NOTE: THE TYPICAL SECTION FOR STA. 63+50 TO STA. 65+00 VARIES. AT STA. 63+50 THE EXISTING CONCRETE PAVEMENT IS 42' FACE TO FACE WIDE AND IS CENTERED ON THE R/W CENTER LINE. IN 150' TO STA. 65+00 THE STREET SECTION WIDENS TO 44' FACE TO FACE AND THE STREET CENTER LINE IS 1' SOUTH OF THE R/W CENTER LINE.

20' RADIUS TO BACK OF CURB - UNLESS DESIGNATED OTHERWISE. (20.67' RAD. TO FACE OF CURB.)

ALL PANEL CORNER ELEVATIONS (EXCEPT CENTERLINE) WILL BE STAKED IN THE FIELD. ENGINEER RESERVES THE RIGHT TO CHANGE THE ELEVATIONS SHOWN ON THE PLANS BEFORE SUB-GRADE PREPARATION.

PEDESTRIAN CURB RAMP - ALL CORNERS
THE CONSTRUCTION OF THE PEDESTRIAN CURB RAMP WILL BE CONSIDERED TO BE INCIDENTAL TO CURB & GUTTER AND NO DIRECT COMPENSATION WILL BE MADE THEREFORE.

TYPICAL RETAINING WALL
SCALE: NONE

TYPICAL INTERSECTION LAYOUT

NOTE : PAVEMENT STRIPING TO BE DONE BY THE CITY

★ 1 1/2" TYPE 41 WEARING COURSE (MIX DESIGNATION 41WEA50055B)
1 1/2" TYPE 31 BASE COURSE (MIX DESIGNATION 31BBB50000B)
6" AGGREGATE BASE, CLASS 2
UNLESS SPECIFIED OTHERWISE.

TO BE PAID FOR AS ADDITIONAL STRUCTURAL CONCRETE. (10 CU. YDS.)

PERMANENT HEADER SECTION
STANDARD PLATE NO. 1150Q
EAST END STA. 86+97

DETAIL & TYPICAL SECTIONS
MINERAL SPRINGS ROAD

State Aid Proj. No. 153-020-33 & 74-608-13 Sheet No. 4 of 33 Sheets

Figure 3.3. Typical PCC pavement construction plan for City of Owatonna.

The county's PCC mix meets Mn/DOT specifications, including design compressive strength of 3900 psi. Figure 3.4 presents a typical low-volume road construction plan. This plan shows a typical pavement cross-section, pavement detail, and joints layout.

Traffic information obtained from a traffic count conducted in 1999 ranges from 350 to 2550 ADT for different sites.

A properly constructed PCC pavement is expected to serve for up to 40 years in Waseca County. Pavement maintenance and rehabilitation tasks are based upon the performance criteria established for cracking of 20%-25% and are performed as needed.

3.3.3 City of Moorhead

The city of Moorhead is located in the Northwest climatic zone of Minnesota, approximately 232 miles northwest of Minneapolis near Fargo, ND. Mr. Claire Hanson from the Public Works Department was contacted to obtain the required information regarding low-volume PCC roads in Moorhead. He provided detailed information on three typical PCC pavements constructed in 1973, 1987, and 2003.

Typical PCC pavements in the city of Moorhead are 8 in. or 9 in. thick. They usually have a 6-in. or 8-in. base layer of Class 5 aggregate on top of a clay subgrade or 6 in. of granular borrow soil. The joints are doweled with spacing equal to 15 ft. The dowel diameter is 1.25 in. The pavements do not have dedicated shoulders, but PCC curbs and gutters serve as tied PCC shoulder. 4-in. and 6-in. drain tiles are used for drainage. Figure 3.5 presents a typical low-volume road construction drawing.

The city's PCC mix meets Mn/DOT specifications, including design compressive strength of 3900 psi. Most current ADT ranges from 11500 to 14500. Table 3.3 provides an example of design traffic and ESALs calculation for a typical design of a low-volume road in Moorhead.

Pavement maintenance and rehabilitation tasks are based upon engineering judgments and are performed as needed. Although no strict guidelines are available, cracking of more than 40 percent of PCC slabs constitutes the end of the performance period and triggers major rehabilitation or reconstruction. However, no major pavement rehabilitation task has been performed in the city of Moorhead to date.

Table 3.3 Example of design traffic for the City of Moorhead

Vehicle Class	AADT Current	Base Year	Ridged ESAL	Base Year	Design Year	Design
Car	0.757	8,554.10	0.0007	5.9879	15,519.00	10.86
Pick Up	0.160	1,808.00	0.0007	1.27	3,280.00	2.30
SU 2 Ax 4 Tires	0.024	271.20	0.0007	0.19	492.00	0.34
SU 2 Ax 6 Tires	0.026	293.80	0.2400	70.56	533.00	127.92
SU3+Ax	0.017	192.10	0.8400	161.28	349.00	293.16
TST3Ax		0.00				0.00
TST4AX	0.001	11.30	0.5300	5.83	21.00	11.13
TST5Ax	0.005	56.50	1.8900	107.73	102.00	19278
TST6AX		0.00				0.00
Twin Trailers/Buses	0.010	113.00	0.7400	83.62	205.00	151.70
TOTAL		11,300.00		436.47	20,501.00	790.19

(Base Year ADL + Design Year ADL) / 2 = (436 + 790) / 2 = 613

Number of days in 20 years x 365 = 7300

7300 x 613 = 4,474,900

Design Lane Factor = 1 @ 4,474,900 = 4,474,900

Load Limit Increase Factor x 4,474,900 = 1.12 x 4,474,900 = 5.011,888

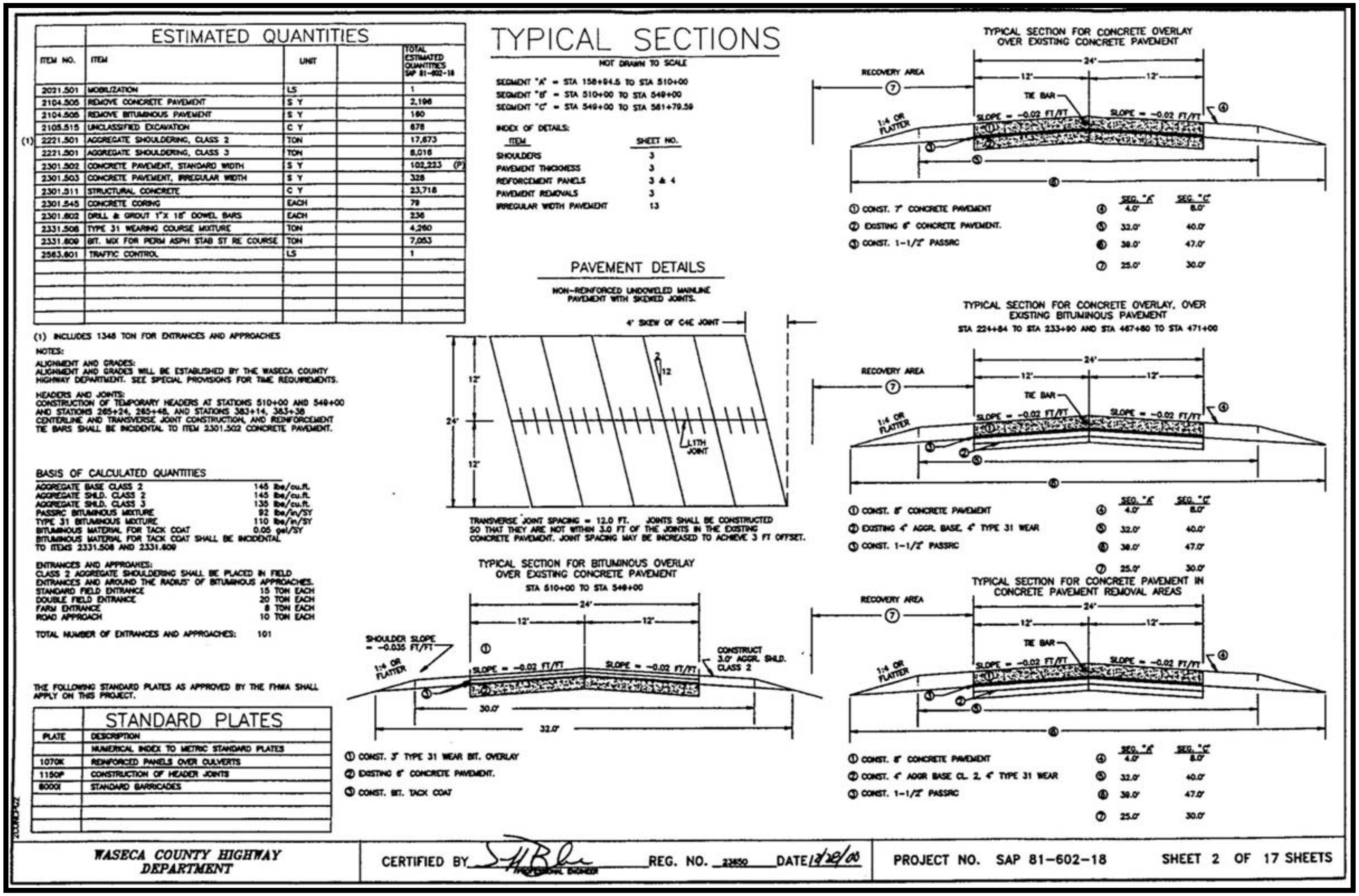
Subgrade = R7

Cumulative 20-Year Design Lane ESAL (rounded) = 5,000,000

CRITERIA:

Rigid ESAL Factors 4-4.0 (9)

2000 Traffic Count & SRF Report for 2020 Design Year.



ESTIMATED QUANTITIES

	ITEM NO.	ITEM	UNIT		TOTAL ESTIMATED QUANTITIES SAP 81-602-18
	2021.501	MOBILIZATION	LS		1
	2104.505	REMOVE CONCRETE PAVEMENT	S Y		2,196
	2104.505	REMOVE BITUMINOUS PAVEMENT	S Y		160
	2105.515	UNCLASSIFIED EXCAVATION	C Y		678
(1)	2221.501	AGGREGATE SHOULDERING, CLASS 2	TON		17,673
	2221.501	AGGREGATE SHOULDERING, CLASS 3	TON		8,016
	2301.502	CONCRETE PAVEMENT, STANDARD WIDTH	S Y		102,223 (P)
	2301.503	CONCRETE PAVEMENT, IRREGULAR WIDTH	S Y		328
	2301.511	STRUCTURAL CONCRETE	C Y		23,718
	2301.545	CONCRETE CORING	EACH		79
	2301.602	DRILL & GROUT 1"X 18" DOWEL BARS	EACH		236
	2331.508	TYPE 31 WEARING COURSE MIXTURE	TON		4,260
	2331.609	BIT. MIX FOR PERM ASPH STAB ST RE COURSE	TON		7,053
	2563.601	TRAFFIC CONTROL	LS		1

(1) INCLUDES 1348 TON FOR ENTRANCES AND APPROACHES

NOTES:

ALIGNMENT AND GRADES:
ALIGNMENT AND GRADES WILL BE ESTABLISHED BY THE WASECA COUNTY HIGHWAY DEPARTMENT. SEE SPECIAL PROVISIONS FOR TIME REQUIREMENTS.

HEADERS AND JOINTS:
CONSTRUCTION OF TEMPORARY HEADERS AT STATIONS 510+00 AND 549+00 AND STATIONS 265+24, 265+48, AND STATIONS 383+14, 383+38 CENTERLINE AND TRANSVERSE JOINT CONSTRUCTION, AND REINFORCEMENT TIE BARS SHALL BE INCIDENTAL TO ITEM 2301.502 CONCRETE PAVEMENT.

BASIS OF CALCULATED QUANTITIES

AGGREGATE BASE CLASS 2	145 lbs/cu.ft.
AGGREGATE SHLD. CLASS 2	145 lbs/cu.ft.
AGGREGATE SHLD. CLASS 3	135 lbs/cu.ft.
PASSRC BITUMINOUS MIXTURE	92 lbs/in/SY
TYPE 31 BITUMINOUS MIXTURE	110 lbs/in/SY
BITUMINOUS MATERIAL FOR TACK COAT	0.05 gal/SY

BITUMINOUS MATERIAL FOR TACK COAT SHALL BE INCIDENTAL TO ITEMS 2331.508 AND 2331.609

ENTRANCES AND APPROAHES:
CLASS 2 AGGREGATE SHOULDERING SHALL BE PLACED IN FIELD ENTRANCES AND AROUND THE RADIUS' OF BITUMINOUS APPROACHES.

STANDARD FIELD ENTRANCE	15 TON EACH
DOUBLE FIELD ENTRANCE	20 TON EACH
FARM ENTRANCE	8 TON EACH
ROAD APPROACH	10 TON EACH

TOTAL NUMBER OF ENTRANCES AND APPROACHES: 101

THE FOLLOWING STANDARD PLATES AS APPROVED BY THE FHWA SHALL APPLY ON THIS PROJECT.

STANDARD PLATES

PLATE	DESCRIPTION
	NUMERICAL INDEX TO METRIC STANDARD PLATES
1070K	REINFORCED PANELS OVER CULVERTS
1150P	CONSTRUCTION OF HEADER JOINTS
8000I	STANDARD BARRICADES

TYPICAL SECTIONS

NOT DRAWN TO SCALE

SEGMENT "A" = STA 158+94.5 TO STA 510+00
SEGMENT "B" = STA 510+00 TO STA 549+00
SEGMENT "C" = STA 549+00 TO STA 581+79.59

INDEX OF DETAILS:

ITEM	SHEET NO.
SHOULDERS	3
PAVEMENT THICKNESS	3
REINFORCEMENT PANELS	3 & 4
PAVEMENT REMOVALS	3
IRREGULAR WIDTH PAVEMENT	13

PAVEMENT DETAILS

NON-REINFORCED UNDOWELED MAINLINE PAVEMENT WITH SKEWED JOINTS.

TRANSVERSE JOINT SPACING = 12.0 FT. JOINTS SHALL BE CONSTRUCTED SO THAT THEY ARE NOT WITHIN 3.0 FT OF THE JOINTS IN THE EXISTING CONCRETE PAVEMENT. JOINT SPACING MAY BE INCREASED TO ACHIEVE 3 FT OFFSET.

TYPICAL SECTION FOR BITUMINOUS OVERLAY OVER EXISTING CONCRETE PAVEMENT

STA 510+00 TO STA 549+00

① CONST. 3" TYPE 31 WEAR BIT. OVERLAY
② EXISTING 6" CONCRETE PAVEMENT.
③ CONST. BIT. TACK COAT

TYPICAL SECTION FOR CONCRETE OVERLAY OVER EXISTING CONCRETE PAVEMENT

① CONST. 7" CONCRETE PAVEMENT
② EXISTING 6" CONCRETE PAVEMENT.
③ CONST. 1-1/2" PASSRC

	SEG. "A"	SEG. "C"
④	4.0'	8.0'
⑤	32.0'	40.0'
⑥	39.0'	47.0'
⑦	25.0'	30.0'

TYPICAL SECTION FOR CONCRETE OVERLAY, OVER EXISTING BITUMINOUS PAVEMENT

STA 224+84 TO STA 233+90 AND STA 467+80 TO STA 471+00

① CONST. 8" CONCRETE PAVEMENT
② EXISTING 4" AGGR. BASE, 4" TYPE 31 WEAR
③ CONST. 1-1/2" PASSRC

	SEG. "A"	SEG. "C"
④	4.0'	8.0'
⑤	32.0'	40.0'
⑥	39.0'	47.0'
⑦	25.0'	30.0'

TYPICAL SECTION FOR CONCRETE PAVEMENT IN CONCRETE PAVEMENT REMOVAL AREAS

① CONST. 8" CONCRETE PAVEMENT
② CONST. 4" AGGR BASE CL. 2, 4" TYPE 31 WEAR
③ CONST. 1-1/2" PASSRC

	SEG. "A"	SEG. "C"
④	4.0'	8.0'
⑤	32.0'	40.0'
⑥	39.0'	47.0'
⑦	25.0'	30.0'

WASECA COUNTY HIGHWAY DEPARTMENT

CERTIFIED BY ____ PROFESSIONAL ENGINEER REG. NO. 23850 DATE 12/28/00

PROJECT NO. SAP 81-602-18

SHEET 2 OF 17 SHEETS

Figure 3.4. Typical PCC pavement construction plan for Waseca County.

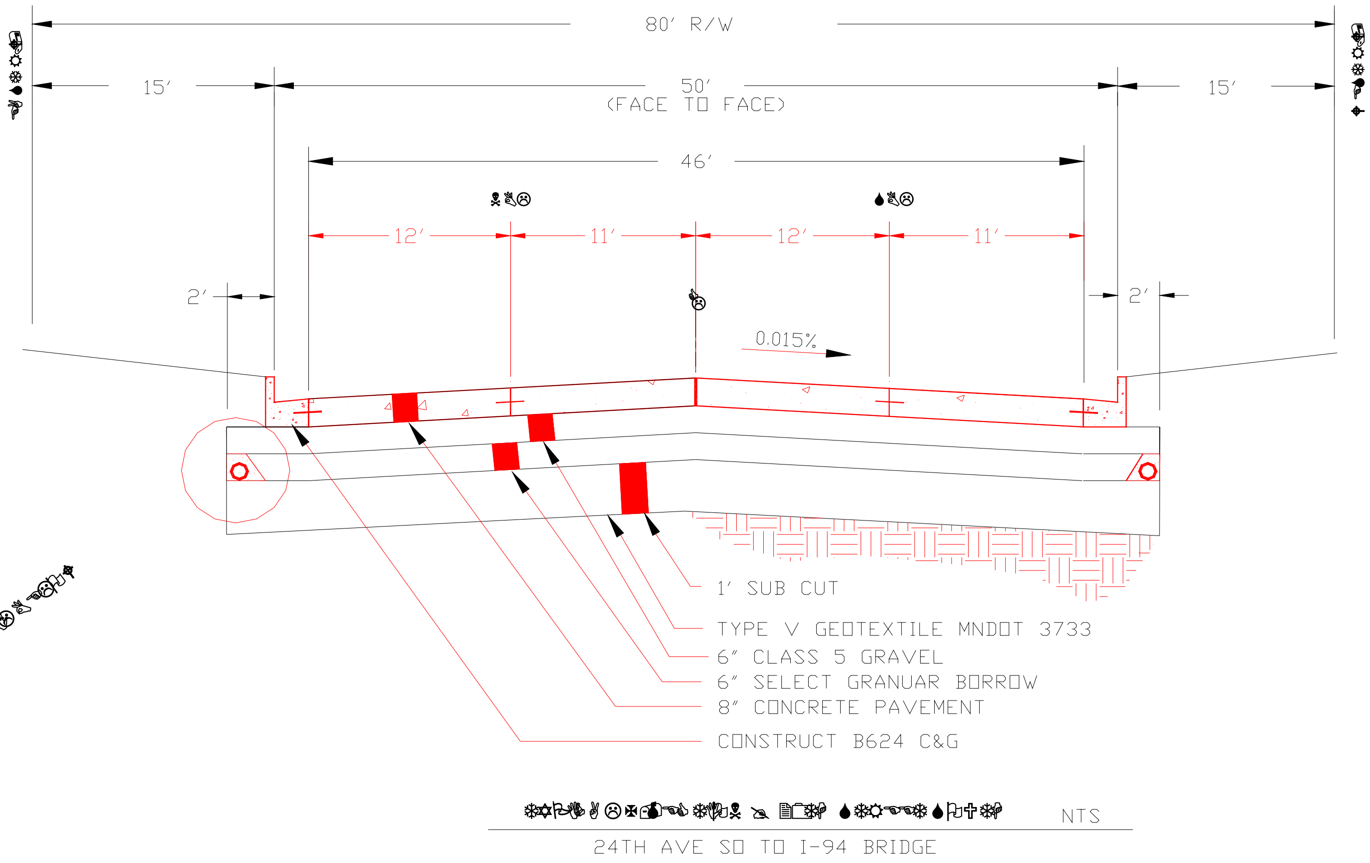


Figure 3.5. Typical PCC pavement cross-section for the City of Moorhead

3.3.4 City of E. Grand Forks

The city of East Grand Forks is also located in the northwest climatic zone of Minnesota, approximately 316 miles northwest of Minneapolis and north of Fargo, ND, near the North Dakota/Minnesota border. Mr. Tom Stenseth from Floan-Sanders, Inc. was contacted to obtain the required information on low-volume roads in the city of E. Grand Forks. He supplied information on nine typical PCC pavements constructed from 1995 to 2003.

A typical PCC pavement in E. Grand Forks is 7 in. thick, undoweled, and has a 2-in. or 5-in. base layer of Class 5 aggregate over a clay or clay-loam subgrade. The joint spacing ranges from 10 to 15 feet. The pavements do not have dedicated shoulders, but PCC curbs and gutters serve as PCC shoulders. Storm sewers, curbs, and gutters serve as drainage.

The city's PCC mix meets Mn/DOT specifications, including design compressive strength of 3900 psi. Figure 3.6 presents a typical low-volume road construction plan. It shows a typical pavement cross-section, accessible ramp detail, standard joint detail, intersection layout, and curb and gutter layout.

ADT is 3600 for typical low-volume roads.

Pavement maintenance and rehabilitation tasks are based upon engineering judgments and are performed as needed. No strict guidelines are available for cracking and faulting of PCC slabs that would constitute the end of the performance period and trigger major rehabilitation or reconstruction.

3.3.5 City of Rochester

The city of Rochester is located in the southeast climatic zone of Minnesota, approximately 83 miles south of Minneapolis. A design engineer, Mr. Russell Kelm, was asked to provide information regarding low-volume roads in the city of Rochester. He supplied the detailed information on two recently constructed projects in the city of Rochester.

A typical PCC pavement in Rochester is 8.5 in. thick with 1.25 in. dowel bars. It has a 5-in. base layer of Class 2 material on top of 12 in of select granular borrow soil (sand-bed) over a clay subgrade, to provide a 2-ft frost-free permeable zone section. Granular borrow soils are in accordance with the Mn/DOT provision 2105 and 3149. The pavements have dedicated tied PCC shoulders.

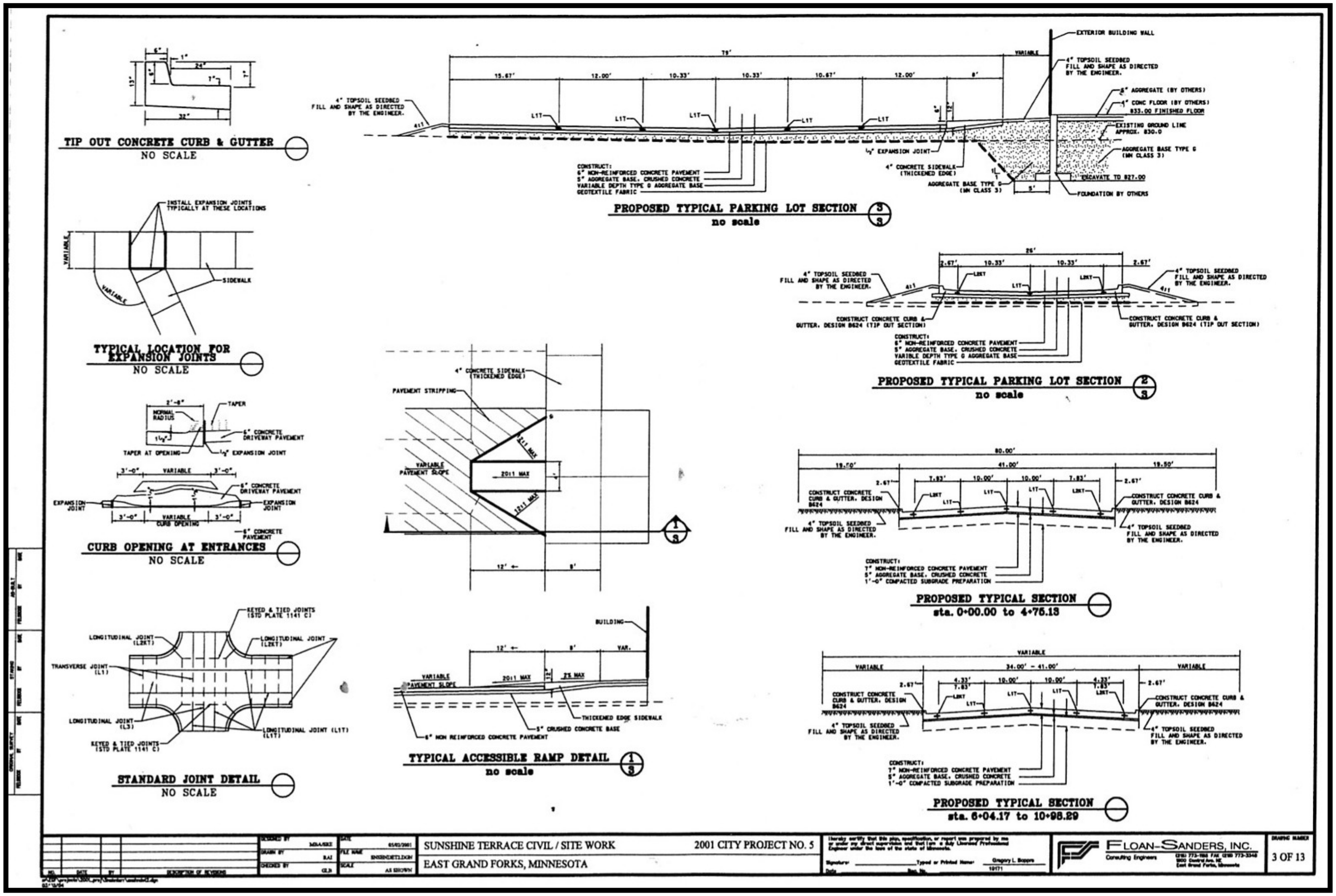


Figure 3.6. Typical PCC pavement construction plan for the City of E. Grand Forks.

The city's PCC mix meets Mn/DOT specifications, including design compressive strength of 3900 psi, but the field-observed average concrete compressive strength is 5300 psi. Construction plans for the city of Rochester are not available.

ADT available for two typical low-volume roads project sites is 9820 and 18640 ADT, and heavy commercial average daily traffic (HCADT) is 490 and 1099. Design loading is 9-10 tons.

A properly constructed PCC pavement is expected to serve the city for 35 to 50 years. Pavement maintenance and rehabilitation tasks are based upon field visits and engineering judgments and are performed as needed. No strict guidelines are available for cracking and faulting of PCC slabs that would constitute the end of the performance period and trigger major rehabilitation or reconstruction. Major maintenance and rehabilitation tasks consist of grinding of faults, joint and crack repair and sealing, and panel replacement.

3.3.6 Ramsey County

Ramsey County is located in the central climatic zone of Minnesota, approximately 14 miles north of Minneapolis near the interstate highway I-694. A typical PCC pavement in Ramsey County ranges from 7.5 in. to 9 in. thick. The most typical slab thickness is 8 in. with 1.25-in. dowel bars. Ramsey County has more than 30 miles of PCC pavement. It has 4-in. or 5-in. base layers of class 5, 6, or 7 aggregate over 6 in. or 2 ft of select granular material. The joint spacing ranges from 15 ft (effective) to 20 ft. The pavements have tied PCC shoulders and storm sewers serve as drainage. The county's PCC mix meets Mn/DOT specifications, including design compressive strength of 3900 psi.

Ramsey County PCC pavement history is included in table 3.4. Pavement construction years range from 1964 to 2000. AADT (Annual Average Daily Traffic) available for several projects and sites ranges from 3850 to 34600.

A properly constructed PCC pavement is expected to serve the county for 30 to 40 years. Pavement maintenance and rehabilitation tasks are based upon engineering judgments and are performed as needed. Although no strict guidelines are available, cracking of more than 30% and faulting of more than 0.25 in. of PCC slabs would constitute the end of the performance period and trigger major rehabilitation or reconstruction. A total of three rehabilitation task histories are available, which were performed on pavements constructed in 1964, 1966, and 1970. Typically, rehabilitation consists of a bituminous layer being placed over an existing concrete pavement.

3.3.7 Minnesota Department of Transportation (Mn/DOT)

Mn/DOT's Office of Materials provided information regarding pavement selection process and design standards that are currently in practice by the agency. Mn/DOT follows design standards outlined in TM (Technical Memo) No. 04-06-MAT-01.

A typical PCC pavement ranges from 7.0-in. to 9-in. PCC slabs. Typical thicknesses are 7 in. and 7.5 in. with 1-in. to 1.25-in. dowel bars. It has 2-in, 3-in. or 5-in. base layer of class 5 aggregate. Under certain conditions, Mn/DOT also uses 36-in. select granular material or 3 in. of class 3 aggregate subbase. Soil types are A-6 and A-7-6 (based on AASHTO Soils Classification), which are clay-loam and clay. Subgrade R-Values obtained using stabilometer, typically have values of 8, 10, 12, and 20. Typical non-skewed joint spacing is 15 ft, but a joint spacing of up to 27 ft has been used with skewed joints. Shoulders for the pavements are constructed with bituminous, aggregate, and/or with a combination of both. Lane design consists of two 13.5-ft lanes for 2-lane, 2-way road and 13-ft and 14-ft lanes for multi-lane divided roadways. Elastic modulus of 4,200 ksi and modulus of rupture of 500 psi is typically used for PCC properties required for the design.

AADT obtained ranges from 1,400 to 8,200 and HCAADT ranges from 180 to 460 for typical low-volume roads.

Pavement maintenance and rehabilitation tasks are based upon engineering judgments and are performed as needed. No strict guidelines are available for cracking and faulting of PCC slabs that would constitute the end of the performance period and trigger major rehabilitation or reconstruction.

Table 3.4 List of PCC pavement projects in Ramsey County.

Ramsey County Public Works

Concrete Paving History

Road	Termini	Road No.	Thickness	Width(ft)	Length (miles)	Year Paved	AADT	Comments
County Road B	Snelling Avenue to Lexington Avenue	25	8" Reinforced	v 48-58	0.967	1966	12500	Rehab 2002
County Road C	West County Line to 2090 Co. Rd. C	23	9" Reinforced	70	0.957	1979	16650	
County Road C	2090 Co Rd. C to Snelling Avenue	23	8" Reinforced	48	1.078	1963	17100	
County Road I	Highway 10 to 507 west of I35W ramp	3	7"	50	0.940	1987	4350	
Fairview Avenue	651' So of Cy Rd C to 2720 Fairview	48	8" Reinforced	51	0.242	1968	16300	
Highway 88	West County Line to Co. Rd. D	88	8"	88	0.905	1965	12350	
Highway 96	275' W of Lexington to Mackubin	96	200mm	v89-107	1.253	1998	24150	
Highway 96	MacKubin to 755' W of Rice	96	200mm	v89-104	0.941	2000	19100	
Highway 96	755' W of Rice to 1330 W of McMenemy	96	200mm	67	0.825	1999	16800	
Highway 96	1330' W of McMenemy to 190' E of Brblwd	96	200mm	90	1.114	1998	17950	
Highway 96	190' E of Brblwd to 35E ramps	96	200mm	v93-105	0.711	2000	34600	
Highway 96	White Bear Parkway to Otter Lake Road	96	8"	85	0.687	1995	22550	
Highway 96	Otter Lake Road to TH 61	96	7"	60	0.963	1996	16550	
Larpenteur Avenue	Malvern to Cleveland	30	200mm	66	0.81	1997	14550	
Larpenteur Avenue	Cleveland to 295' W of Snelling	30	200mm	77	0.994	1998	16950	
Larpenteur Avenue	Arona to Oxford	30	200mm	70	0.96	2000	16900	
Larpenteur Avenue	Oxford to Dale	30	9"	66	0.89	1958	15900	
Larpenteur Avenue	White Bear Avenue to Van Dyke Street	30	8"	64	0.127	1969	7900	
North Saint Paul Road	White Bear Avenue to Ripley	29	8"	51	0.312	1969	3850	
Parkway Drive	Larpenteur to 61	27	8"	44	0.124	1964	9300	
White Bear Avenue	Larpenteur Avenue to Frost Avenue	65	8"	66	0.5	1993	23050	
White Bear Avenue	Frost to TH 36	65	7.5"	51	0.93	1964	29850	
White Bear Avenue	TH 36 to Beam Avenue	65	8"	V48-60	1.095	1964	29850*	
White Bear Avenue	Beam Avenue to County Road E	65	8"	v55-76	1.484	1969	32900	
White Bear Avenue	County Road E to TH 61	65	8"	55	2.111	1970	10050	Rehab 1986

******C to White Bear Court Rehabbed in 1997*

Ramsey County Road Miles

County State Aid Highway			County Road		
Bituminous	222.0	miles	Bituminous	28.2	miles
Concrete	31.1	miles	Concrete	0.2	miles
Bituminous Over Conrete	19.6	miles	Bituminous Over Conrete	1.4	miles
Total	272.6	miles	Total	29.7	miles

Chapter 4

Sensitivity Analysis Using MEPDG Software

4.1 Introduction

This chapter summarizes the results of sensitivity runs using the MEPDG software version 0.861 for typical Minnesota low-volume road site conditions and a wide range of portland cement concrete (PCC) pavement design features (layer thickness, material properties, shoulder types, load transfer mechanisms, etc.). This sensitivity study had the following objectives:

- Classify the design inputs in order of their effect on predicted pavement performance and determine the level of detail actually required for the numerous inputs to the program performance prediction models.
- Evaluate if the predicted pavement performance falls within the expected limits and if the performance trends (change in predicted performance with change in design features) are reasonable.

4.2 Research Methodology

A factorial of MEPDG runs was conducted to evaluate predictions of the MEPDG software for Minnesota low-volume road conditions. The sensitivity analyses were performed by changing one parameter (for example, traffic level, PCC thickness, or subgrade type) at a time from one run to the next while limiting others to a constant value. The following is the list of MEPDG software design factors that were considered in the sensitivity analysis:

- Traffic volume
- Coefficient of thermal expansion (COTE) of PCC
- Modulus of rupture of PCC (MR)
- Base thickness
- Base type
- Subgrade type
- Joint spacing
- Edge support
- Slab width

- Dowel diameter

4.3 Description of Sensitivity Runs

Sensitivity analysis was conducted in two phases. In the first phase of simulation, 84 basic MEPDG projects were created using the inputs shown in Table 4.1. In the second phase, 48 runs for each project were performed in a batch mode. The factorials of design features and input parameters shown in Table 4.2 were analyzed.

After all the cases were screened, Excel macro based programming codes were used to plot the cracking and faulting output results in the Excel chart format.

Table 4.1. Factorial of input parameters – Phase 1

Parameter	Cases	Description
PCC thickness, in	4	6 7 8 9
Base Thickness, in	3	6 18 48
Base type	2	A-1-a A-1-b
Subgrade type	2	A-3 A-6

4.4 Sensitivity Analysis

Preliminary sensitivity analysis was performed by comparing the cracking and faulting predictions for the pavement sections with all but one of the design features or site conditions remaining constant. Over 1200 and 4800 charts for cracking and faulting predictions, respectively, were developed based on the sensitivity data runs. 28 predicted cracking charts and 30 predicted faulting charts were selected to represent different parameters. Table 4.3 presents the list of parameters that were used to determine trend lines separately for cracking and faulting development for each of the seven PCC thicknesses.

Table 4.2. Factorial of input parameters – Phase 2

Parameter	Cases	Description
PCC modulus of rupture	1	700 psi
PCC coefficient of thermal expansion, in/in/ °F	3	4.8×10^{-6} 5.5×10^{-6} 6.7×10^{-6}
Joint spacing, ft	2	15 20
Slab width, ft	2	12 13.5
Shoulder type	2	PCC AC
Dowel diameter, in	4	No Dowels 1 1.25 1.5
Traffic AADTT	3	30 300 1200

Table 4.3. List of Parameters used to determine trend lines for cracking and faulting

Distress Type	**Number of Parameters**	**Parameters**
Cracking	6	Traffic volume PCC coefficient of thermal expansion Base thickness Base & subgrade material (Combined) Joint spacing Edge support & slab width (Combined)
Faulting	7	Traffic volume Dowel diameter PCC coefficient of thermal expansion Base thickness Base & subgrade material (Combined) Joint Spacing Edge support & slab width (Combined)

4.5 PCC Pavements Cracking Analysis

The design input parameters used for the analysis shown in Table 4.4 remained the same for all cases unless mentioned otherwise.

Table 4.4. Design input parameters used for the analysis

Input Parameters	Values
AADTT	300
COTE	5.5E-06 in/in/^{o}F
M_R	700 psi
Base thickness	6 in
Base type	Class 5 (A-1-a material)
Slab width	12 ft
Joint spacing	15 ft
Dowel diameter	1.25 in
Shoulder type	AC
Subgrade type	A-6

4.5.1. *Effect of traffic volume on cracking*

It was found that with an increase in traffic volume, the percent of cracked slabs increased. Thinner PCC slabs were more sensitive to a lower level of traffic, whereas thicker PCC slabs were more sensitive to a higher level of traffic. This can be explained by the S-shaped form of the fatigue cracking model. When the traffic volume is low, the thicker pavements do not exhibit significant damage and it might be concluded that they are "insensitive" to traffic. Accordingly, when the traffic volume is high, then cracking of the thin slab is close to 100 percent, which makes them "insensitive" to traffic also. The charts illustrating the effect of traffic volume on cracking are presented in Figures A-1 through A-4 in Appendix A.

4.5.2. *Effect of COTE on PCC cracking*

Figures A-5 and A-6 in Appendix A present the predicted cracking for pavements with the AADTT equal to 300. The same design parameters as in previous figures were used, except for slab thickness and COTE. It was observed that an increase in COTE from 4.8E-06/^{o}F to 5.5E-06/^{o}F affected cracking growth less than an increase from 5.5E-06/^{o}F to 6.7E-

06/^{o}F. The increase in PCC slab thickness significantly decreased the maximum percentage of cracked slabs with the same COTE.

4.5.3. *Effect of base thickness on cracking*

Base thicknesses of 6, 18, and 48 inches were selected with different PCC thicknesses to perform the analysis. Figures A-7 through A-9 show the effect of base thickness on predicted cracking for the PCC thicknesses varied from 6 to 9 inches and the joint spacing of 15 ft. As expected, an increase in the base thickness leads to a decrease in the predicted cracking. There is a difference in cracking percentage for 6 to 9 in. thick slabs on a 6-in. or 18-in. base layer, but the predictions for the sections with 48-in. bases are close to zero for all PCC thicknesses.

4.5.4. *Effect of base and subgrade type on cracking*

Two types of bases (class 5 and class 3) and two types of subgrades (A-6 and A-3) were used for the analysis of foundation support. Base class 5 and class 3 were modeled using the material types A-1-a and A-1-b, respectively. Figures A-10 through A-12 in Appendix A present the results for different slab thicknesses. These figures show that the maximum percentage of cracked slabs depended on the slab thickness rather than on the type of material for the supporting layers when other parameters were fixed. The A-3 type subgrade performed better than the A-6 subgrade regardless of the base type.

4.5.5. *Effect of joint spacing on cracking*

The effect of an increase in joint spacing from 15 ft to 20 ft was analyzed. The same fixed parameters and the range of PCC slab thicknesses were used as in previous analysis. As presented in figures A-13 through A-16 (Appendix A), all pavements were predicted to have a higher level of cracking at increased joint spacing. There was a decrease in this effect for thicker pavements.

4.5.6. *Effect of edge support (shoulder type) and slab width on cracking*

The effects of shoulder type (i.e. AC, PCC) and slab widths (12-ft and 13.5-ft - widened) were evaluated. Sensitivity runs were performed for all slab thicknesses with different joint spacing. The results are presented in figures A-17 through A-20 in Appendix A. All pavements (6 to 9 in thick) with joint spacing of 15 ft exhibited the worst performance with AC shoulders and slab widths of 12 ft. The percent of cracked slabs was lower in slabs with PCC shoulders and widened slabs with no shoulders.

4.6 PCC Joint Faulting Analysis

4.6.1. Effect of traffic volume on faulting

Faulting plots were created individually for each slab thickness (6, 7, 8, and 9 in) and dowel diameter (none, 1, 1.25, and 1.5 in). Figures A-21 through A-28 in appendix A include faulting predictions for three levels of AADTT: 30, 300, and 1200. An increase in faulting was found to be directly correlated to an increase in traffic volume. The absence of dowels strengthened the effect of traffic volume growth, while an increase in slab thickness weakened such an effect.

4.6.2. Effect of dowel diameter on faulting

Dowel diameters of 0, 1, 1.25, and 1.5 in. were used for this analysis. Figures A-29 and 30 in Appendix A present the results of sensitivity runs for all 6 and 8-in thick PCC slab thicknesses. Faulting dropped significantly in slabs with dowels. There was a greater decrease in faulting for a change in dowel diameter from 1 in to 1.25 in than the decrease that occurred for a change in dowel diameter from 1.25 in to 1.5 in.

4.6.3. Effect of COTE of PCC on faulting

Analysis of figure A-31 in Appendix A presents the effect of the coefficient of thermal expansion (COTE) on predicted faulting in PCC pavements with 1.25-in dowels. Three levels of COTE (4.8E-06, 5.5E-06, and 6.7E-06 /^{o}F) were considered in the analysis. There was an observed increase in faulting with an increase in COTE.

4.6.4. Effect of base thickness on faulting

As shown in figures A-32 and A-33 in Appendix A, a change in base thickness from 6 in to 18 in did not affect the level of faulting as much as an increase from 18 in to 48 in. This trend for predicted faulting for undoweled pavements was similar to that for predicted cracking. Finally, although the effect of base thickness on faulting was found significant, it was diminished by the presence of dowels in pavements.

4.6.5. Effect of base and subgrade type on faulting

Base classes 3 and 5 and subgrade types A-3 and A-6 were used for this analysis. The results of the sensitivity runs for undoweled pavements are presented in figure A-34 in Appendix A. The plot shows no significant difference in faulting for different base and subgrade types. Nevertheless, the subgrade strength was found to have a higher effect on faulting than base quality. Overall, the effect of the strength of supporting layers on the level of predicted faulting appeared to be insignificant.

4.6.6. Effect of joint spacing on faulting

Figure A-35 presents faulting prediction with joint spacing of 15 ft and 20 ft for undoweled pavements. The other parameters were kept constant as in the previous analysis. The predicted faulting charts show that greater joint spacing resulted in higher faulting.

4.6.7. Effect of edge support (shoulder type) and slab width on faulting

As shown in figures A-36 and A-37 in Appendix A, undoweled pavements did not exhibit any visible difference in faulting at any combination of shoulder types (AC or PCC) and slab width (12 or 13.5 ft), although the use of PCC shoulders caused a decrease in faulting compared with AC shoulders for 12-ft wide slabs. As in cracking analysis, the presence of a widened slab diminishes the effect of PCC shoulders.

4.6.8. Summary of Sensitivity Analysis for Cracking and Faulting

Based on previously discussed observations, the following preliminary conclusions were drawn:

- An increase in traffic volume (AADTT) caused an increase in both cracking and faulting.

- The presence of dowels did not make a significant difference in the cracking level, but significantly decreased faulting. An increase in dowel diameter decreased faulting.

- An increase of the coefficient of thermal expansion (COTE) caused an increase in both cracking and faulting.

- An increase in the base thickness from 6 in to 18 in caused little decrease in both cracking and faulting. However, further increase in base thickness from 18 to 48 in diminished the level of both cracking and faulting to zero. This effect was stronger for undoweled pavements than for doweled ones.

- A change in base material from class 5 to class 3 and in the subgrade from A-6 to A-3 did not cause a significant difference in the level of either cracking or faulting. However, it was noticed that an increase of base strength decreased the level of cracking, while an increase in subgrade modulus caused a decrease in faulting.

- An increase in joint spacing caused an increase in both cracking and faulting, while an increase in slab thickness weakened such an effect.

- The presence of PCC shoulders affected both cracking and faulting less than the use of a widened (13.5-ft wide) slab, while both actions caused a decrease in both distress levels.

4.7 Conclusions

Over 200,000 MEPDG software simulations were run to obtain the results for predicted cracking and faulting. A large number of charts were prepared and analyzed to evaluate the trends with respect to the development of cracking and faulting and the effect of traffic volume and design features on the level of these distresses.

Based on the analysis of sensitivity curves for predicted cracking and faulting, the following conclusions were made:

- A traffic volume (AADTT) increase resulted in higher cracking and faulting.

- An increase in dowel diameter resulted in lower faulting.
- A COTE increase resulted in higher cracking and faulting.
- A base thickness increase from 6 to 18 in caused a small decrease in cracking and faulting, but an increase of the base thickness from 18 to 48 in reduced cracking and faulting close to the zero level. A stronger effect was observed for undoweled than for doweled pavements.
- The choice of base and subgrade materials did not show a significant effect on the cracking and faulting levels. Nevertheless, it was observed that a stronger base decreased cracking, while an increase in subgrade modulus reduced faulting.
- A joint spacing increase resulted in higher cracking and faulting, while an increase in slab thickness provided the opposite results.
- The presence of PCC shoulders affected both cracking and faulting less than using widened slabs. Both design features resulted in lower cracking and faulting.

Chapter 5

Prediction of Mn/Road Pavement Performance

5.1 Introduction

This chapter documents prediction of pavement performance of the low-volume PCC pavements at the Minnesota Road Research Project (MnROAD) using the MEPDG program version 0.868. Comparison is also made between predicted and measured distresses.

5.2 Description of the PCC Low-Volume Road at MnROAD

5.2.1 General Description of the Low Volume Roadway

The Low Volume Roadway (LVR) is a 2.5 mile (4.0 km) closed loop where controlled weight and traffic volume simulate conditions on rural roads. It is located 40 miles west of Minneapolis/St. Paul, and runs parallel to Interstate 94 near Otsego, Minnesota. The LVR consists of 26 pavement sections of various lengths. The sections also differ by pavement type (flexible (AC) and rigid (PCC)), and design parameters, such as layer thickness, material properties, edge support and other parameters. A detailed description of traffic and design features for PCC LVR sections is given below.

5.2.2 Traffic

LVR traffic is restricted to a MnROAD-operated 18-wheel, 5-axle tractor/trailer with two different loading configurations of 102 Kip and 80 Kip. The 102 Kip truck moves in the outer lane, while the 80 Kip truck operates in the inner lane of the loop. Annual Truck Traffic for the period between 1994 and 2002 was approximately 28,000 ESALs for each lane, as calculated from the available MnROAD data (see Figures B-1 through B-4 in Appendix B). A detailed description of axle load distribution, axle configuration and wheelbase is also given in Appendix B.

5.2.3 Design Features of PCC LVR Sections

The PCC pavements of MnROAD LVR are represented by cells 32, 36, 37, 38, 39, 40, 52, and 53.

Cells 36, 37, 38, 39, and 40 were constructed consecutively in July 1993. They have a very similar layer structure consisting of a top 6.3-6.5 inch thick PCC layer (7.6-in thick PCC layer in section 40), supported by a 5 inch thick Class 5 base layer (12 inches in cell 37), resting on a clay subgrade with an R-value of 12 (sections 38, 39, and 40) or a sandy subgrade with an R-value of 70 (cells 36 and 37). Also, cells 36 through 40 have different joint spacing, or panel length, as well as different transverse joint characteristics (presence of dowels and dowel diameter). The full list of initial design parameters for cells 36 through 40 is shown in Table 5.1.

In June 2000, unpaved cell 32 was reconstructed with full-depth reconstruction, which included partial replacement of the lower Class 1C base and Class 4 base, and full replacement of top Class 1 base layer with PCC of various thicknesses. New cells 52 and 53 replaced an AC transitional section. Table 5.2 presents the list of the initial design parameters for those cells (See also FigureB-5 in Appendix B).

Table 5.1. Initial design parameters for cells 36-40

Cell #	**36**		**37**		**38**		**39**		**40**	
Construction	Jul-93		Jul-93		Jul-93		Jul-93		Jul-93	
Slab Width, ft	12		12		12		12		12	
Panel Length,ft	15		12		15		20		15	
Dowel D, in	1		none		1		1		none	
Structure	**Material**	**h, in**	**Material**	**h, in**	**Material**	**h, in**	**Material**	**h, in**	**Material**	**h, in**
Top Layer	PCC	6.35	PCC	6.40	PCC	6.35	PCC	6.38	PCC	7.6 / 6.3
Base	Class 5	5	Class 5	12	Class 5	5	Class 5	5	Class 5	5
Subgrade R-value	70		70		12		12		12	

Table 5.2. Initial design parameters for cells 32, 52, 53

Cell #	**32**		**52**		**53**	
Construction	Jun-00		Jul-00		Aug-00	
Slab Width, ft	12		14/13		14/13	
Panel Length,ft	10		15		15	
Dowel D, in	none		1 ; 1.25		none	
Structure	**Material**	**h, in**	**Material**	**h, in**	**Material**	**h, in**
Top Layer	PCC	5	PCC	7.5	PCC	7.5
Base	Class 1	1	Class 4	5	Class 4	5
Subbase	Class 1C	6				
Subgrade R-value	12		12		12	

5.3 Research Methodology

The following steps were involved in this research to achieve the objective of Chapter 5:

1. Identify the MEPDG inputs that adequately reflect the MnROAD Low-Volume Roadway site conditions and design features.

2. Perform the MEPDG software run for each test cell to obtain predicted cracking and faulting.

3. Analyze predicted values of cracking and faulting and compare them with actual measured values.

4. Provide recommendations for local calibration of the MEPDG.

A detailed description of the procedures executed in each step of the research is provided in the next section.

5.3.1 Step1 – Identify the MEPDG inputs for the MnROAD Low-Volume Roadway

Traffic inputs

MEPDG traffic inputs were replaced with the MnROAD site specific values, which are presented in Table 5.3 and Table 5.4. The initial two-way AADTT (average annual daily truck traffic) used was 6 and 21 for the in-loop and out-loop, respectively. The other traffic data is shown below:

- Number of lanes in the design direction = 1
- Percent of trucks in the design direction = 100
- Percent of trucks in the design lane = 100
- AADTT distribution by vehicle class (Class 9) = 100 %
- Axle load distribution factors by axle type:

a- For in-loop (“80-kip” truck):

single axle – 13,000 lb

tandem axle – 36,000 lb

b- For outer lane loop (“102-kip” truck)

single axle – 13,000 lb

tandem axle – 40,000 lb and 48,000 lb

- Average axle spacing for wheelbase truck tractor = 16.9-ft with 100% trucks

Table 5.3. Hourly truck traffic distribution

Midnight	0.0%	Noon	8.3%
1:00 am	0.0%	1:00 pm	8.3%
2:00 am	0.0%	2:00 pm	8.3%
3:00 am	0.0%	3:00 pm	8.3%
4:00 am	0.0%	4:00 pm	8.3%
5:00 am	0.0%	5:00 pm	8.3%
6:00 am	8.4%	6:00 pm	0.0%
7:00 am	8.4%	7:00 pm	0.0%
8:00 am	8.4%	8:00 pm	0.0%
9:00 am	8.4%	9:00 pm	0.0%
10:00 am	8.3%	10:00 pm	0.0%
11:00 am	8.3%	11:00 pm	0.0%

Table 5.4. Number of axles per truck

Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	0.00	0.00	0.00	0.00
Class 5	0.00	0.00	0.00	0.00
Class 6	0.00	0.00	0.00	0.00
Class 7	0.00	0.00	0.00	0.00
Class 8	0.00	0.00	0.00	0.00
Class 9	1.00	2.00	0.00	0.00
Class 10	0.00	0.00	0.00	0.00
Class 11	0.00	0.00	0.00	0.00
Class 12	0.00	0.00	0.00	0.00
Class 13	0.00	0.00	0.00	0.00

Climate input

A virtual weather station for MnROAD was developed by interpolation of the climatic data obtained from several Metro area weather stations located nearby. The data included measurements obtained over a 7-year period since 1996.

Design features

The design features presented in Table 5.1 and Table 5.2 were used to create the MEPDG projects. Note that for each test cell involved in the research, several MEPDG projects were created to reflect the variation of traffic and other design inputs for the same cell. Table B-1 in Appendix B summarizes the MEPDG projects. It should be noted that cell 32 with a 5-in thick PCC layer was excluded from the analysis because the MEPDG software versions 0.850 and 0.868 could not analyze the pavement with a PCC slab thickness less than 6 in.

The PCC properties were derived from MnROAD concrete testing data, obtained courtesy of the Office of Materials of Mn/DOT. The inputs for base, subbase, and subgrade material were developed based on the Mn/DOT Grading and Base Manual (Specification 3138).

5.3.2 Step 2 – Perform the MEPDG software runs

Initially, the MEPDG runs for the MnROAD low-volume PCC test cells were performed using version 0.850 of the MEPDG software (referred here as MEPDG 0850). The results of the initial runs revealed that the MEPDG predicted values of PCC slab cracking were far beyond the existing values of this distress. This discrepancy was partially attributed to incorrect prediction of the temperature gradients in the PCC slabs by the Enhanced Integrated Climatic Model (EICM) embedded into the MEPDG software. This problem was reported to ARA, Inc (a developer of the MEPDG software). ARA modified the EICM and incorporated the revisions in the updated versions of the MEPDG. In this study, the analysis of MnROAD sections using version 0.868 of the MEPDG software (MEPDG 0.868) was performed. The results were compared with the predictions of the MEPDG 0.850 version,

5.3.3 Step-3 – Analyze the pavement performance prediction of Low-Volume Road

Cracking analysis

The MEPDG Software cracking predictions for the MnROAD low-volume PCC pavements are presented in figures C-1 through C-18. All of the charts show that the MEPDG 0.868 version of the software predicts a lower level of cracking compared to the corresponding predictions by the MEPDG 0.850 version. A summary of the predicted and actual cracking values at the end of the analysis period is provided in Table 5.5.

Table 5.5. Summary of predicted vs. measured total cracking

Cell No.	Project	Analysis period years	Total % Crack		
			Predicted MEPDG_0850	Predicted MEPDG_0868	Measured
36	IM36-1	10	56.6	1.4	0
	IM36-2	10	78.5	10.9	0
37	IM37_1	10	5.2	0.1	0
	IM37_2	10	22.5	1	0
38	IM38_1	10	51.8	14.6	0
	IM38_2	10	81.3	65.5	0
39	IM39_1	10	67.3	38.8	0
	IM39_2	10	87.7	82.4	0
40	IM40-6.3-1	10	54.3	16.2	0
	IM40-6.3-2	10	82.7	68	0
	IM40-7.6-1	10	8.9	0.4	0
	IM40-7.6-2	10	31.1	7.3	0
52	IM52-1.0-1	5	0.1	0	0
	IM52-1.0-2	5	0.3	0	0
	IM52-1.25-1	5	0.1	0	0
	IM52-1.25-2	5	0.3	0	0
53	IM53-1	5	0.1	0	0
	IM53-2	5	0.5	0	0

One can observe that the cracking predictions from version 0.868 are much closer to measured cracking than the cracking predictions from version 0.850. The improvement was the most significant for Cells 36 and 37 with 6.3-in thick PCC slabs placed over a very strong subgrade (sand with R-value of 70). Some improvements in predictions were observed for cells 52 and 53 (7.5-in thick PCC slabs), but the discrepancy between the predicted and measured cracking was not significant, even for version 0.850. On the other hand, MEPDG version 0.868 predicted lower cracking levels for cells 38, 39, and 40 as compared with that of version 0.858, but the discrepancy between the predicted and measured cracking remains significant.

Faulting Analysis

The results of faulting predictions for the MnROAD low-volume PCC pavements obtained from the MEPDG Software are presented in figures C-19 through C-36. It can be observed that the MEPDG 0.868 and MEPDG 0.850 versions of the software predict a similar level of faulting for doweled sections. At the same time, the newer version predicts much lower faulting for undoweled sections compared to predictions by the MEPDG 0.850 version. A summary of the predicted and actual faulting values at the end of the analysis period is provided in Table 5.6.

Table 5.6. Summary of predicted vs. measured total faulting

Cell No.	Project	Analysis period years	Total Faulting		
			Predicted MEPDG_0850	Predicted MEPDG_0868	Measured
36	IM36-1	10	0.001	0.002	0.02
	IM36-2	10	0.004	0.002	0.04
37	IM37_1	10	0.036	0.027	0.02
	IM37_2	10	0.042	0.031	0
38	IM38_1	10	0.001	0.001	0
	IM38_2	10	0.001	0.001	0.01
39	IM39_1	10	0.002	0.001	0.04
	IM39_2	10	0.002	0.001	0
40	IM40-6.3-1	10	0.064	0.03	0.05
	IM40-6.3-2	10	0.074	0.037	0
	IM40-7.6-1	10	0.044	0.021	0.05
	IM40-7.6-2	10	0.052	0.026	0
52	IM52-1.0-1	5	0	0	0
	IM52-1.0-2	5	0	0	0.01
	IM52-1.25-1	5	0	0	0
	IM52-1.25-2	5	0	0	0.01
53	IM53-1	5	0.004	0.004	0
	IM53-2	5	0.005	0.005	0.03

5.4 Conclusions and Recommendations

The performance of six MnROAD Low-Volume Roadway PCC test cells was analyzed using the Mechanistic-Empirical Pavement Design Guide software. Two versions of the MEPDG software were used for the analysis: MEPDG 0.850 released in June 2004 and MEPDG version 0.868 released in April 2006.

Based on a wide range of the design features from the LVR PCC test cells, eighteen projects were created and analyzed to evaluate transverse cracking and joint faulting over a 10-year design life. The following observations were made:

- The latest MEPDG 0.868 version improved the accuracy of cracking prediction for the MnROAD sections. Nevertheless, some discrepancy between the predicted and measured cracking was observed and local calibration of the MEPDG model was recommended.
- The difference between the measured faulting and the predictions from both versions of the DG software was not significant and no additional calibration was recommended.

Chapter 6

Recalibration of the MEPDG Performance Prediction Models to Minnesota Conditions

6.1 Introduction

This chapter presents a re-calibration of the Mechanistic-Empirical Pavement Design Guide (MEPDG) cracking model for Minnesota conditions. The mechanistic-empirical performance prediction models in the MEPDG design procedure were calibrated using nationwide pavement performance databases, such as LTPP GPS-3, LTPP SPS-2, and FHWA RPPR databases. This resulted in performance prediction models which are not necessarily optimal for Minnesota conditions. Comparison of the predicted and measured distresses for six MnROAD Low-Volume Roadway PCC test cells revealed a need for re-calibration of the cracking model.

6.2 Approach to Calibration

To conduct calibration of the MEPDG cracking model for Minnesota conditions, design and performance data for 65 sections located in Minnesota, Iowa, Wisconsin, and Illinois were obtained. The MEPDG version 0.868 software runs were performed using this information, and the predicted values of transverse cracking were compared with the actual values. A paired t-test was conducted to determine the statistical significance of the difference between predicted and measured damage.

The calibration coefficients were modified using an iterative optimization procedure. The goal of this procedure was to minimize the discrepancy between predicted and actual values of cracking. Finally, the calibrated cracking values were obtained using the modified coefficients, and compared with the actual values to validate the statistical insignificance of the error. The details of the calibration process are presented below.

6.3 Step-by-step Calibration Procedure

6.3.1 Step1 – Collection of the Calibration Dataset

To calibrate the MEPDG cracking model for the Minnesota conditions, a subset of 65 sections were selected from the database compiled by Applied Research Associates, Inc. under the NCHRP 1-40D project for the national calibration of the MEPDG. The selected sections are located in Minnesota, Iowa, Wisconsin, and Illinois. Pavement design and performance information for these sections was obtained from the LTPP database, AASHTO road test, and MnROAD database. Tables D-1 and D-2 in Appendix D provide a summary of the site conditions and the design features, respectively, for the pavement sections selected for the local calibration. Since many sections had time series cracking data, the final data set consisted of a total of 193 observations.

6.3.2 Step 2 – Compute Corresponding Predicted Values

The second step in the process of recalibrating the MEPDG cracking model involved computing fatigue damage and prediction of the cracking for each pavement section in the calibration dataset. The MEPDG JPCP cracking model has the following form:

$$TOTCRACK = 100 * (BUCRACK + TDCRACK - BUCRACK * TDCRACK) \tag{6.1}$$

where

$TOTCRACK$ = total percentage of slabs cracked

$BUCRACK$ = percentage of cracked slabs with the cracking propagated from bottom up

$TDCRACK$= percentage of cracked slabs with the cracking propagated from top down.

Bottom-up cracking and top-down cracking are determined from the cumulative fatigue damage at the bottom and the top of the PCC slab, respectively. The relationships between cracking and the corresponding damage have the following form:

$$BUCRACK = \frac{1}{1 + C1 * BU^{C2}} \tag{6.2}$$

$$TDCRACK = \frac{1}{1 + C1 * TD^{C2}} \tag{6.3}$$

where:

BU = fatigue damage associated with bottom-up cracking

TD = fatigue damage associated with top-down cracking

$C1$ and $C2$ = regression coefficients

In the original model the values of the regression coefficients were as follows:

$$C1=1 \tag{6.4}$$

$$C2= -1.68 \tag{6.5}$$

6.3.3 Step-3 – Compare predicted vs. measured cracking

The predicted cracking values were compared with the corresponding measured cracking for each observation in the calibration data base. A summary of the predicted and measured cracking is presented in table D-3 of Appendix D. A plot of predicted versus actual data (see figure 6.1) was prepared to compare the general location of the data points to a one-to-one line (representing predicted = actual). In addition, this plot allowed for evaluating the data by identifying any potential bias, lack of precision, and trends associated with the original model.

Thus, the trendline equation presented in the plot suggested that the actual cracking values, on average, corresponded to 47.6 percent of the values predicted by the MEPDG original cracking model with overall correlation $R^2 = 0.57$.

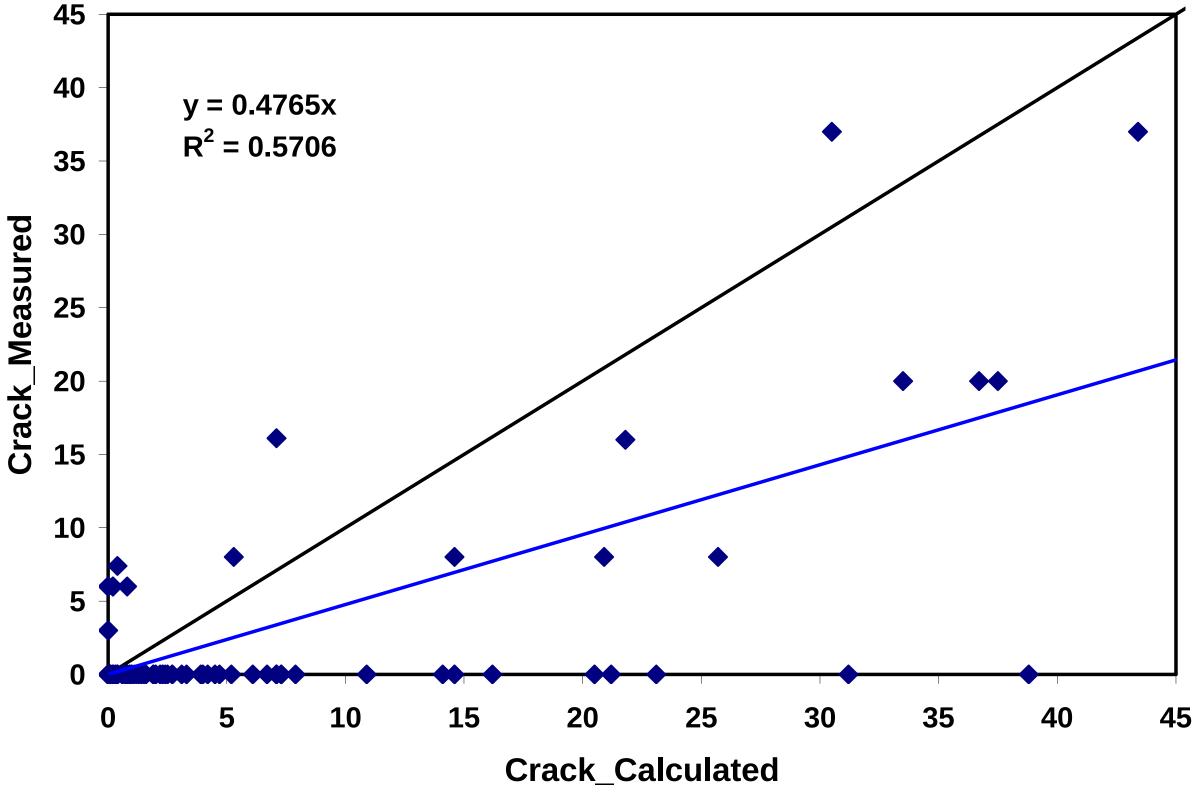


Figure 6.1. Measured vs. predicted cracking plot – Original cracking model

A paired t-test was performed to determine if there is a significant difference between sets of predicted and actual cracking values. For this analysis, the null hypothesis was as follows:

$$H_0: \mu_{MEASURED} - \mu_{PREDICTED} = 0 \quad (6.6)$$

where:

$\mu_{MEASURED}$ = Mean of measured values

$\mu_{PREDICTED}$ = Mean of values predicted using the original model

The 5% level of significance was chosen for analysis. This meant that the null hypothesis would be rejected if the p-value of the t-test is less than 0.05.

The results of the paired t-test for the calibration dataset are summarized in Table 6.1. Based on the very low p-value (p=0.00001 <<0.05), the difference between measured and predicted values was recognized to be highly significant. This called for the modification of the regression coefficients in the original model described by equations 6.4 and 6.5.

Table 6.1 Summary of the paired t-test for the calibration dataset - Original cracking model

Before calibration	***Measured % Crack***	***Calculated % Crack***
Mean	3.45	1.49
Variance	79.02	32.30
Observations	193	193
Pearson Correlation	**0.76**	
Hypothesized Mean Difference	0	
df	192	
t Stat	4.61	
P(T<=t) one-tail	0.000004	
t Critical one-tail	1.65	
P(T<=t) two-tail	**0.00001**	
t Critical two-tail	1.97	

6.3.4 Step-4 – Modify regression coefficients

According to the trend line equation presented in Figure 6.1, the linear regression relationship between measured and predicted values of cracking can be described by the following equation:

$$MEASCRACK = A * CALCCRACK \tag{6.7}$$

Where:

$MEASCRACK$= measured value of cracking

$CALCCRACK$= predicted (calculated) value of cracking

A= regression coefficient representing the slope of the mean function

The predicted value of cracking can be calculated using the equations (6.1) through (6.3) and can be expressed in the following way:

$$CALCCRACK = 100 * [\frac{1}{1 + C1 * BU^{C2}} + \frac{1}{1 + C1 * TD^{C2}} - \frac{1}{(1 + C1 * BU^{C2}) * (1 + C1 * TD^{C2})}] \quad (6.8)$$

The objective of Step 5 is to find a set of the coefficients C1-C2 that will satisfy the equality of measured and predicted values, so that the slope A (See equation 6.7) would be equal 1. To achieve this goal, the iterative optimization procedure was executed automatically using the macro-driven VBA application and MS Excel. It included the following subroutines:

1. Calculate the value of CALCCRACK for each point of data set using the regression coefficients C1 and C2 from the original model.

2. Calculate the squared difference between predicted and measured value for each point of dataset, or individual squared error (SE)

3. Calculate the sum of the individual squared errors for the whole dataset (SSE)

4. Define the range for each regression coefficient C

5. Define a number of iterations

6. Calculate and record the values of *CALCCRACK* for each of the iterations using equation 6.8

7. Calculate and record the value of the SSE for each iteration

8. Choose the set of coefficients C1-C2 with the minimum value of SSE

9. For the chosen set of the coefficients C1-C2, plot *MEASCRACK* vs. *CALCCRACK* values including the linear trendline with zero-intercept

10. Obtain the slope *A* from the trendline equation. If A=1 then the procedure will stop, otherwise the subroutine will choose the new range of the coefficients C1 and C2, and repeat steps 1 through 9.

The results of the procedure described above are summarized in Table 6.2. The modified set of the coefficients presented in this table satisfies the minimum total error (SSE) and the requirement of the equality of predicted and measured values of cracking.

Table 6.2 Summary of the iterative optimization procedure

	Coefficients		SSE	R^2	Slope A
	C1	C2			
Original	**1**	**-1.68**	**7457**	**0.57**	**0.4763**
Trial Range	**0.9-2.2**	**-1.5- -3.5**			
Modified	**1.9875**	**-2.145**	**2402**	**0.61**	**1.0002**

Figure 6.2 represent the measured vs. calibrated cracking values plot including the trendline equation, which yields the slope A=1.0002 and R^2 =0.61.

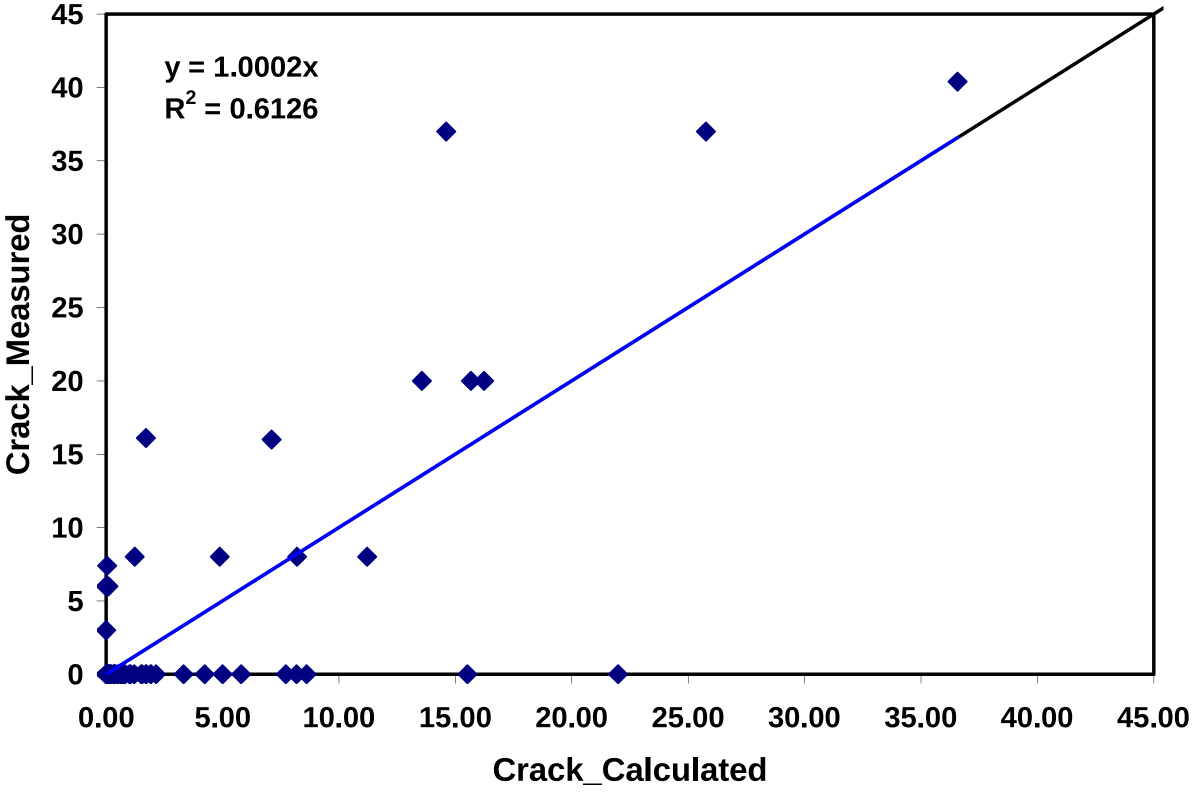


Figure 6.2. Measured vs. predicted cracking plot – Calibrated cracking model

The calibrated values of cracking for each section of the dataset are summarized in Appendix D, table D-4.

6.3.5 Step-5 – Statistical analysis of Calibrated vs. Measured Cracking Values

A paired t-test was repeated to check the significance of the difference between sets of calibrated and actual cracking values.

The results of the paired t-test for the calibration dataset are summarized in Table 6.3. Based on a highly non-significant p-value (p=0.65 >>0.05), the difference between measured and predicted populations can be neglected.

Table 6.3 Summary of the paired t-test for the calibrated cracking model

After calibration	***Measured % Crack***	***Calculated % Crack***
Mean	1.38	1.49
Variance	20.11	32.30
Observations	193	193
Pearson Correlation	**0.78**	
Hypothesized Mean Difference	0	
df	192	
t Stat	-0.46	
P(T<=t) one-tail	0.32	
t Critical one-tail	1.65	
P(T<=t) two-tail	**0.65**	
t Critical two-tail	1.97	

Based on the results of the optimization procedure, the recalibrated cracking model can be expressed by the following equation:

$$CRACK = 100*\left[\frac{1}{1+1.9875*BU^{-2.145}} + \frac{1}{1+1.9875*TD^{-2.145}} - \frac{1}{(1+1.9875*BU^{-2.145})*(1+1.9875*TD^{-2.145})}\right] \qquad (6.9)$$

6.4 Graphical Analysis of the Calibrated Cracking Model

Figures 6.3 through 6.5 provide representative charts for predicted cracking over the analysis period for MnROAD cells 36, 38, and 39, respectively. Each chart contains three series: for the MEPDG version 0.850, version 0.868, and the calibrated values. It can be seen in the charts that, while the major improvement of the cracking model was achieved before calibration, the level of cracking predicted by the calibrated MEPDG version 0.868 are noticeably lower than the one before calibration.

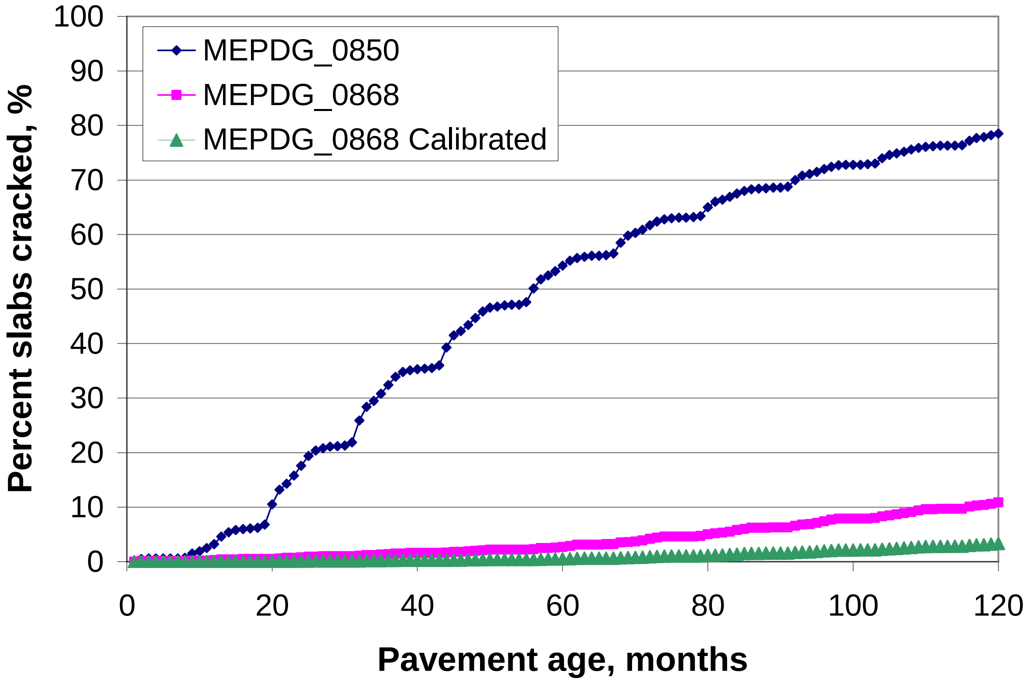


Figure 6.3. Predicted cracking – MnROAD Cell IM36-2, Outside lane, load = 102 Kip, HPCC =6.35, Dowel D = 1

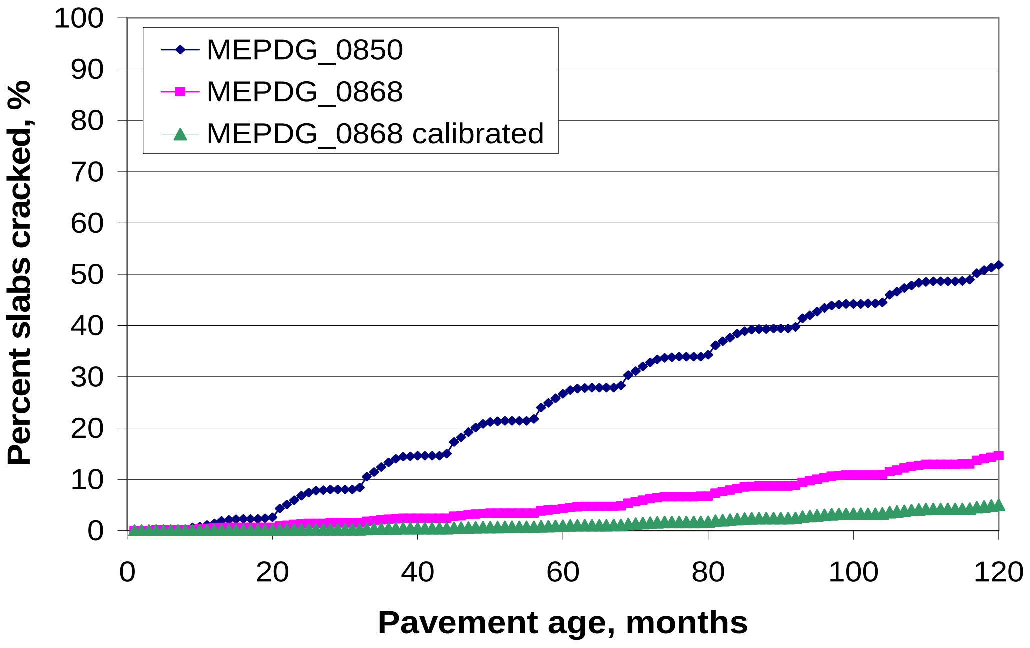


Figure 6.4. Predicted cracking – MnROAD Cell IM38_1, Inside lane, load = 80 Kip, HPCC =6.35, Dowel D = 1

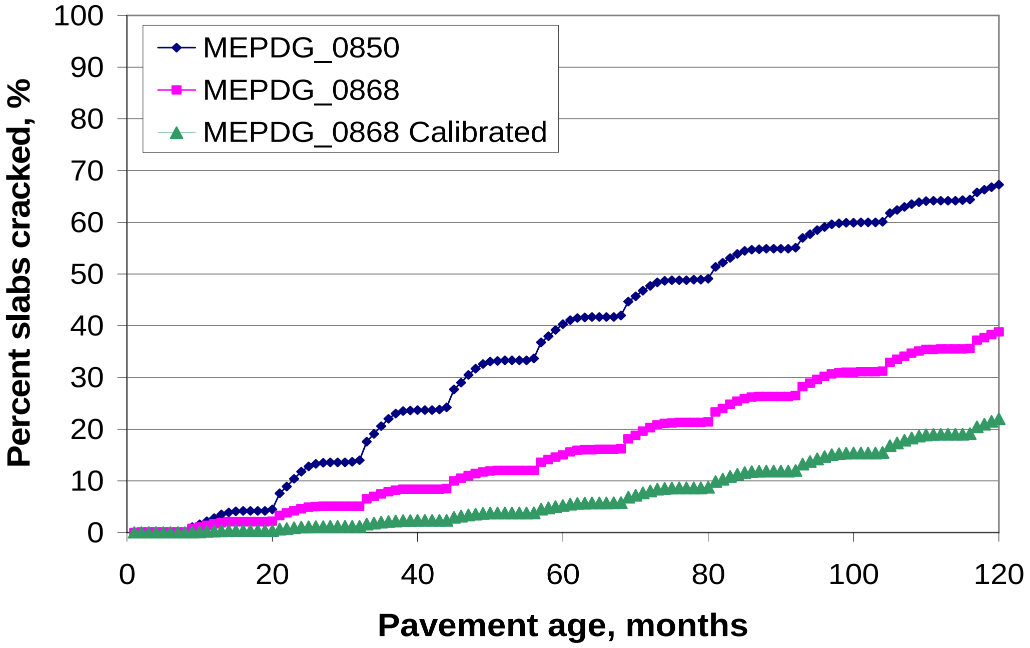


Figure 6.5. Predicted cracking – MnROAD Cell IM39_1, Inside lane, load = 80 Kip, HPCC =6.38, Dowel D = 1

Chapter 7

Prototype of Design Catalog for Minnesota Low-Volume Concrete Pavements

7.1 Introduction

The objective of this study was to develop a prototype of a pavement design catalog for the PCC low-volume roads in Minnesota. Performance predictions required to develop the design catalog were obtained from the more than 46,000 runs of the MEPDG version 0.910 performance prediction model with the cracking model coefficients described in Chapter 6 (10). Only a limited number of design combinations were selected in the final prototype of the pavement design catalog.

7.2 Functional Classification of the Design Catalog

The primary objective of the catalog development was to establish the most feasible and practical pavement design alternatives for typical combinations of site conditions for the Minnesota low-volume pavement systems. To achieve this objective, 46080 combinations of the site conditions and design features were evaluated using the MEPDG version 0.910 performance prediction models.

The following site conditions were considered:

- Location
    - Metro area (Minneapolis weather station)
    - Southeast (Rochester weather station)
    - Southwest (Redwood Falls weather station)
    - Northwest (Grand Rapids, ND, weather station)
    - Northeast (Hibbing weather station)
- Subgrade type
    - Clay A-6 subgrade (approximate R-value is 12)
    - Sandy A-3 subgrade (approximate R-value is 70)
- Traffic
    - 50,000 heavy trucks over the pavement design life
    - 250,000 heavy trucks over the pavement design life
    - 750,000 heavy trucks over the pavement design life

The following performance criteria were established at 50 percent reliability level:

- Transverse Cracking of JPCP: 30 percent or less slabs cracked
- Mean Transverse Joint Faulting of JPCP: 0.25 inch

Table 7.1 presents the values of the design features considered for each combination of the site conditions. A comprehensive analysis of the MEPDG performance predictions was conducted to provide the most economical design alternatives for each combination of the site conditions. The following section presents the iterative methodology adopted in this study for selection of these alternatives.

Table 7.1. Critical design input parameters

Input Parameters	Cases	Values
PCC slab thickness, Hpcc	4	6, 7, 8, and 9 in
Base thickness, Hbase	3	6, 18, and 48 in
Base Type	2	Class 3 Class 5
PCC coefficient of thermal expansion, COTE	2	$4.8\text{x}10^{-6}$ / ^{o}F $5.5\ \text{x}10^{-6}$ / ^{o}F
Joint spacing, JS	2	15 ft 20 ft
Slab width, SW	2	12 ft 13.5 ft
Shoulder type, Sh	2	Tied PCC / Curb & gutter AC
Dowel diameter, D	4	No Dowel 1-in 1.25-in 1.5-in

7.3 Screening Methodology for the Design Catalog

The main purpose of this effort was to identify the most practical and feasible design alternatives (i.e. combinations of the design features such as PCC thickness, joint spacing, dowel diameter, shoulder types, etc.). Following the classification of the possible design combinations, an iterative screening process for the optimum design combinations was performed. This was performed by developing a step-by-step elimination methodology as outlined below with illustrative examples summarizing the process.

First, the design alternatives that did not meet the established performance criteria were eliminated. The remaining design combinations were analyzed separately for each combination of the site conditions, and some combinations were eliminated if found uneconomical. The following procedure was adopted:

- If two combinations of the design inputs satisfied the performance criteria and differed only by the shoulder type, then in those cases the design combination with the AC shoulder was kept and the PCC shoulder design was discarded. An illustrative example is provided in table 7.2.

Table 7.2. Example of a similar design alternative, but with different shoulder types

H_{pcc}	Base	H_{base}	Shoulder	LW	JS	DD
6	Class 3	18	AC	12	15	0
~~6~~	~~Class 3~~	~~18~~	~~PCC~~	~~12~~	~~15~~	~~0~~

- If two combinations of the design inputs satisfied the performance criteria and differed only by the PCC slab thickness as shown in table 7.3, then in those cases the design combination having smaller PCC slab thickness was selected and other discarded.

Table 7.3. Example of a similar design alternative, but with different slab thickness

H_{pcc}	Base	H_{base}	Shoulder	LW	JS	DD
6	Class 3	18	AC	13.5	20	1
~~9~~	~~Class 3~~	~~18~~	~~AC~~	~~13.5~~	~~20~~	~~1~~

- If two combinations of the design inputs satisfied the performance criteria and differed only by the base type, then in those cases the design combination with a base type of Class 3 was selected.

- If two combinations of the design inputs satisfied the performance criteria and differed only by the joint spacing between the slabs, then in those cases the design combination with a joint spacing of 20 ft was selected.

- If two combinations of the design inputs satisfied the performance criteria and differed only by the slab width, then the case consisting of widened lanes (13.5 ft) design was discarded.

- If two combinations of different base thickness satisfied the performance criteria, then the case consisting of thicker base was discarded.

- If combinations of different dowel diameters satisfied the performance criteria, then cases consisting of greater diameter were discarded.

To illustrate the process outlined above, consider the following example of screening design catalog elements.

Table 7.4 presents an example of eleven possible design combinations considered as candidates for inclusion in the design catalog elements. Using the design combination screening methodology described previously, case numbers 1, 3, 9, 10, and 11 were eliminated in the first phase of the screening process. The results obtained are presented in table 7.5. Criteria established in this phase of screening on case-by-case basis are as follows:

- Case # 1: This case was found nearly identical to case number 2, except case 1 had smaller (15-ft) joint spacing. Therefore, case number 1 was eliminated and case 2 was retained.

- Case # 3: This case was eliminated because the only major difference between case 3 and case number 4 was a wider lane width in case 3.

- Case # 9: This case was eliminated on the basis of larger dowel diameter than case number 7, which presents a similar design combination.

- Case # 10 and Case # 11: Cases 10 and 11 were found to have similar design combinations, but higher base thickness, than case numbers 5 and 6, respectively. Therefore, cases 10 and 11 were both discarded.

Table 7.4. Illustration of the elimination process of similar designs in the design catalog development. – Initial design combinations

Case No.	Base	H_{PCC} (in)	H_{base} (in)	Base Type	Shoulder Type	LW (ft)	JS (ft)	DD (in)
1	Class 3	6	6	Class 3	AC	12	15	1
2	Class 3	6	6	Class 3	AC	12	20	1
3	Class 3	6	6	Class 3	Tied PCC	13.5	15	1
4	Class 3	6	6	Class 3	Tied PCC	12	15	1
5	Class 3	6	18	Class 3	AC	12	20	0
6	Class 3	6	18	Class 3	Tied PCC	12	20	0
7	Class 3	6	18	Class 3	AC	12	15	1.25
8	Class 3	6	18	Class 3	Tied PCC	13.5	20	1.25
9	Class 3	6	18	Class 3	AC	12	15	1.5
10	Class 3	6	48	Class 3	AC	12	20	0
11	Class 3	6	48	Class 3	Tied PCC	12	20	0

Table 7.5. Illustration of the elimination process of similar designs in the design catalog development. Design combinations after first iteration of the screening process.

Case No.	Base	H_{PCC} (in)	H_{base} (in)	Base Type	Shoulder Type	LW (ft)	JS (ft)	DD (in)
2	Class 3	6	6	Class 3	AC	12	20	1
4	Class 3	6	6	Class 3	Tied PCC	12	15	1
5	Class 3	6	18	Class 3	AC	12	20	0
6	Class 3	6	18	Class 3	Tied PCC	12	20	0
7	Class 3	6	18	Class 3	AC	12	15	1.25
8	Class 3	6	18	Class 3	Tied PCC	13.5	20	1.25

The second phase of this screening example compares the remaining cases. Case number 6 was found to be similar in design to case number 5, but consisted of tied PCC shoulder design, unlike case number 5. Therefore, the design combination presented in case number 5 was found to be a more successful candidate for inclusion in the final design catalog element and case 6 was eliminated. This elimination process is presented in table 7.6.

Table 7.6. Illustration of the elimination process for similar designs in the design catalog development. Design combinations after the second iteration of the screening process.

Case No.	Base	H_{PCC} (in)	H_{base} (in)	Base Type	Shoulder Type	LW (ft)	JS (ft)	DD (in)
2	Class 3	6	6	Class 3	AC	12	20	1
4	Class 3	6	6	Class 3	Tied PCC	12	15	1
5	Class 3	6	18	Class 3	AC	12	20	0
7	Class 3	6	18	Class 3	AC	12	15	1.25
8	Class 3	6	18	Class 3	Tied PCC	13.5	20	1.25

The above example cases illustrate that only the most viable case scenarios were selected to be included in the design catalog. However, the design catalog does not restrict the possibility of an alternative design, as long as the alternative does not compromise the quality of the pavement. For example, selecting a passing design from the design catalog and replacing LW=12 ft with LW=13.5 ft is acceptable, but a design combination with LW=13.5 ft cannot use LW=12 ft as that substitution may reduce the pavement performance.

7.4 Prototype of Design Catalog

The process described in section 7.3 was applied to evaluate the 46080 design alternatives presented in section 7.2. This research effort resulted in the development of a prototype design catalog for low volume PCC pavements in Minnesota. Only the most feasible pavement design alternatives with respect to different site conditions are listed in the catalog. The design conditions are classified in terms of site conditions (location, traffic volume, and subgrade type). Each design entry in the catalog describes critical design input parameters, such as PCC slab and base thickness, slab width, joint spacing, shoulder type, and load transfer design (dowel diameter). The design catalog does not specify base type since Class 3 was found to be the most economical for all site conditions.

Table 7.7 presents the design alternatives selected for the catalog. One can observe that for the lowest level of traffic (50,000 heavy trucks over the design life) the same design alternative is recommended for all locations and subgrade types. This design consists of a 6-in PCC slab over a 6-in class 3 granular base with a 20-ft joint spacing. It is quite possible that a thinner PCC slab would lead to an acceptable design for a very low traffic level, but the MEPDG software limits the minimum PCC thickness to 6 in.

Table 7.7. Prototype of a Design Catalog for Minnesota Low Volume PCC Pavements.

Site Conditions		**Design Features**							
Subgrade	Traffic, Trucks	PCC Thickness In	Base Thickness In	Base Type	Edge Support	Slab Width ft	COTE in/in/^{o}F	Joint Spacing ft	Dowel Diameter In
Climatic Region:				**Twin Cities (Minneapolis)**					
Clay	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	0
Sand	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	0
Climatic Region:				**South-East (Rochester)**					
Clay	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	0
Sand	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	0
Climatic Region:				**North-West (Grand Forks, ND)**					
Clay	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	18	Class 3	No	12	5.5E-6	20	0
		6	6	Class 3	Yes	12	5.5E-6	20	1
		6	6	Class 5	Yes	12	5.5E-6	20	0
		6	6	Class 3	No	13.5	5.5E-6	20	0
		6	6	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	No	12	5.5E-6	15	0
		7	6	Class 3	No	12	5.5E-6	20	1
		8	6	Class 5	No	12	5.5E-6	20	0
		8	6	Class 3	Yes	12	5.5E-6	20	0
		9	6	Class 3	No	12	5.5E-6	20	0
Sand	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	1
		6	18	Class 3	No	12	5.5E-6	20	0
		6	6	Class 3	Yes	12	5.5E-6	20	0
		6	6	Class 3	No	13.5	5.5E-6	20	0
		6	6	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	No	12	5.5E-6	15	0
		7	6	Class 3	No	12	5.5E-6	20	0
Climatic Region:				**South-West (Redwood Falls)**					
Clay	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	48	Class 3	No	12	5.5E-6	20	0
		6	18	Class 3	Yes	12	5.5E-6	20	0
		6	18	Class 3	No	13.5	5.5E-6	20	0
		6	18	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	Yes	12	4.8E-6	20	0

Table 7.7. Prototype of a Design Catalog for Minnesota Low Volume PCC Pavements (cont.)

Site Conditions		**Design Features**							
Subgrade	Traffic, Trucks	PCC Thickness In	Base Thickness In	Base Type	Edge Support	Slab Width ft	COTE in/in/°F	Joint Spacing ft	Dowel Diameter In
		6	6	Class 3	No	13.5	4.8E-6	20	0
		6	6	Class 3	Yes	12	5.5E-6	15	0
		6	6	Class 3	No	13.5	5.5E-6	15	0
		7	6	Class 3	No	13.5	5.5E-6	20	0
		7	6	Class 3	No	12	5.5E-6	15	0
		8	6	Class 3	Yes	12	5.5E-6	20	0
		8	6	Class 3	No	12	4.8E-6	20	0
		9	18	Class 3	No	12	5.5E-6	20	0
	750,000	6	48	Class 3	No	12	5.5E-6	20	0
		6	18	Class 3	No	13.5	5.5E-6	20	0
		6	18	Class 3	Yes	12	4.8E-6	20	0
		6	18	Class 3	Yes	12	5.5E-6	15	0
		6	6	Class 3	No	13.5	4.8E-6	15	0
		7	6	Class 3	No	13.5	4.8E-6	20	0
		7	6	Class 3	Yes	12	5.5E-6	15	0
		7	6	Class 3	No	13.5	5.5E-6	15	0
		7	18	Class 3	No	12	4.8E-6	15	0
		8	6	Class 3	Yes	12	4.8E-6	20	0
		8	6	Class 3	No	12	5.5E-6	15	0
		9	18	Class 3	Yes	12	5.5E-6	20	0
		9	18	Class 3	No	12	4.8E-6	20	0
Sand	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	48	Class 3	No	12	5.5E-6	20	0
		6	18	Class 3	Yes	12	5.5E-6	20	0
		6	18	Class 3	No	13.5	5.5E-6	20	0
		6	18	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	Yes	12	4.8E-6	20	0
		6	6	Class 3	No	13.5	4.8E-6	20	0
		6	18	Class 3	No	12	5.5E-6	15	0
		6	6	Class 3	Yes	12	5.5E-6	15	0
		6	6	Class 3	No	13.5	5.5E-6	15	0
		7	6	Class 3	No	13.5	5.5E-6	20	0
		7	6	Class 3	No	12	4.8E-6	20	0
		7	6	Class 3	No	12	5.5E-6	15	0
		8	6	Class 3	Yes	12	5.5E-6	20	0
		9	18	Class 3	No	12	5.5E-6	20	0
		6	48	Class 3	No	12	5.5E-6	20	0
	750,000	6	48	Class 3	No	12	5.5E-6	20	0
		6	18	Class 3	No	13.5	5.5E-6	20	0
		6	18	Class 3	Yes	12	4.8E-6	20	0
		6	6	Class 3	No	13.5	4.8E-6	20	0
		6	18	Class 3	Yes	12	5.5E-6	15	0
		6	6	Class 3	No	13.5	5.5E-6	15	0
		6	6	Class 3	Yes	12	4.8E-6	15	0
		7	6	Class 5	Yes	12	4.8E-6	20	0

Table 7.7. Prototype of a Design Catalog for Minnesota Low Volume PCC Pavements (cont.)

Site Conditions		**Design Features**							
Subgrade	Traffic, Trucks	PCC Thickness In	Base Thickness In	Base Type	Edge Support	Slab Width ft	COTE in/in/^{o}F	Joint Spacing ft	Dowel Diameter In
		7	6	Class 3	Yes	12	5.5E-6	15	0
		7	18	Class 3	No	12	4.8E-6	15	0
		8	6	Class 3	Yes	12	4.8E-6	20	0
		8	6	Class 3	No	12	5.5E-6	15	0
		9	18	Class 3	No	12	4.8E-6	20	0
Climatic Region: **North-East (Hibbing)**									
Clay	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	1
		6	18	Class 3	No	12	5.5E-6	20	0
		6	6	Class 3	Yes	12	5.5E-6	20	0
		6	6	Class 3	No	13.5	5.5E-6	20	0
		6	6	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	No	12	5.5E-6	15	0
		7	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	1
		6	48	Class 3	No	12	5.5E-6	20	0
		6	18	Class 3	Yes	12	5.5E-6	20	0
		6	18	Class 3	No	13.5	5.5E-6	20	0
		6	18	Class 3	No	12	4.8E-6	20	0
		6	6	Class 3	Yes	12	4.8E-6	20	0
		6	6	Class 3	No	13.5	4.8E-6	20	0
		6	18	Class 3	No	12	5.5E-6	15	0
		6	6	Class 3	Yes	13.5	5.5E-6	15	0
		6	6	Class 3	No	12	4.8E-6	15	0
		7	6	Class 3	No	12	4.8E-6	20	0
		7	6	Class 3	Yes	12	5.5E-6	15	0
		7	6	Class 3	No	13.5	5.5E-6	15	0
		8	6	Class 3	Yes	13.5	5.5E-6	20	0
		8	6	Class 3	No	12	5.5E-6	15	0
		9	18	Class 3	No	12	5.5E-6	20	0
		9	6	Class 3	Yes	12	5.5E-6	20	0
		9	6	Class 3	No	13.5	5.5E-6	20	0
Sand	50,000	6	6	Class 3	No	12	5.5E-6	20	0
	250,000	6	6	Class 3	No	12	5.5E-6	20	0
	750,000	6	6	Class 3	No	12	5.5E-6	20	1
		6	18	Class 3	No	12	5.5E-6	20	0
		6	6	Class 3	Yes	13.5	5.5E-6	20	0
		6	6	Class 3	No	13.5	5.5E-6	15	0
		6	6	Class 3	No	12	4.8E-6	20	0
		7	6	Class 3	No	13.5	5.5E-6	20	0
		7	6	Class 5	No	12	5.5E-6	15	0
		7	6	Class 3	Yes	12	5.5E-6	15	0
		8	6	Class 3	Yes	12	5.5E-6	20	0
		8	6	Class 3	No	12	5.5E-6	15	0
		9	6	Class 3	No	12	5.5E-6	20	0

Table 7.7. Prototype of a Design Catalog for Minnesota Low Volume PCC Pavements (cont.)

Site Conditions		**Design Features**							
Subgrade	Traffic, Trucks	PCC Thickness In	Base Thickness In	Base Type	Edge Support	Slab Width ft	COTE in/in/^oF	Joint Spacing ft	Dowel Diameter In
		6	6	Class 3	No	13.5	5.5E-6	15	0

Analysis of table 7.7 also shows that for higher traffic levels (250,000 and 750,000 heavy trucks over the design life) the design recommendations are not the same for different locations. Moreover, more than one design alternative can be recommended for a given location and subgrade type. For example, if a pavement is designed in a northwestern part of Minnesota on a sand subgrade for a traffic level up to 250,000 heavy trucks over the pavement design life, the designer has the following options:

- Select a 6-in PCC slab over a 6-in thick class 3 granular base with a 20-ft joint spacing and doweled joint
- Use the same design features, but increase the base thickness and eliminate dowels, or
- Use a 6-in thick base, but increase the PCC slab width and provide an edge support (a tied PCC shoulder or tied PCC curb) or reduce the joint spacing, or
- Use a PCC mix with a lower coefficient of thermal expansion, or
- Increase the PCC slab thickness.

This demonstrates that the proposed design catalog is not just a catalog of recommended PCC thicknesses, but it provides the designer with a wide range of design alternatives. Selection of the most economical design alternative may depend on local experience, available materials (PCC aggregates), available construction equipment, etc.

7.4 Limitations of the Prototype of Design Catalog

One of the main challenges of this study was on-going modification of the MEPDG. During the course of this study, the design guide software was substantially modified. Several modifications addressed the bugs or process flaws identified in this study, so the updated versions of the MEPDG software are better suited for design of concrete pavements for Minnesota conditions. However, the software modifications made created many obstacles for the catalogue development. It resulted in the following inconsistencies:

- The performance prediction models were calibrated using the MEPDG version 0.868.
- The catalog was developed using the version 0.910, which incorporates several modifications in temperature and moisture analysis compare to version 0.868. The decision was made not to re-calibrate the models for version 0.910 because it is not intended to be the final version.
- During the process of the catalogue finalization, several bugs in version 0.910 were identified by the ARA, Inc. MEPDG software development team. One of the most

serious problems which may directly affect the catalog development process is the bug in the climatic analysis in large factorial runs.

- The latest version of the MEPDG software (version 0.976) addresses the bugs identified in this and other studies. It also modifies handling of granular base layers of concrete pavements. This version, however, is not publicly available. The next official version, version 1.0, will be available only in April of 2007 (11). This makes use of the version 1.0 in this study unfeasible.

Therefore, the catalogue developed in this study cannot be considered as a final recommendation, but rather as a prototype which should be updated after the next official version of the MEPDG is released. The entire process should be repeated after the MEPDG software is finalized.

In addition to the challenges with the modifications in the MEPDG software, there are some inherent limitations of the MEPDG design process that the designer should be aware of and account for in the design process. The following limitations may have major implications for design of low volume concrete pavements:

- The MEPDG considers only transverse cracking and joint faulting. Other distresses important for low volume concrete pavements, like longitudinal and corner cracking, are not included. These distresses may cause premature failure if long thin slabs with undoweled joints are used. The designer should consider use of doweled joints even if the MEPDG does not require them, to reduce the potential for longitudinal and corner cracking.

- The MEPDG software does not permit an analysis of concrete pavements with the PCC slab thickness less than 6 inches. Performance of MnROAD 5-in thick concrete pavement cells suggests that in some cases thinner than 6-in concrete pavement may provide acceptable performance.

- The base thickness selected in the design catalog is based on the structural contribution of the base layer toward reduction of transverse cracking and joint faulting. Thicker base layers may be required to provide substantial protection against frost heave, since the MEPDG Guide does not consider the effect of frost heave on pavement performance.

Nevertheless, in spite of the aforementioned limitations of the MEPDG, after the design catalog has been updated with the latest version of the MEPDG it can serve as a good starting point for the design process.

Chapter 8

Summary and Conclusions

The MEPDG presents a tremendous opportunity for improvement of the pavement design practices of concrete pavements in Minnesota. Its user-oriented computational software implements an integrated analysis approach for predicting pavement condition over time. These predictions account for the interaction of traffic, climate, and pavement structure. The MEPDG has the capability of changing and adapting to new developments in pavement design by relying on the mechanics of materials. However, the implementation of this Guide is not a trivial task. Local calibration and adaptation of the performance prediction models are required to optimize the design process for Minnesota conditions.

In this study, a comprehensive evaluation of the MEPDG for Minnesota was conducted. It involved the following activities:

- Evaluation of the MEPDG default inputs
- Evaluation of prediction capabilities of the MEPDG
- Recalibration of the MEPDG performance prediction models
- Develop a prototype design catalog for Minnesota low volume concrete roads

The typical inputs of the MEPDG for Minnesota low-volume roads- such as climate, traffic, subgrade, and materials- were evaluated, and recommendations for default values of these parameters were developed. To determine typical design features of Minnesota low-volume Portland Cement Concrete (PCC) pavements, the agencies that actively build low-volume PCC pavements were contacted and information collected from these agencies was summarized.

A factorial of MEPDG runs was conducted to evaluate predictions of the MEPDG software for Minnesota low-volume road conditions. The sensitivity analyses were performed by changing one parameter (for example, traffic level, PCC thickness, or subgrade type) at a time from one run to the next while limiting others to a constant value. The predicted cracking and faulting were evaluated and the following observations were made:

- A traffic volume increase resulted in higher cracking and faulting.
- An increase in dowel diameter resulted in lower faulting.
- A COTE increase resulted in higher cracking and faulting.
- A base thickness increase from 6 to 18 in caused a small decrease in cracking and faulting, but an increase of the base thickness from 18 to 48 in reduced cracking and faulting close to the zero level. A stronger effect was observed for undoweled than for doweled pavements.

- The choice of base and subgrade materials did not show a significant effect on the cracking and faulting levels. Nevertheless, it was observed that a stronger base decreased cracking, while an increase in subgrade modulus reduced faulting.

- A joint spacing increase resulted in higher cracking and faulting, while an increase in slab thickness provided the opposite results.

- The presence of PCC shoulders affected both cracking and faulting less than using widened slabs. Both design features resulted in lower cracking and faulting.

The performance of six MnROAD Low-Volume Roadway PCC test cells was analyzed using the Mechanistic-Empirical Pavement Design Guide software. Two versions of the MEPDG software were used for the analysis: MEPDG 0.850 released in June 2004 and MEPDG version 0.868 released in April 2006. The following observations were made:

- The MEPDG 0.868 version improved the accuracy of cracking prediction for the MnROAD sections. Nevertheless, some discrepancy between the predicted and measured cracking was observed and local calibration of the MEPDG model was recommended.

- The difference between the measured faulting and the predictions from both versions of the DG software was not significant and no additional calibration was recommended.

To conduct calibration of the MEPDG cracking model for Minnesota conditions, design and performance data for 65 sections located in Minnesota, Iowa, Wisconsin, and Illinois were obtained. The MEPDG version 0.868 software runs were performed using this information, and a modified set of cracking model coefficients to better match predicted and measured cracking was obtained. Comparison of the measured cracking for MnROAD cells 36, 38, and 39 with the predicted cracking using the MEPDG versions 0.850, 0.868, and the re-calibrated version 0.868 was conducted. It was observed that major improvement of the cracking model was achieved by re-calibration of the MEDPG cracking model.

Finally, a catalog of the recommended design features for Minnesota low volume PCC pavements was developed using the MEPDG version 0.910. The catalog offers a variety of acceptable design alternatives (PCC and base thickness, joint spacing and PCC slab width, edge support type, and dowel diameter) for a given combination of site conditions (traffic, location, and subgrade type). Selection of the most economical design alternative may also depend on local experience, available materials (PCC aggregates), available construction equipment, or other factors.

Although it was demonstrated that the process developed in this study can be used for development of a rational design catalog for low volume concrete pavements based on the MEPDG performance predictions, the catalog produced in this study cannot be considered as a final recommendation. Instead, it should be treated as a prototype which should be updated after the next official version of the MEPDG is released. During the process of the catalog finalization, several bugs in MEPDG version 0.910 were identified by the ARA, Inc. MEPDG software development team, including a bug involving climatic analysis in large factorial runs.

This could directly affect the catalog development results. Therefore, the catalog should be updated after the MEPDG software is finalized.

References

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Appendix A. Cracking and Faulting Sensitivity Plots

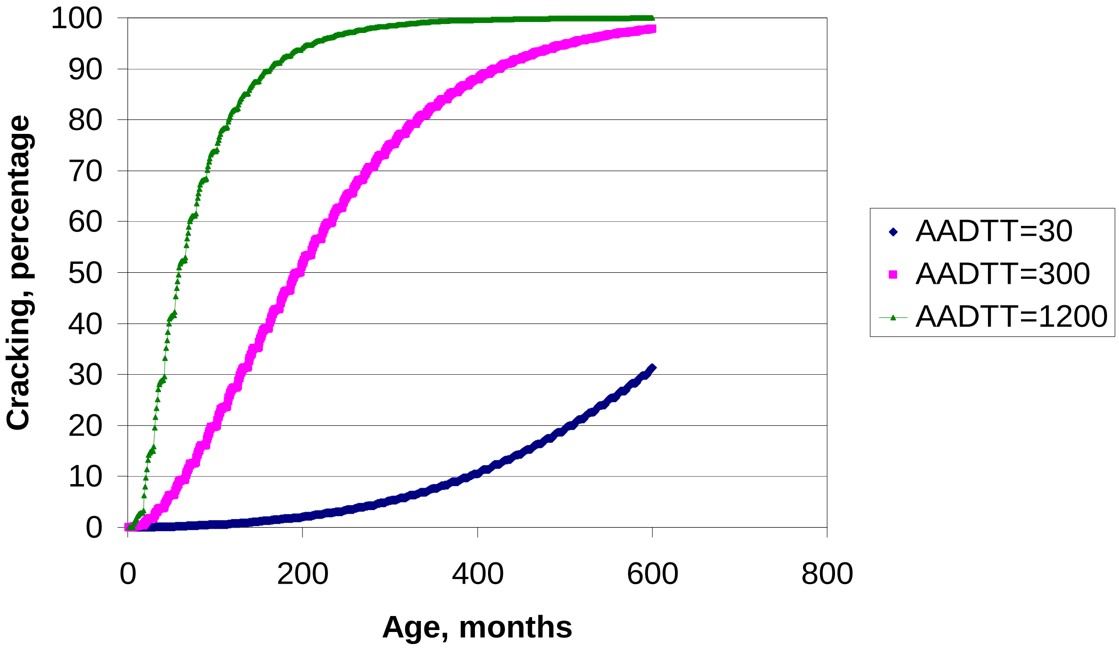


Figure A-1. Effect of traffic on cracking, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

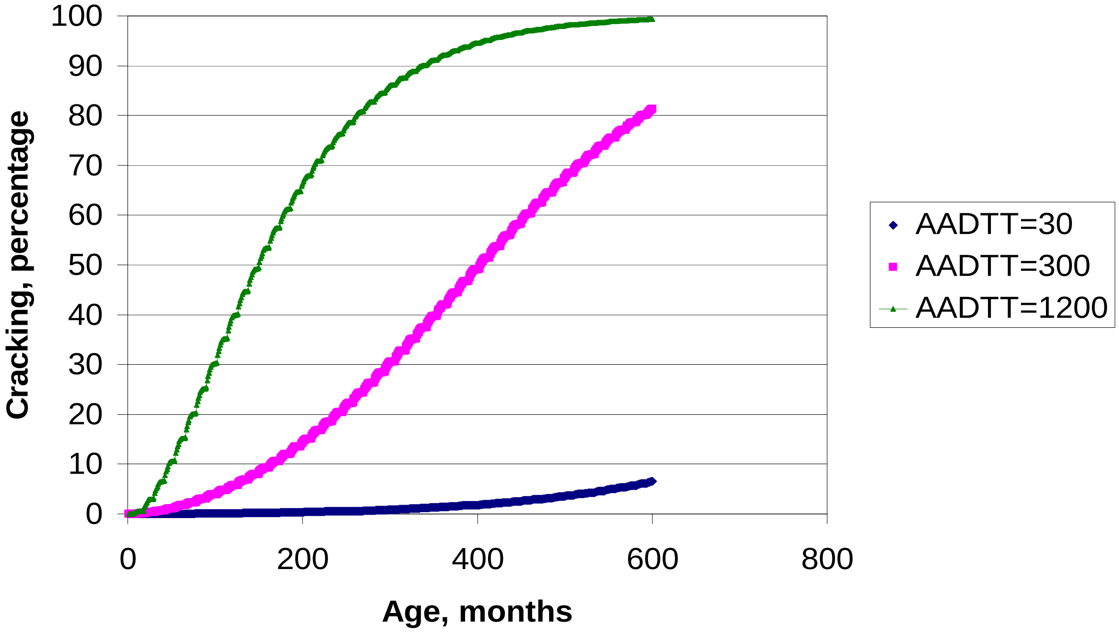


Figure A-2. Effect of traffic on cracking, HPCC =7, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

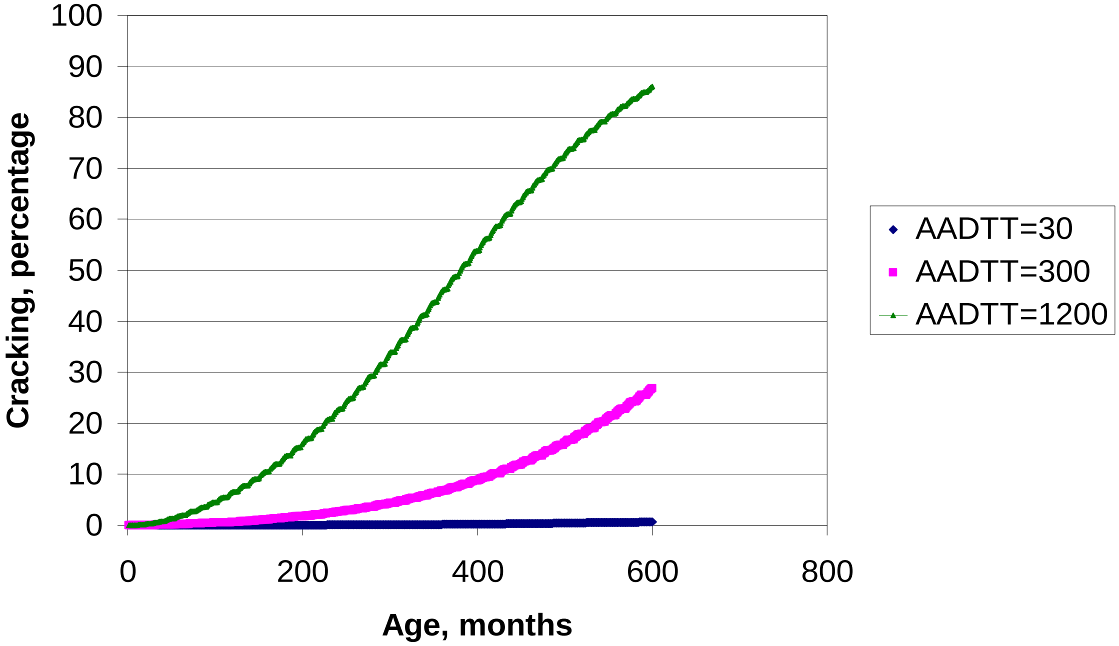


Figure A-3. Effect of traffic on cracking, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

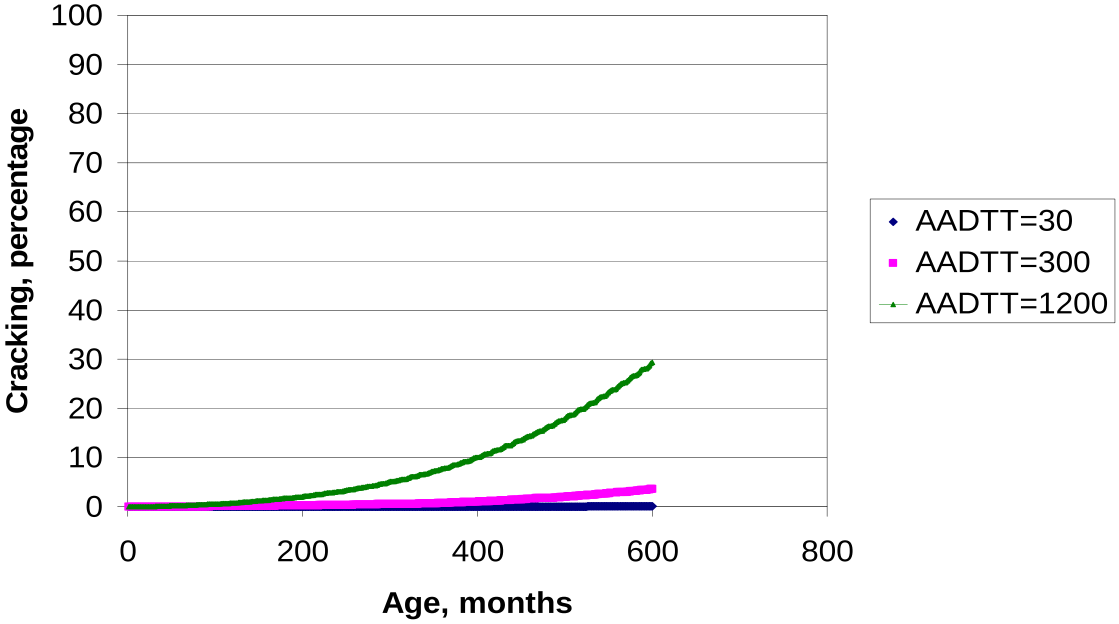


Figure A-4. Effect of traffic on cracking, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

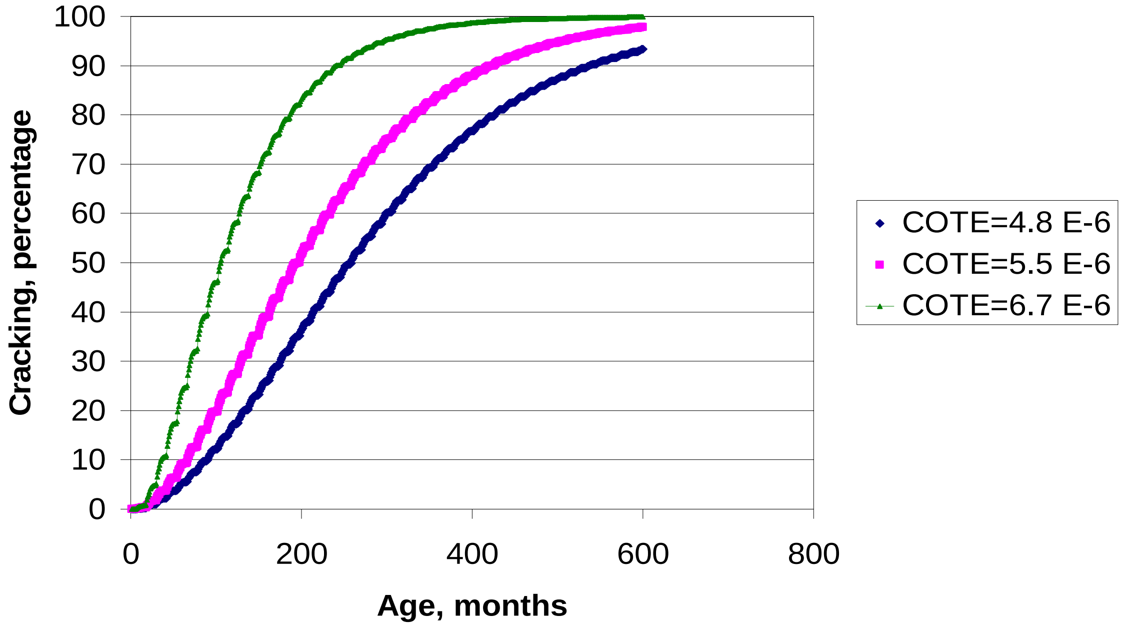


Figure A-5. Effect of COTE on cracking, AADTT=300, HPCC =6,, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

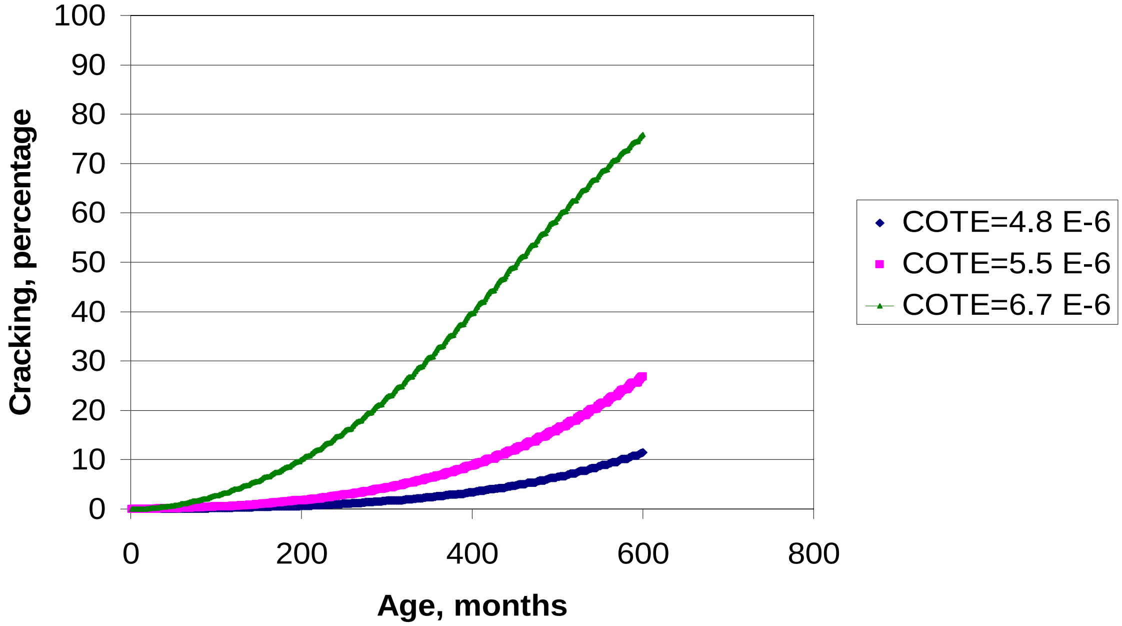


Figure A-6. Effect of COTE on cracking, AADTT=300, HPCC =8, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

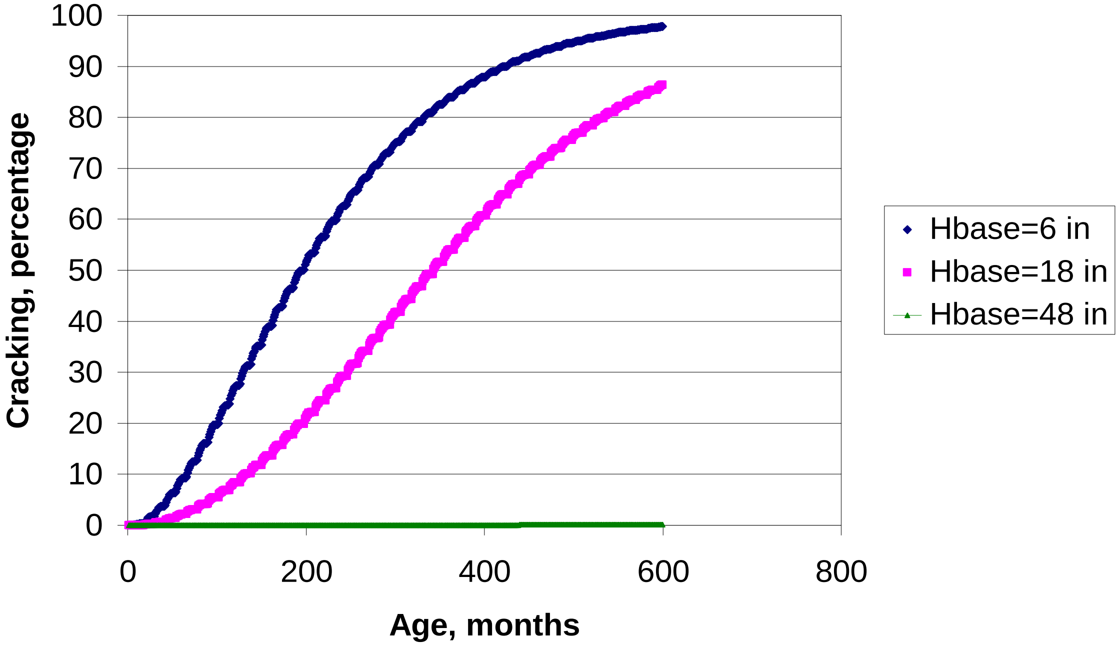


Figure A-7. Effect of base thickness on cracking, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

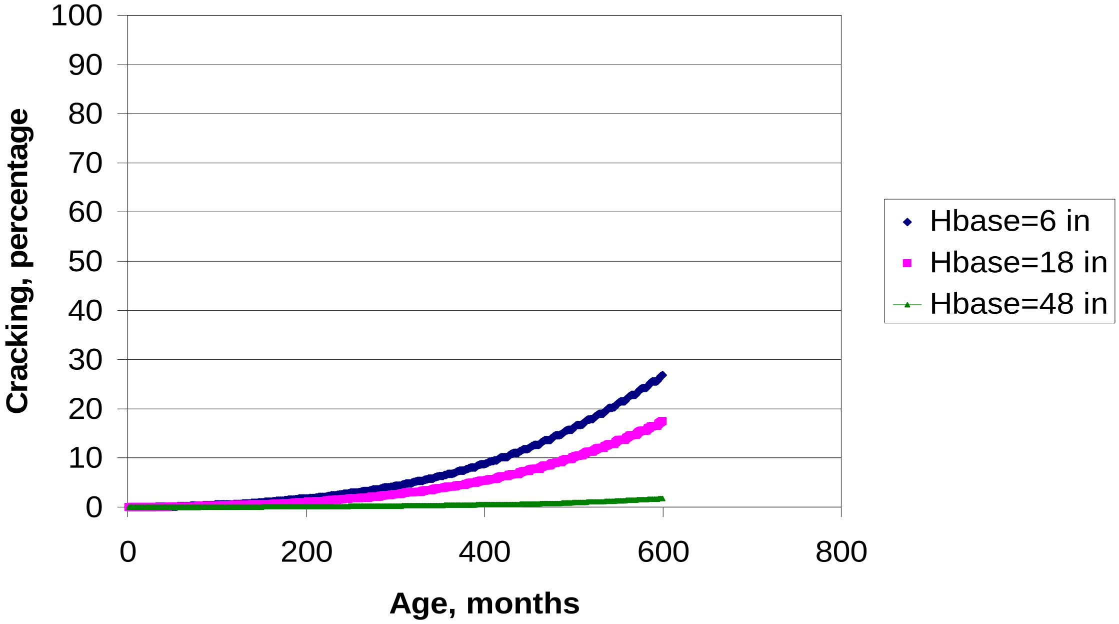


Figure A-8. Effect of base thickness on cracking, AADTT=300, HPCC =8, COTE =0.0000055, MR=700, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

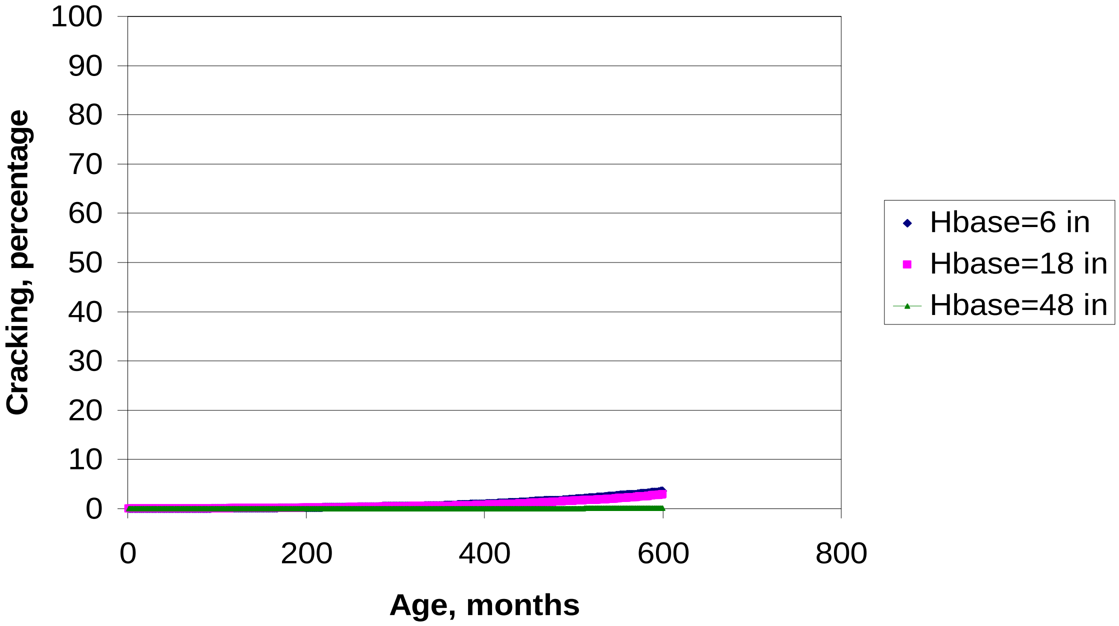


Figure A-9. Effect of base thickness on cracking, AADTT=300, HPCC =9, COTE =0.0000055, MR=700, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

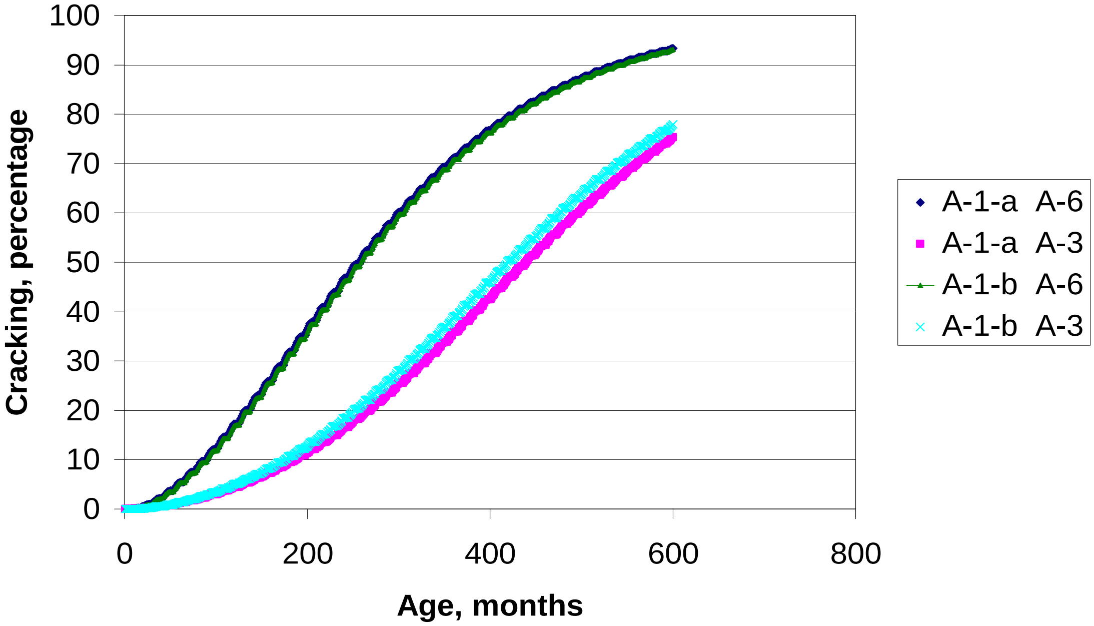


Figure A-10 Effect of base and subgrade type on cracking, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC

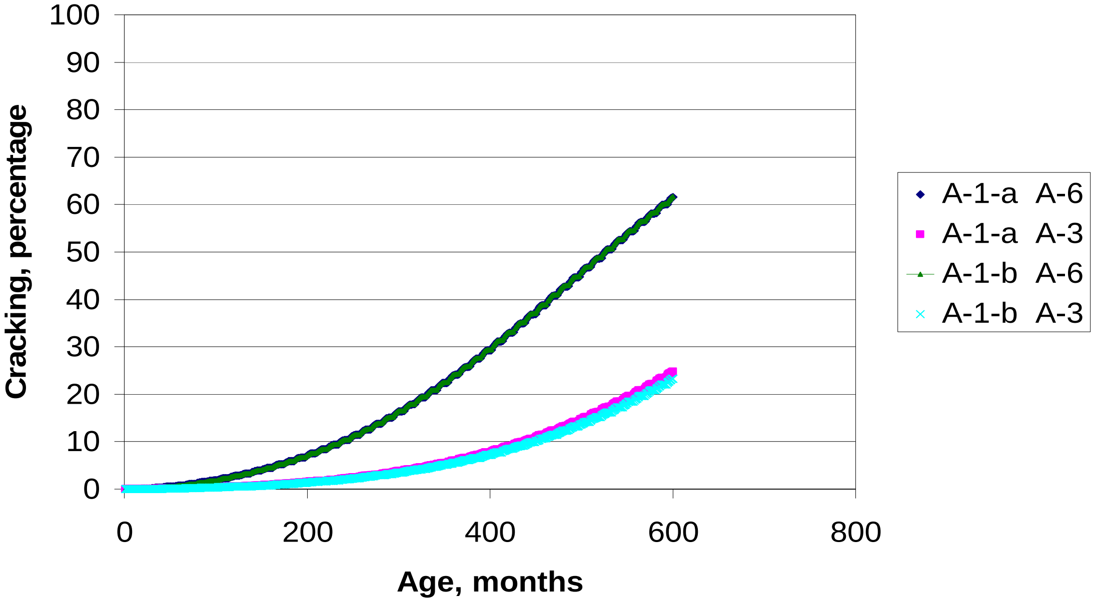


Figure A-11. Effect of base and subgrade type on cracking, AADTT=300, HPCC =7, COTE =0.0000055, MR=700, HBase=6-, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC

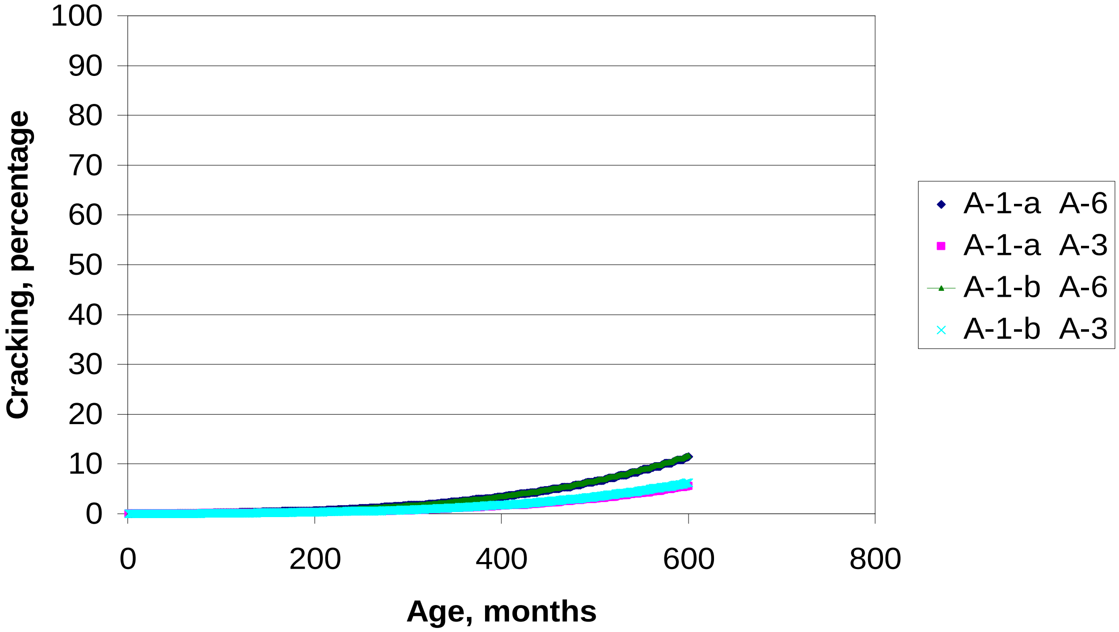


Figure A-12. Effect of base and subgrade type, AADTT=300, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders – AC.

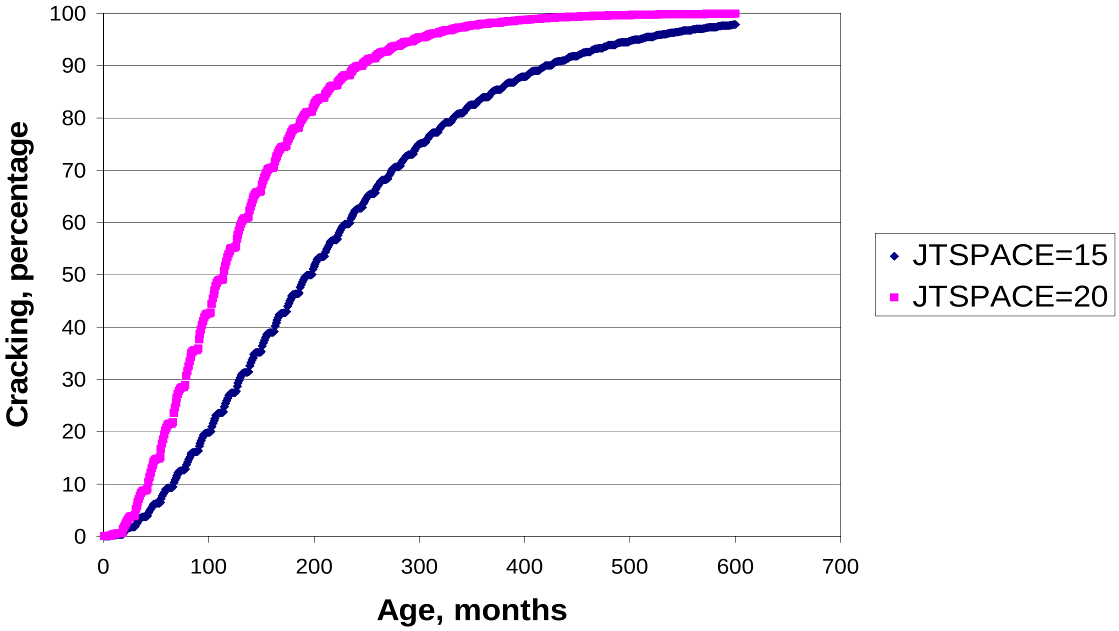


Figure A-13. Effect of joint spacing on cracking, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

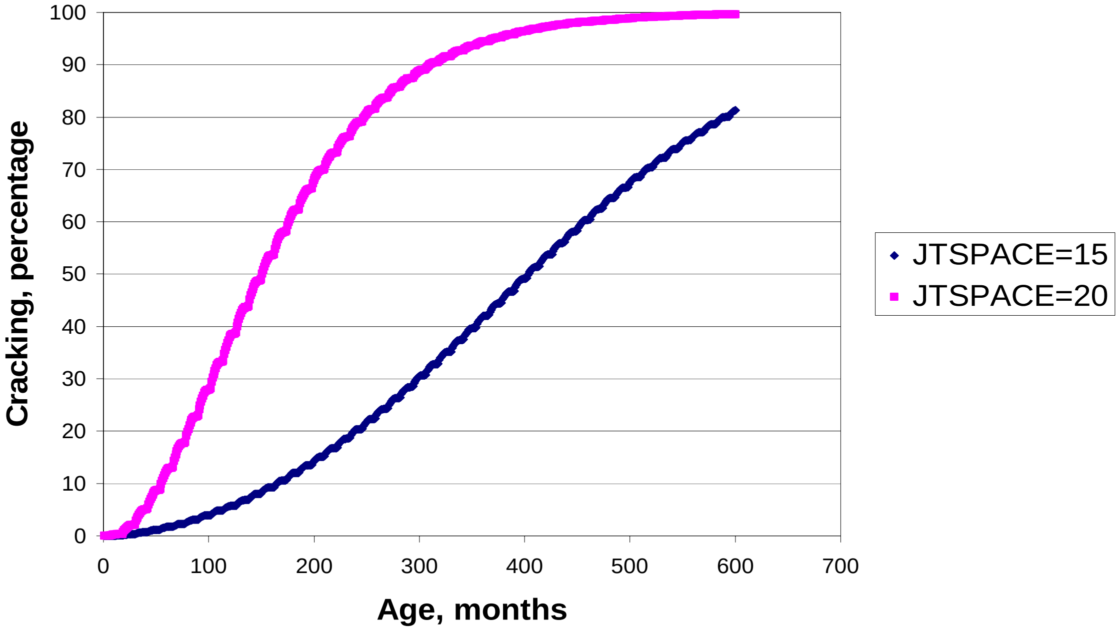


Figure A-14. Effect of joint spacing on cracking, AADTT=300, HPCC =7, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

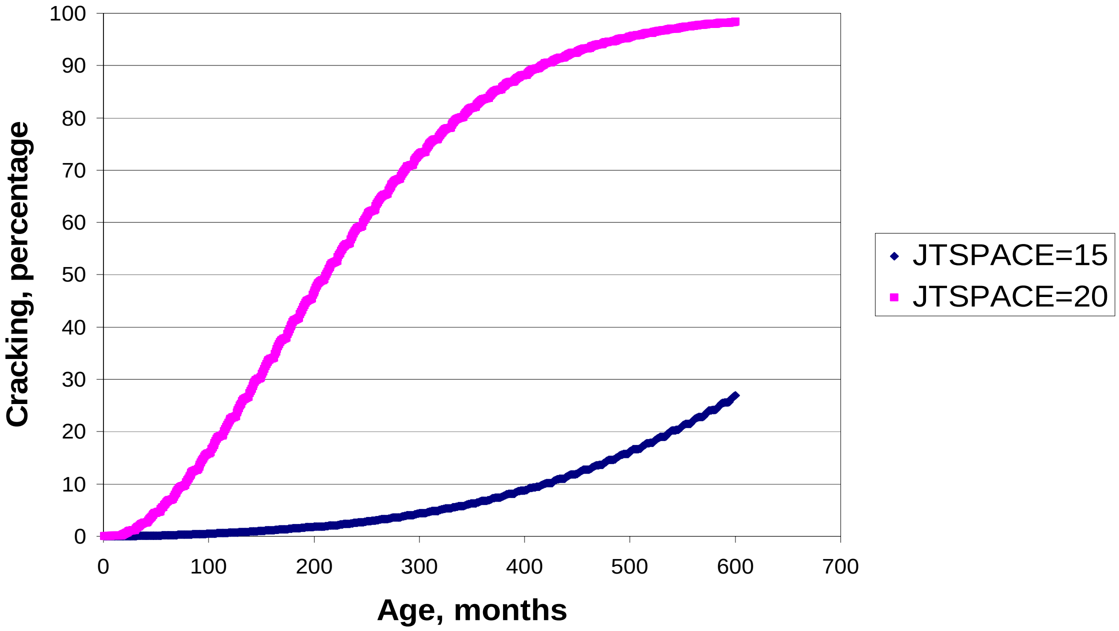


Figure A-15. Effect of joint spacing on cracking, AADTT=300, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

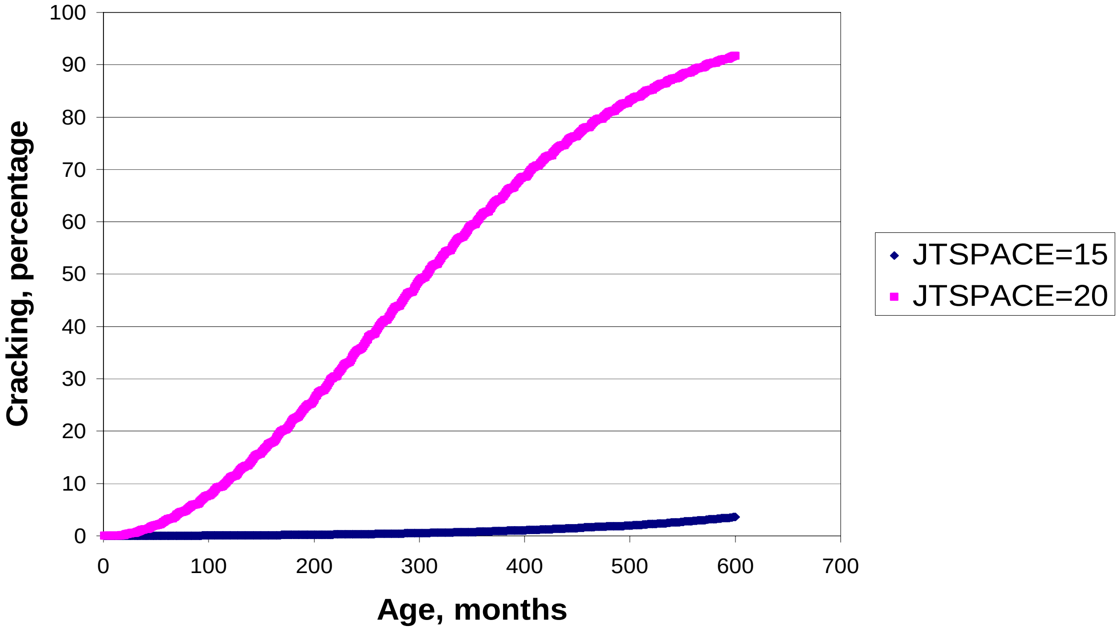


Figure A-16. Effect of joint spacing on cracking, AADTT=300, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

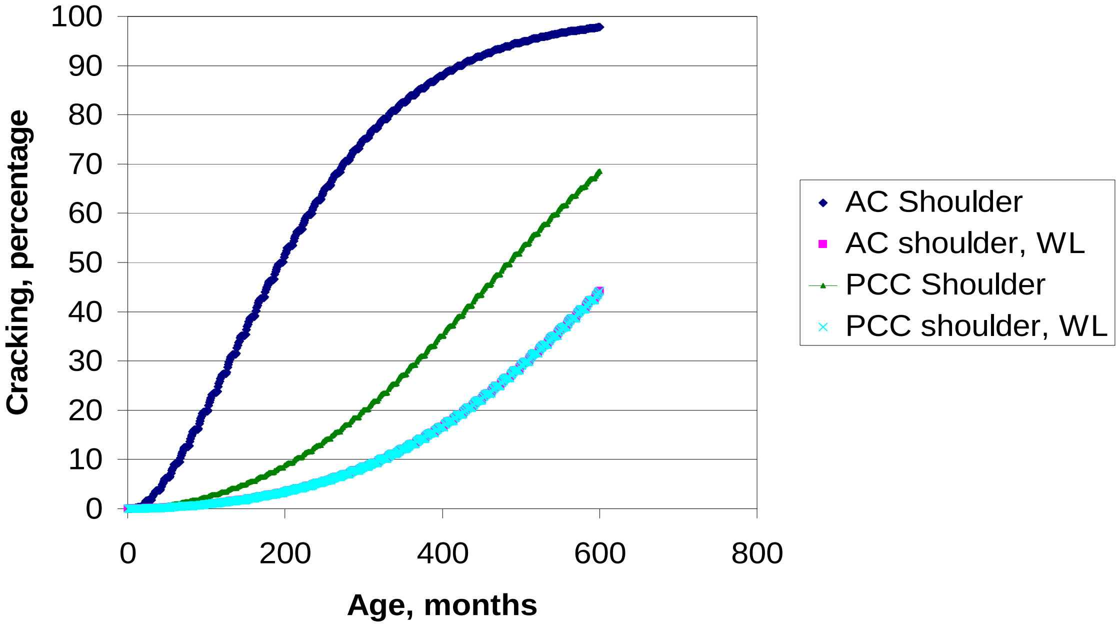


Figure A-17. Effect of edge support on cracking, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6

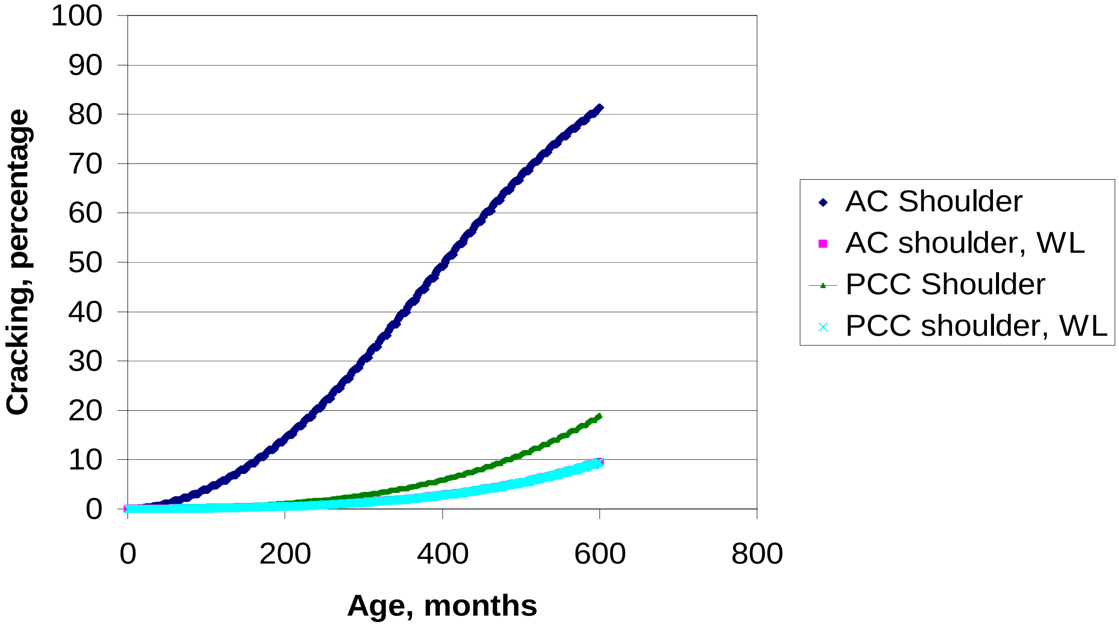


Figure A-18. Effect of edge support on cracking, AADTT=300, HPCC =7, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6

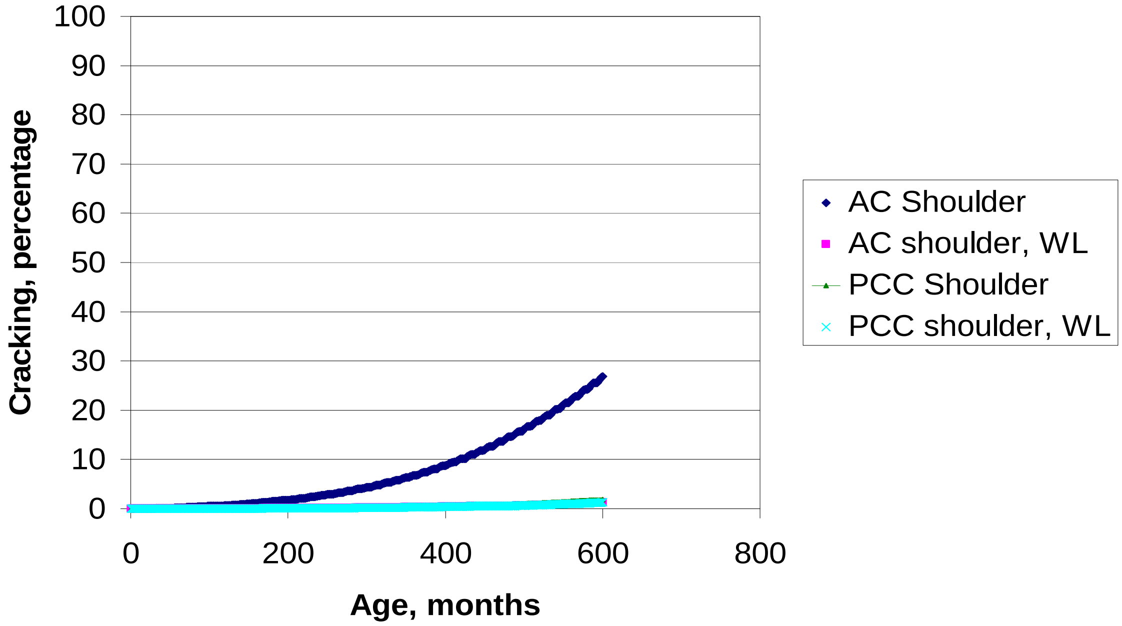


Figure A-19. Effect of edge support on cracking, AADTT=300, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6

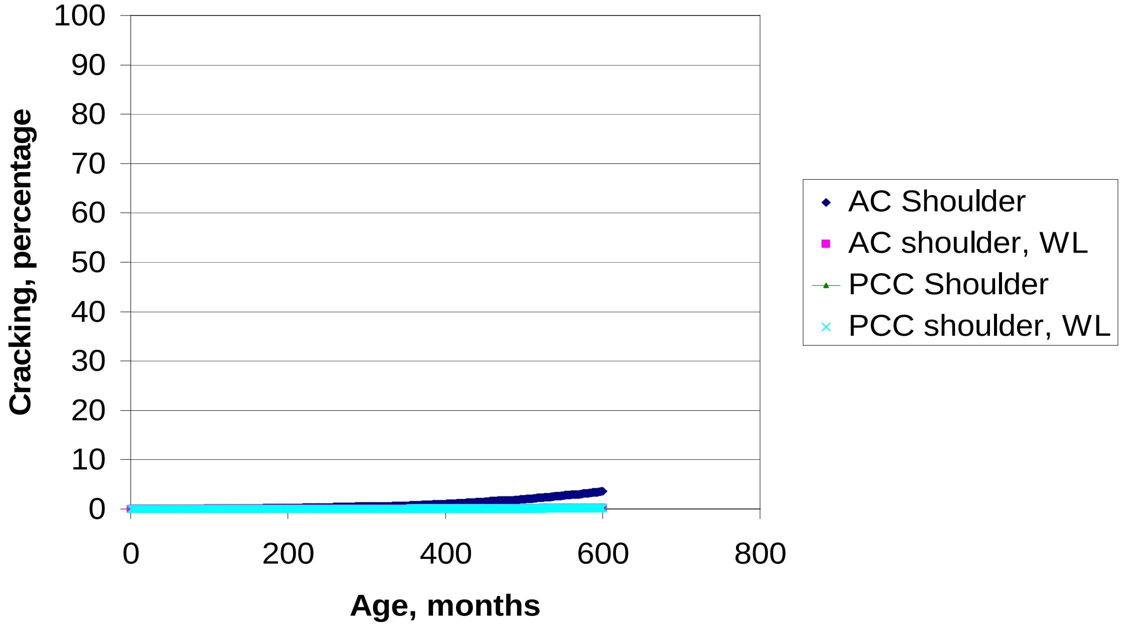


Figure A-20. Effect of edge support on cracking, AADTT=300, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6

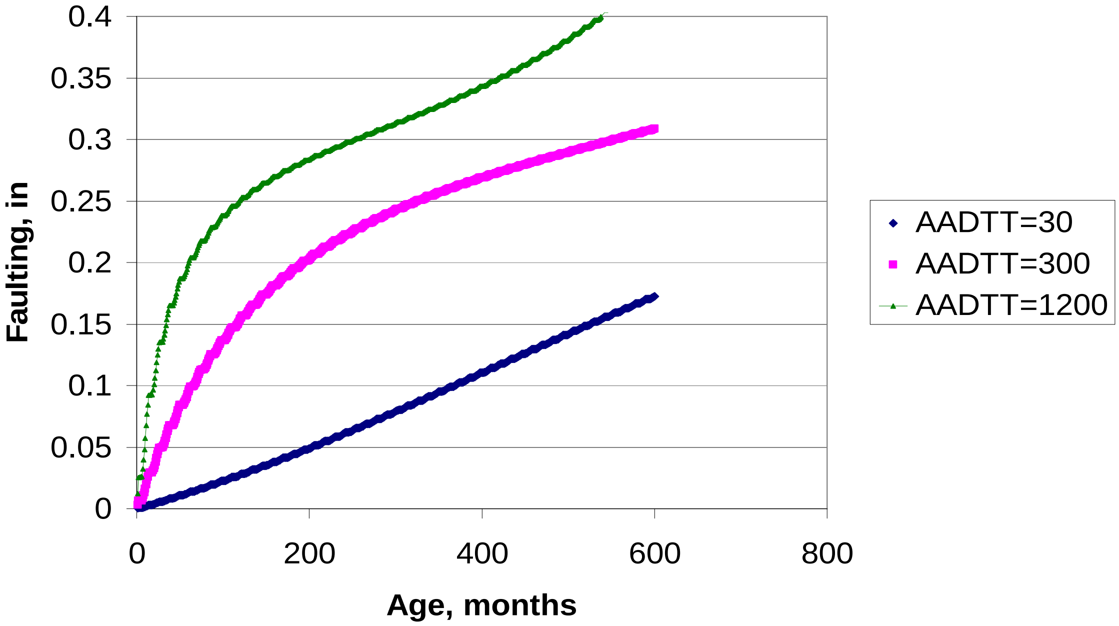


Figure A-21. Effect of traffic on faulting, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 0, Shoulders - AC, Subgrade - A-6

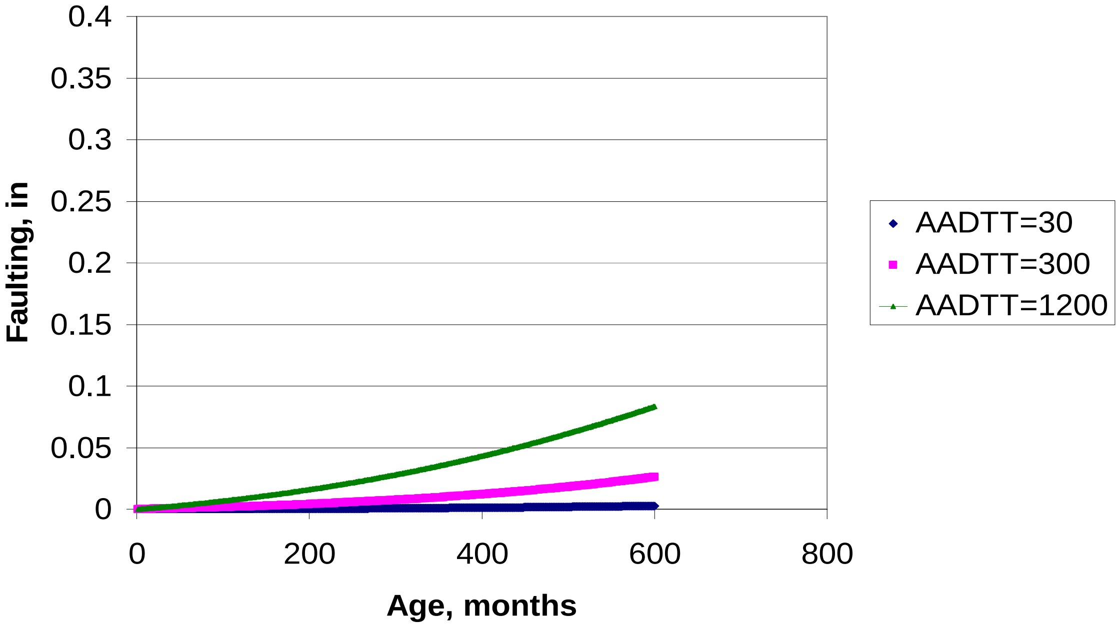


Figure A-22. Effect of traffic on faulting, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.5, Shoulders - AC, Subgrade - A-6

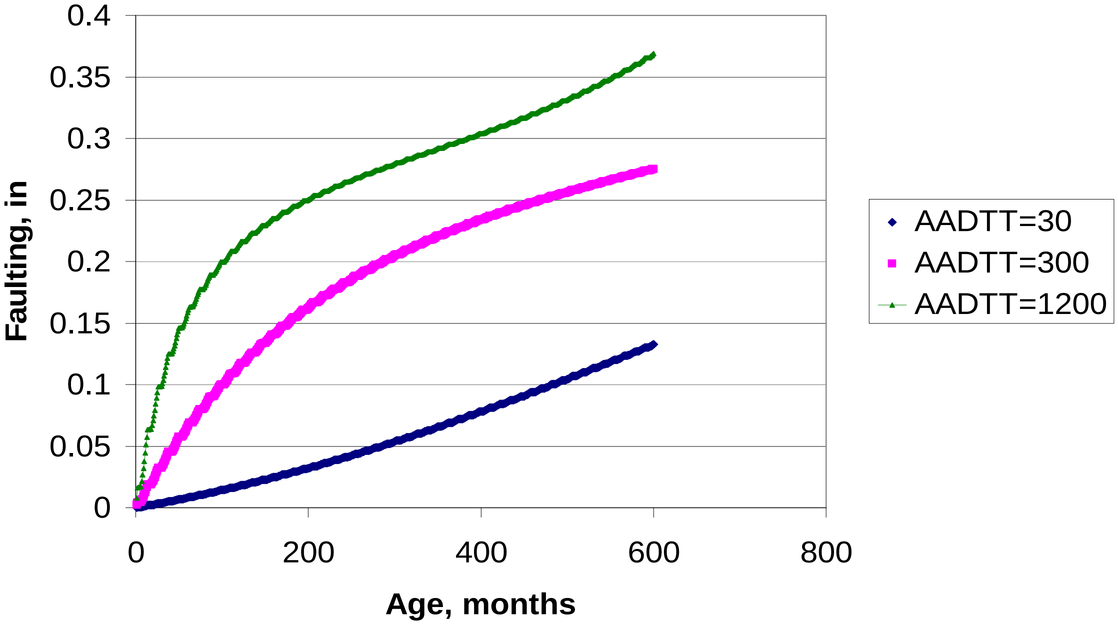


Figure A-23. Effect of traffic on faulting, HPCC =7, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 0, Shoulders - AC, Subgrade - A-6

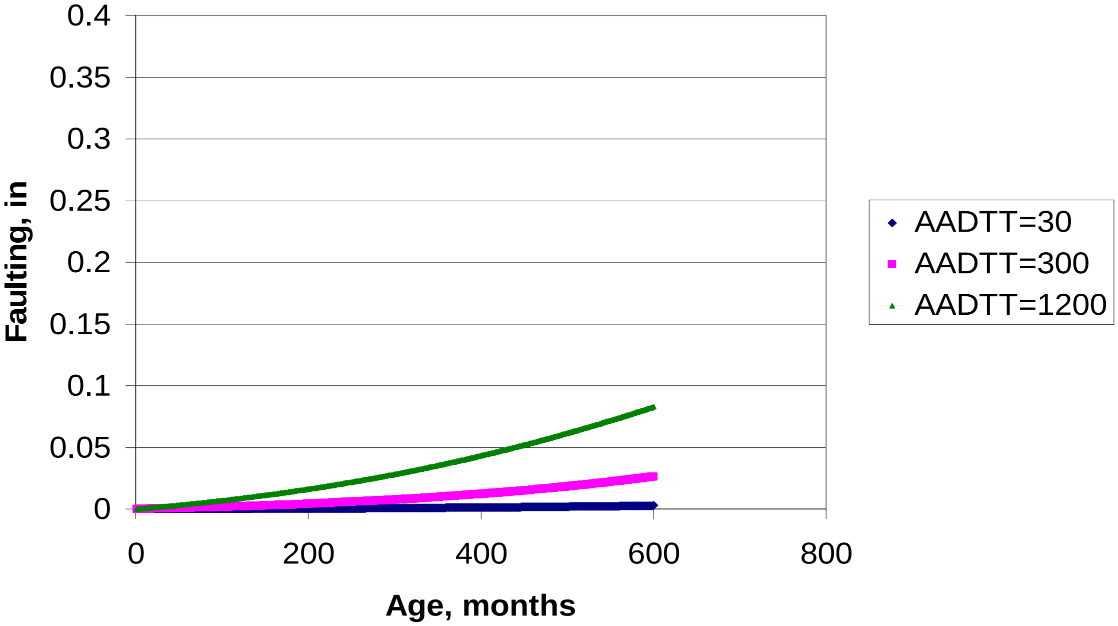


Figure A-24. Effect of traffic on faulting, HPCC =7, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.5, Shoulders - AC, Subgrade - A-6

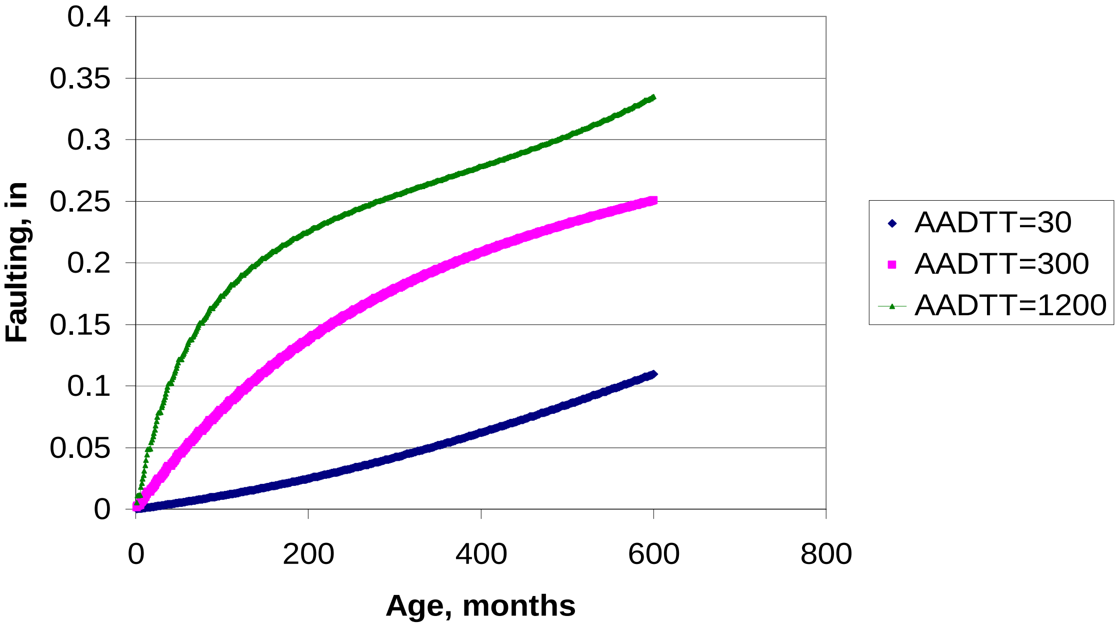


Figure A-25. Effect of traffic on faulting, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 0, Shoulders - AC, Subgrade - A-6

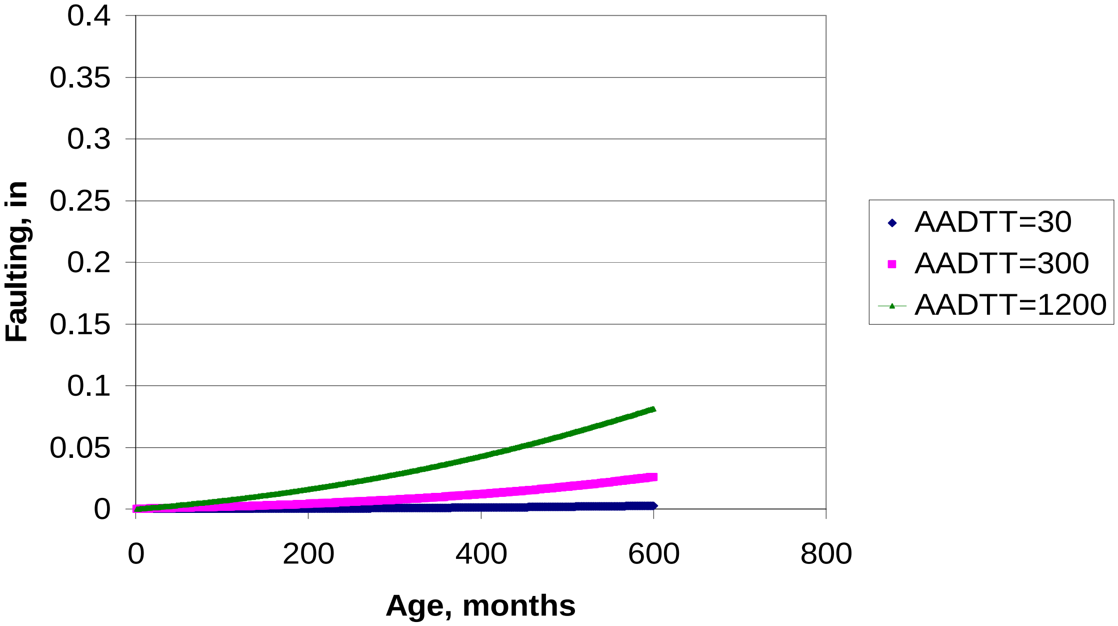


Figure A-26. Effect of traffic on faulting, AADTT=, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.5, Shoulders - AC, Subgrade - A-6

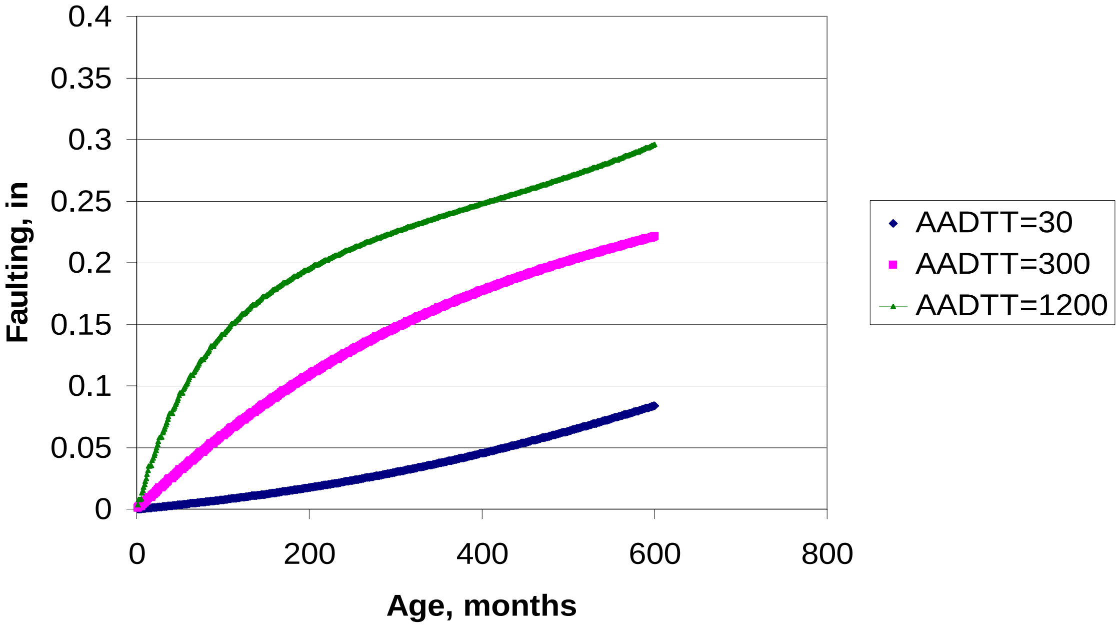


Figure A-27. Effect of traffic on faulting, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 0, Shoulders - AC, Subgrade - A-6

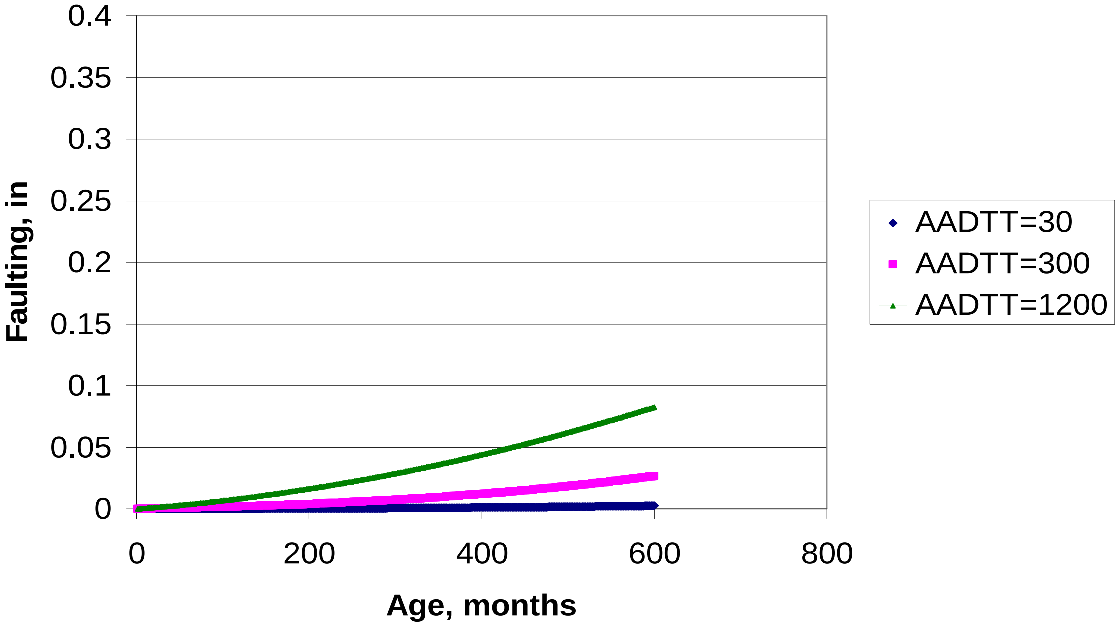


Figure A-28. Effect of traffic on faulting, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.5, Shoulders - AC, Subgrade - A-6

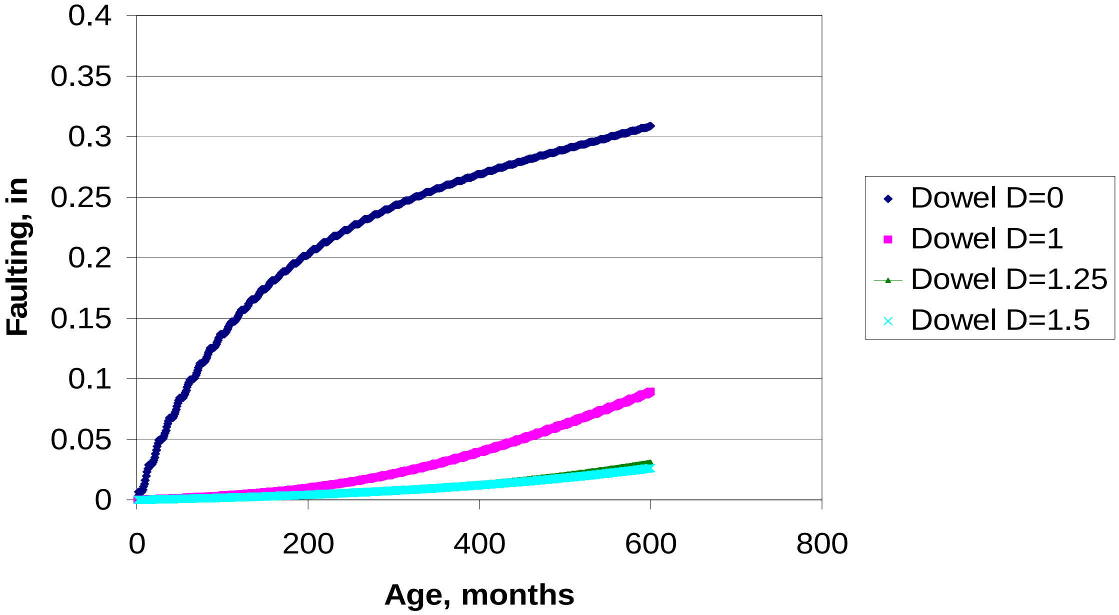


Figure A-29. Effect of dowel diameter on faulting, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Shoulders - AC, Subgrade - A-6

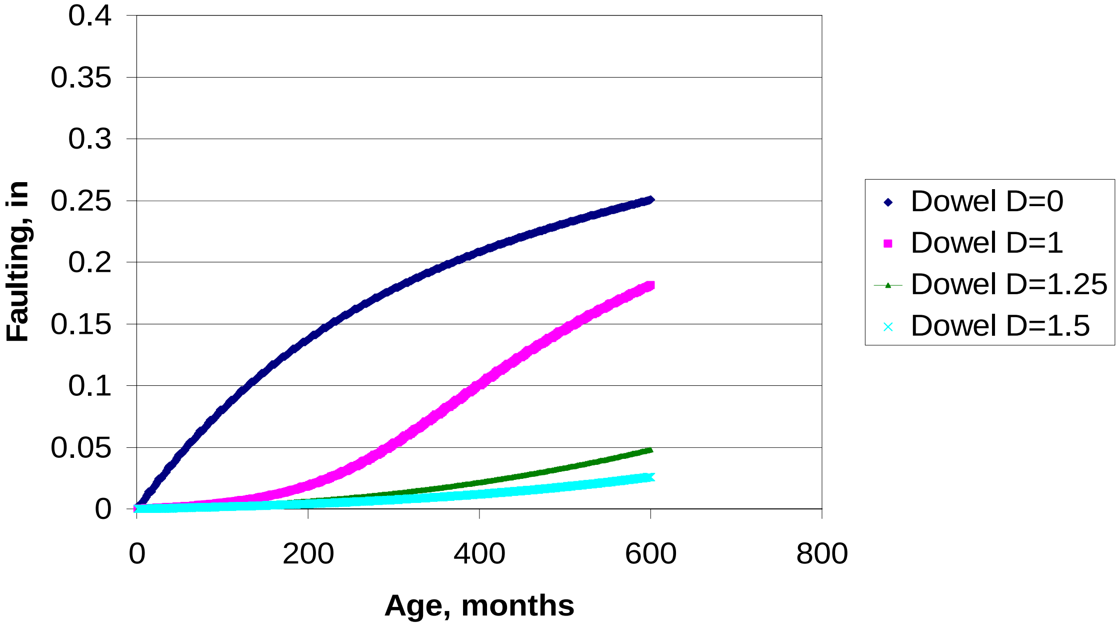


Figure A-30. Effect of dowel diameter on faulting, AADTT=300, HPCC =8, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Shoulders - AC, Subgrade - A-6

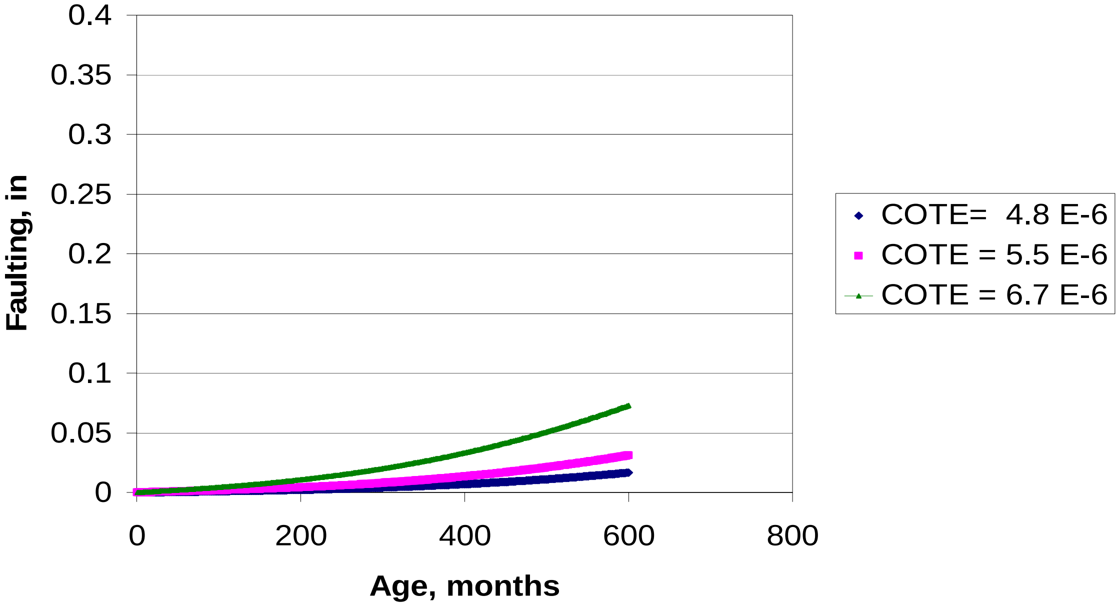


Figure A-31. Effect of COTE on faulting, AADTT=300, HPCC =6, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

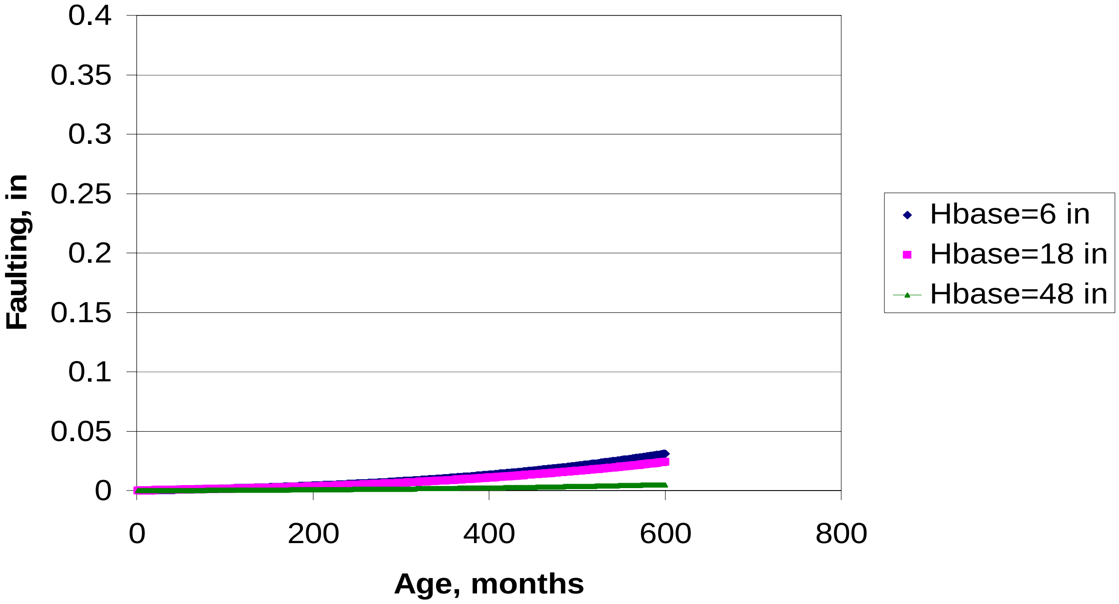


Figure A-32. Effect of base thickness on faulting, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

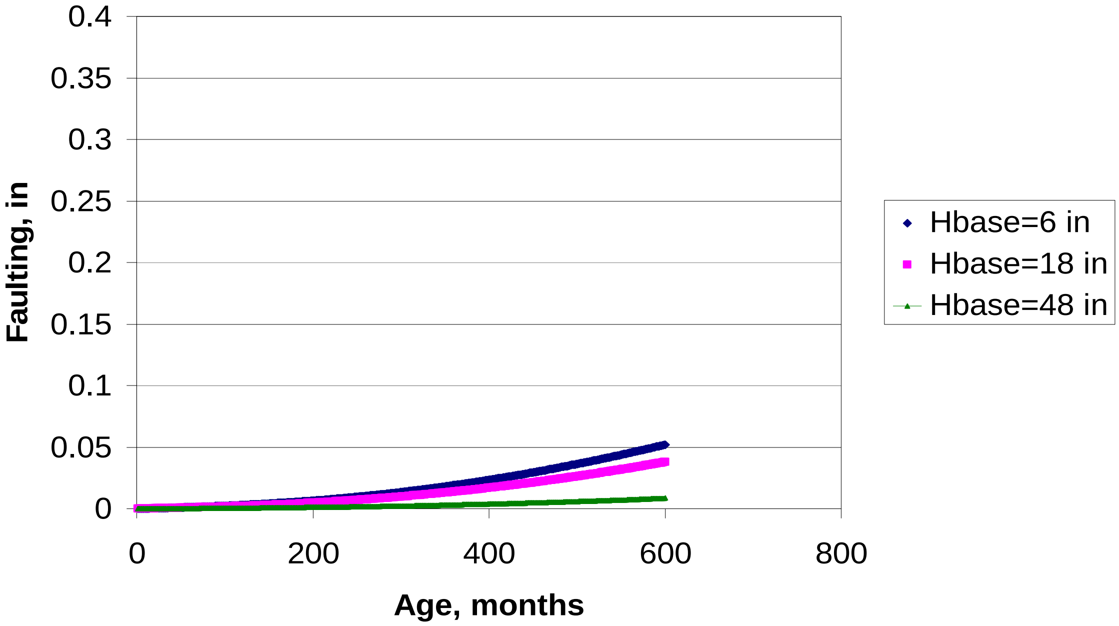


Figure A-33. Effect of base thickness on faulting, AADTT=300, HPCC =9, COTE =0.0000055, MR=700, Base -A-1-a, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

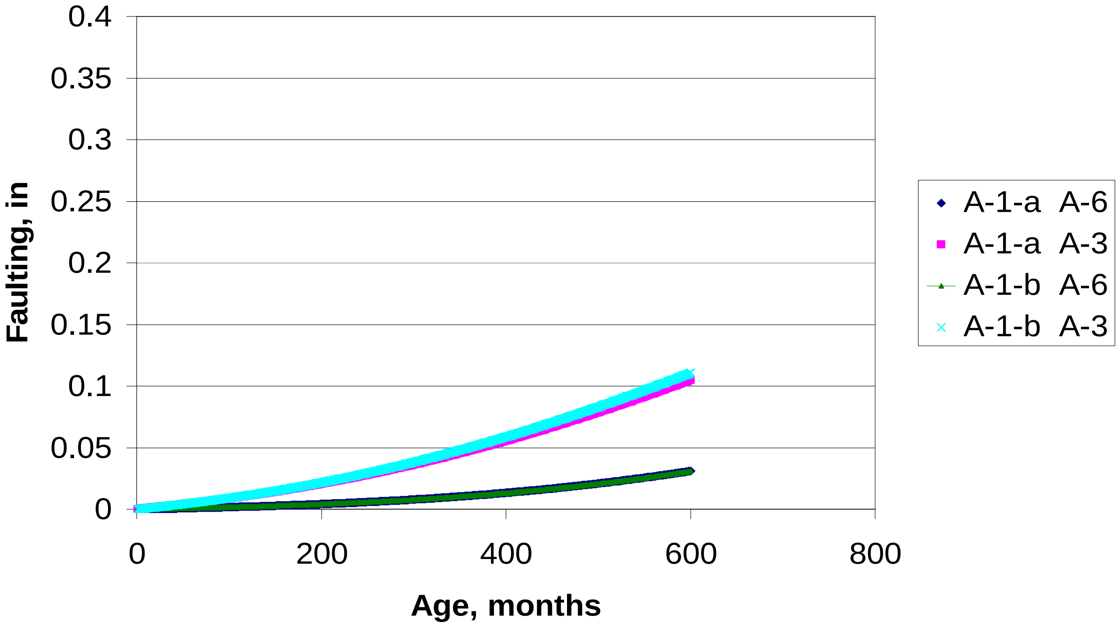


Figure A-34. Effect of base and subgrade type on faulting, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Lane Width =12, Joint Spacing =15, Dowel D = 1.25, Shoulders - AC,

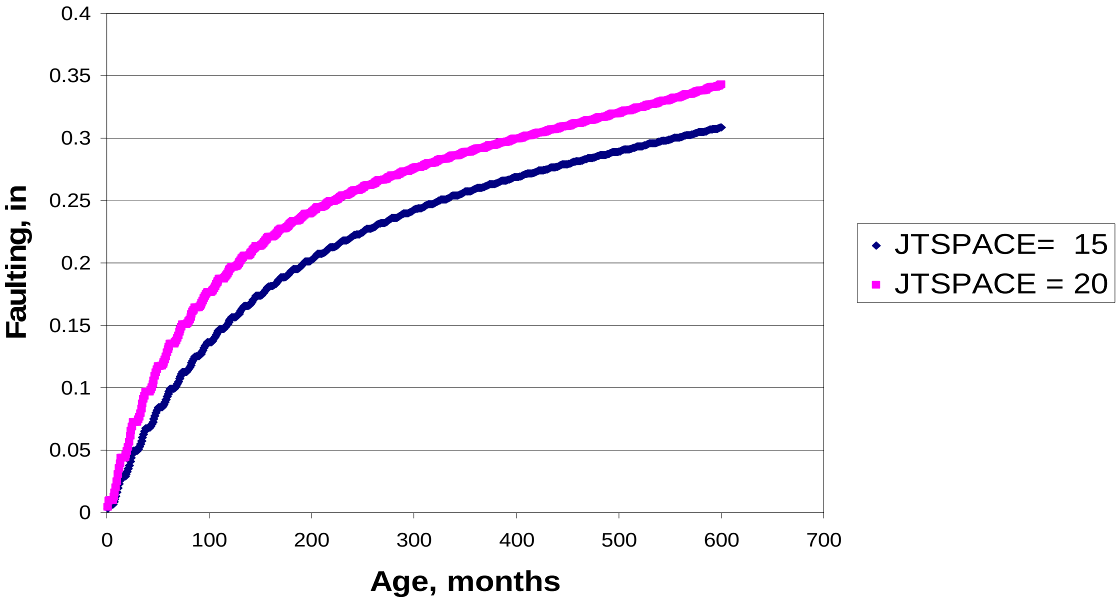


Figure A-35. Effect of joint spacing on faulting, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =12, Dowel D = 1.25, Shoulders - AC, Subgrade - A-6

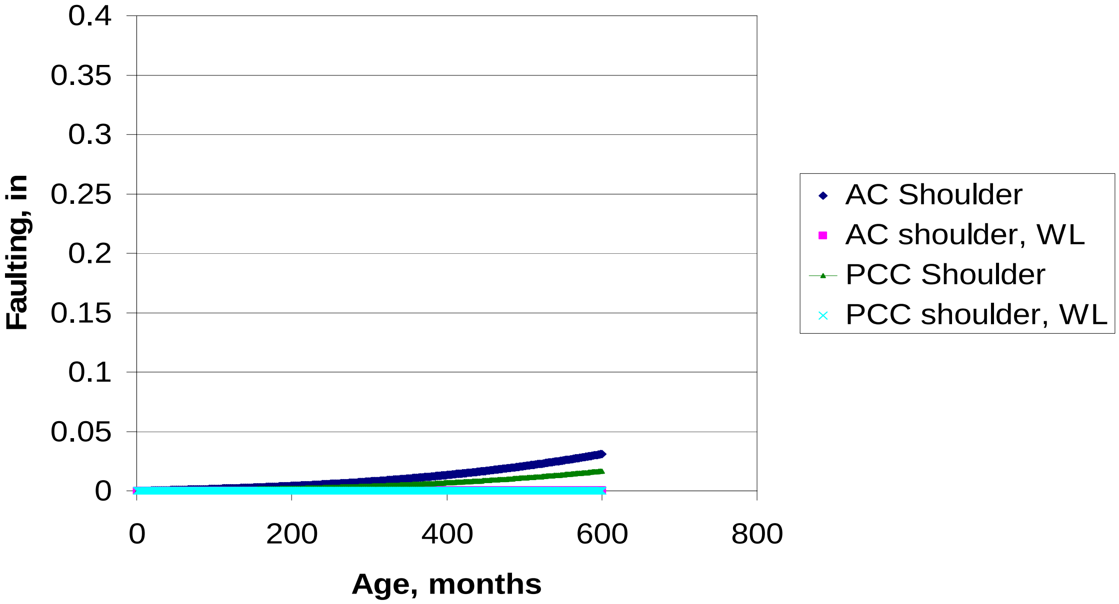


Figure A-36: Effect of edge support on faulting, AADTT=300, HPCC =6, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6

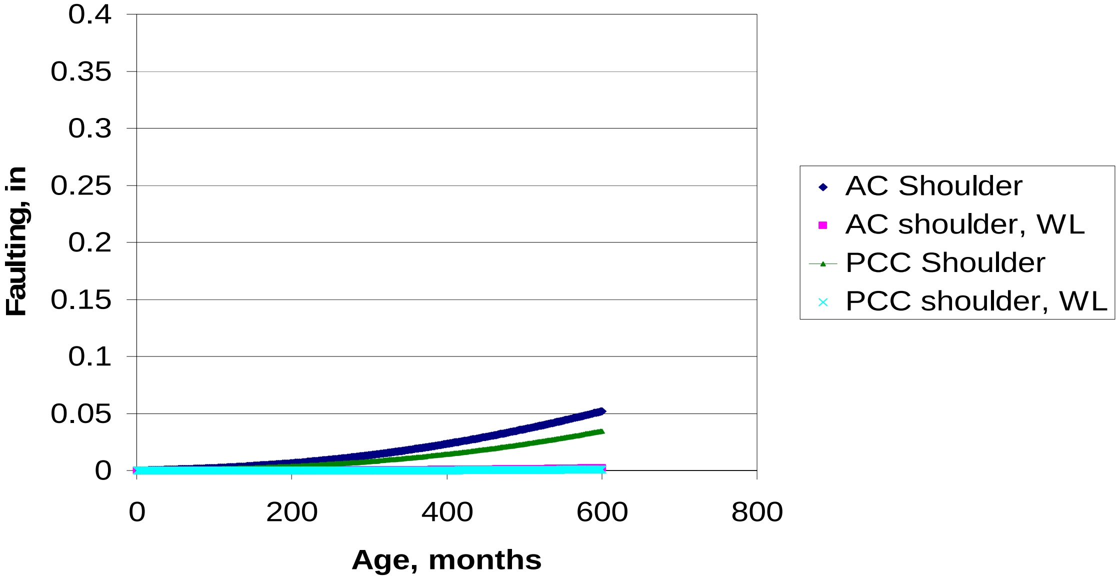
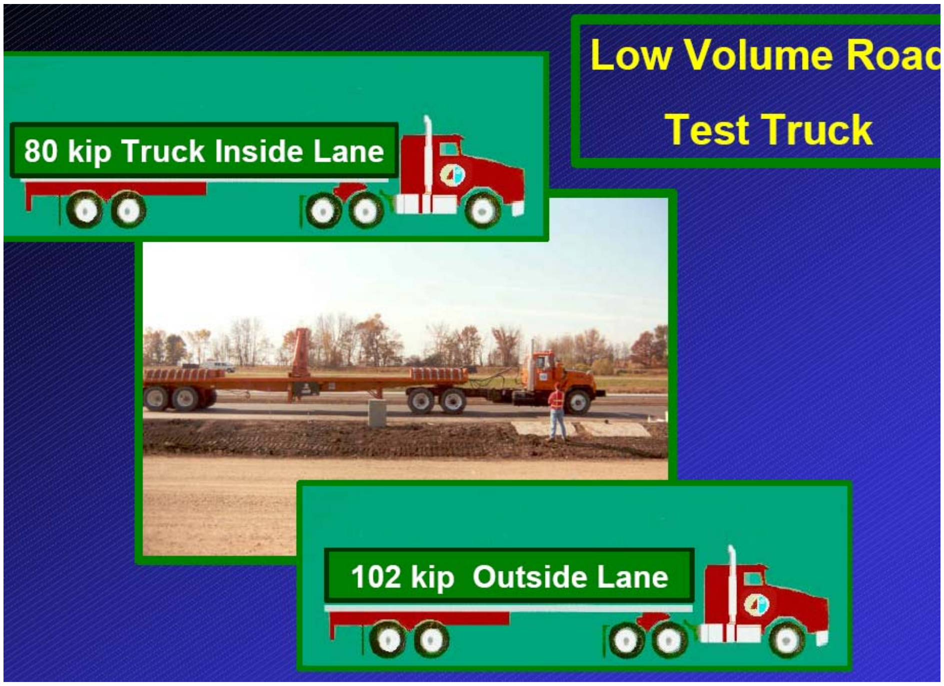


Figure A-37: Effect of edge support on faulting, AADTT=300, HPCC =9, COTE =0.0000055, MR=700, HBase=6, Base -A-1-a, Lane Width =, Joint Spacing =15, Dowel D = 1.25, Subgrade - A-6.

Appendix B. Traffic and Design Parameters at MnROAD Low-Volume Loop



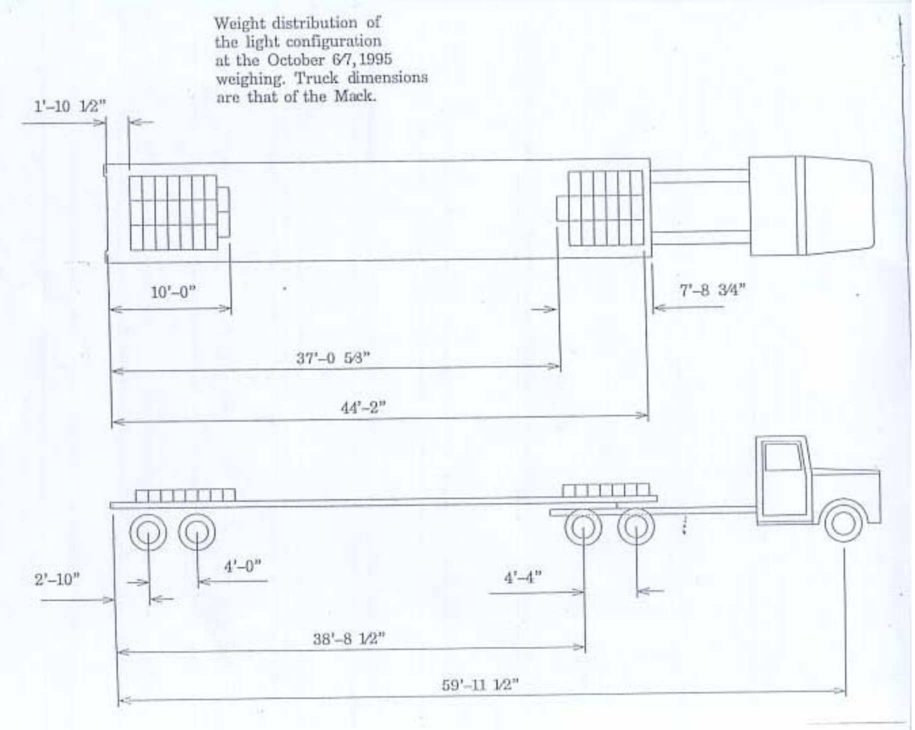
Low Volume Roa

Test Truck

80 kip Truck Inside Lane

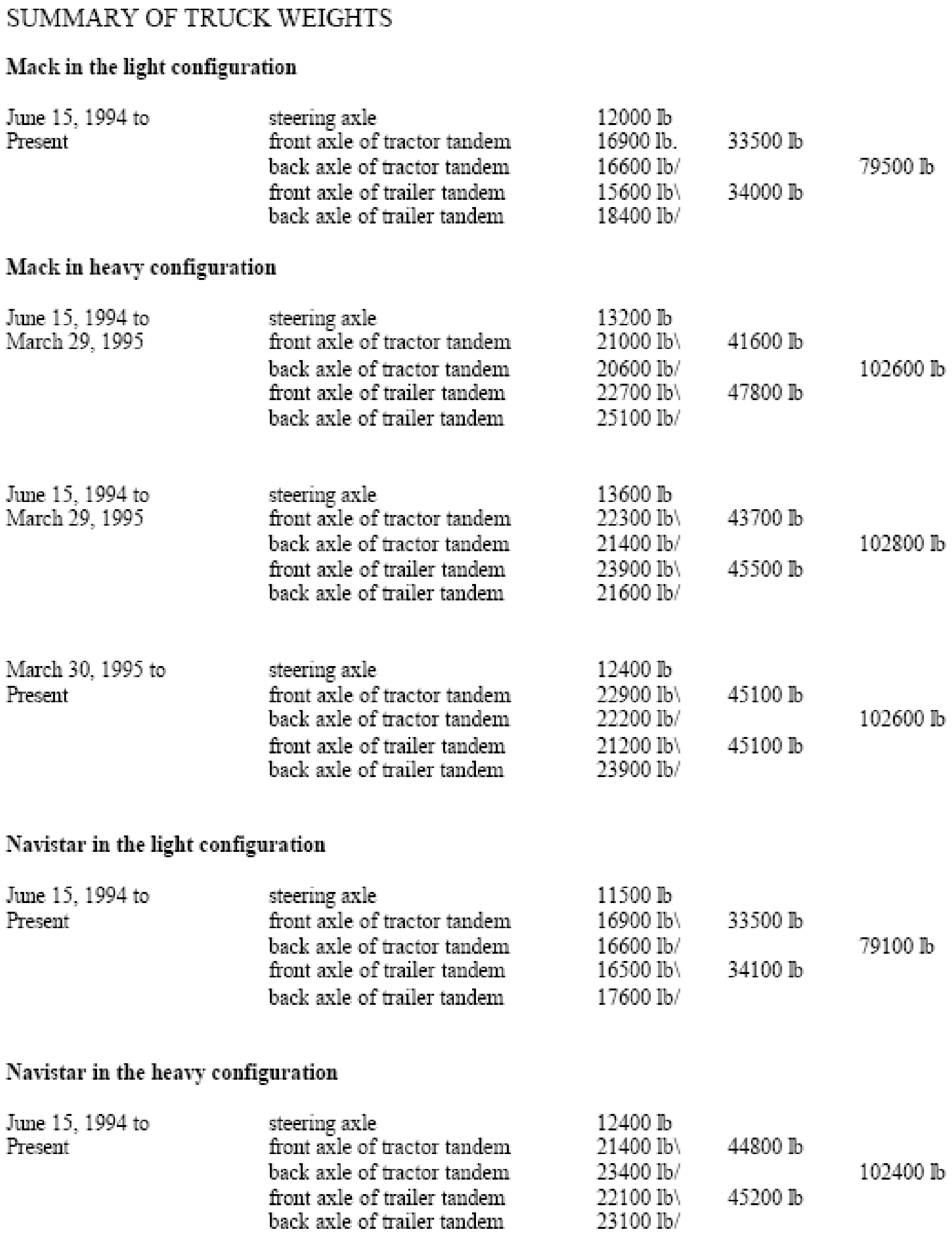
102 kip Outside Lane

Figure B-1 Traffic distribution



Weight distribution of the light configuration at the October 6/7, 1995 weighing. Truck dimensions are that of the Mack.

Figure B-2 Axle distribution



SUMMARY OF TRUCK WEIGHTS

Mack in the light configuration

June 15, 1994 to Present	steering axle	12000 lb		
	front axle of tractor tandem	16900 lb.	33500 lb	
	back axle of tractor tandem	16600 lb/		79500 lb
	front axle of trailer tandem	15600 lb\	34000 lb	
	back axle of trailer tandem	18400 lb/		

Mack in heavy configuration

June 15, 1994 to March 29, 1995	steering axle	13200 lb		
	front axle of tractor tandem	21000 lb\	41600 lb	
	back axle of tractor tandem	20600 lb/		102600 lb
	front axle of trailer tandem	22700 lb\	47800 lb	
	back axle of trailer tandem	25100 lb/		

June 15, 1994 to March 29, 1995	steering axle	13600 lb		
	front axle of tractor tandem	22300 lb\	43700 lb	
	back axle of tractor tandem	21400 lb/		102800 lb
	front axle of trailer tandem	23900 lb\	45500 lb	
	back axle of trailer tandem	21600 lb/		

March 30, 1995 to Present	steering axle	12400 lb		
	front axle of tractor tandem	22900 lb\	45100 lb	
	back axle of tractor tandem	22200 lb/		102600 lb
	front axle of trailer tandem	21200 lb\	45100 lb	
	back axle of trailer tandem	23900 lb/		

Navistar in the light configuration

June 15, 1994 to Present	steering axle	11500 lb		
	front axle of tractor tandem	16900 lb\	33500 lb	
	back axle of tractor tandem	16600 lb/		79100 lb
	front axle of trailer tandem	16500 lb\	34100 lb	
	back axle of trailer tandem	17600 lb/		

Navistar in the heavy configuration

June 15, 1994 to Present	steering axle	12400 lb		
	front axle of tractor tandem	21400 lb\	44800 lb	
	back axle of tractor tandem	23400 lb/		102400 lb
	front axle of trailer tandem	22100 lb\	45200 lb	
	back axle of trailer tandem	23100 lb/		

Figure B-3 Load distribution

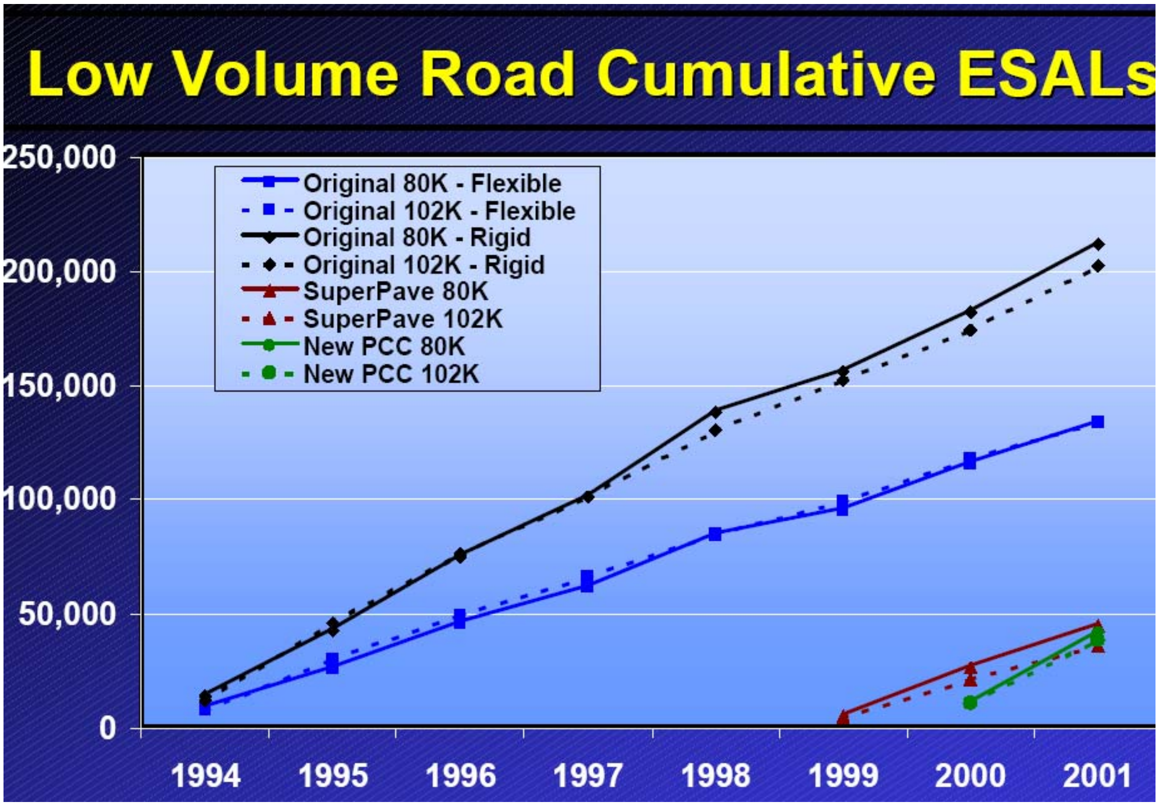
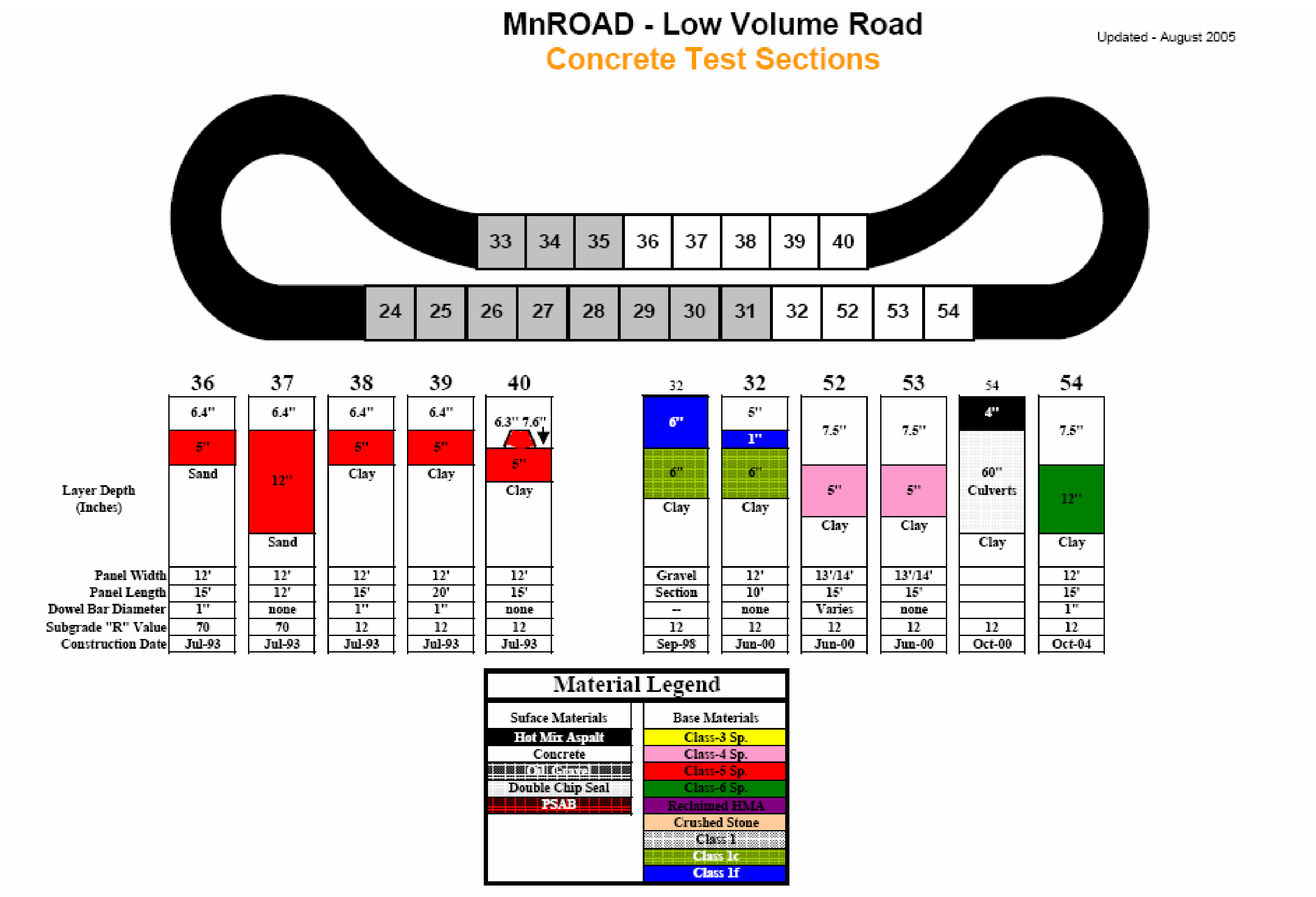


Figure B-4 MnROAD low volume loop ESALs



	36	37	38	39	40	32	32	52	53	54	54
Panel Width	12'	12'	12'	12'	12'	Gravel	12'	13'/14'	13'/14'		12'
Panel Length	15'	12'	15'	20'	15'	Section	10'	15'	15'		15'
Dowel Bar Diameter	1"	none	1"	1"	none	--	none	Varies	none		1"
Subgrade "R" Value	70	70	12	12	12	12	12	12	12	12	12
Construction Date	Jul-93	Jul-93	Jul-93	Jul-93	Jul-93	Sep-98	Jun-00	Jun-00	Jun-00	Oct-00	Oct-04

Figure B-5: MnROAD Low-Volume Test Road Sections

Table B-1. Design features for the MEPDG projects – MnROAD LVR test cells

Cell No.	Project	Design Features								
		Analysis Period years	H PCC in	H Base in	Base	Subgrade	Slab Width ft	Joint Spacing ft	Dowel Diameter in	Load
36	IM36-1	10	6.35	5	Class 5	A-3	12	15	1	80 Kip
	IM36-2	10	6.35	5	Class 5	A-3	12	15	1	102 Kip
37	IM37_1	10	6.4	12	Class 5	A-3	12	12	0	80 Kip
	IM37_2	10	6.4	12	Class 5	A-3	12	12	0	102 Kip
38	IM38_1	10	6.35	5	Class 5	A-6	12	15	1	80 Kip
	IM38_2	10	6.35	5	Class 5	A-6	12	15	1	102 Kip
39	IM39_1	10	6.38	5	Class 5	A-6	12	20	1	80 Kip
	IM39_2	10	6.38	5	Class 5	A-6	12	20	1	102 Kip
40	IM40-6.3-1	10	6.3	5	Class 5	A-6	12	15	0	80 Kip
	IM40-6.3-2	10	6.3	5	Class 5	A-6	12	15	0	102 Kip
	IM40-7.6-1	10	7.6	5	Class 5	A-6	12	15	0	80 Kip
	IM40-7.6-2	10	7.6	5	Class 5	A-6	12	15	0	102 Kip
52	IM52-1.0-1	10	7.5	5	Class 4	A-6	14	15	1	80 Kip
	IM52-1.0-2	10	7.5	5	Class 4	A-6	14	15	1	102 Kip
	IM52-1.25-1	10	7.5	5	Class 4	A-6	14	15	1.25	80 Kip
	IM52-1.25-2	10	7.5	5	Class 4	A-6	14	15	1.25	102 Kip
53	IM53-1	10	7.5	5	Class 4	A-6	14	15	0	80 Kip
	IM53-2	10	7.5	5	Class 4	A-6	14	15	0	102 Kip

Appendix C. Comparison of Predicted Cracking and Faulting of MnROAD LVR Loop: MEPDG 0.850 vs MEPDG 0.861 Distress Output

Comparison of Predicted Cracking: MEPDG 0.850 vs. MEPDG 0.868

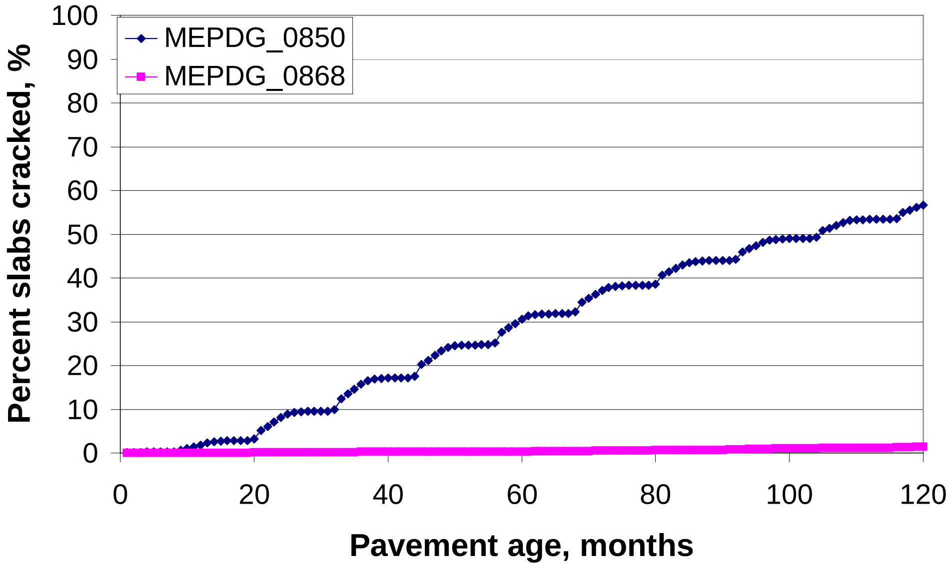


Figure C-1: Predicted cracking - Cell IM36-1, Inside lane, load = 80 Kip, HPCC =6.35, Dowel D = 1

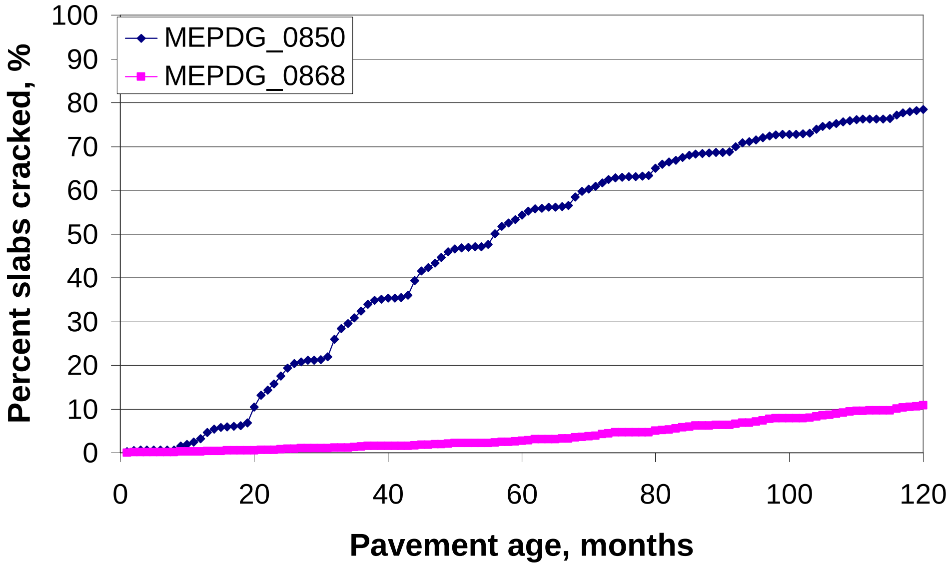


Figure C-2: Predicted cracking - Cell IM36-2, Outside lane, load=102 Kip, HPCC =6.35, Dowel D=1

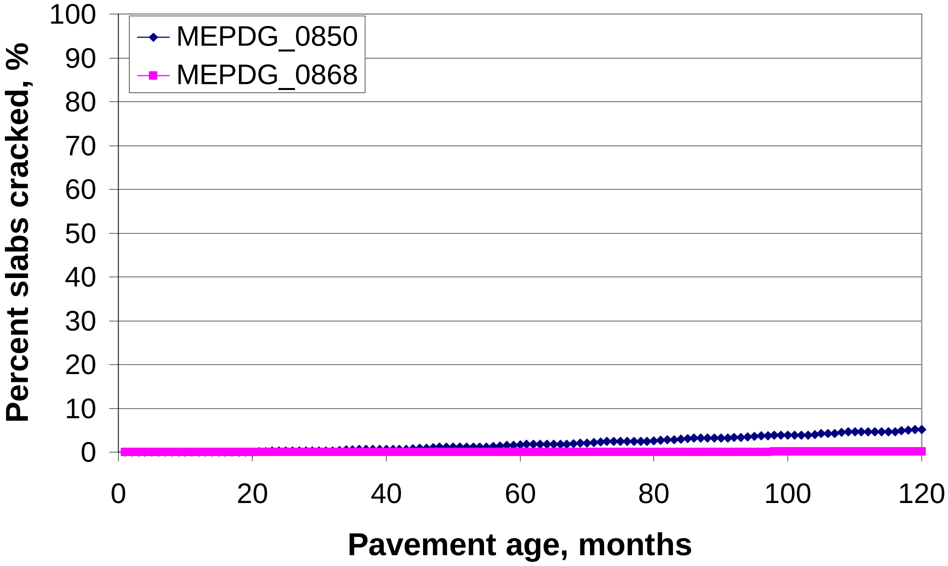


Figure C-3: Predicted cracking - Cell IM37_1, Inside lane, load = 80 Kip, HPCC =6.4, Dowel D = 0

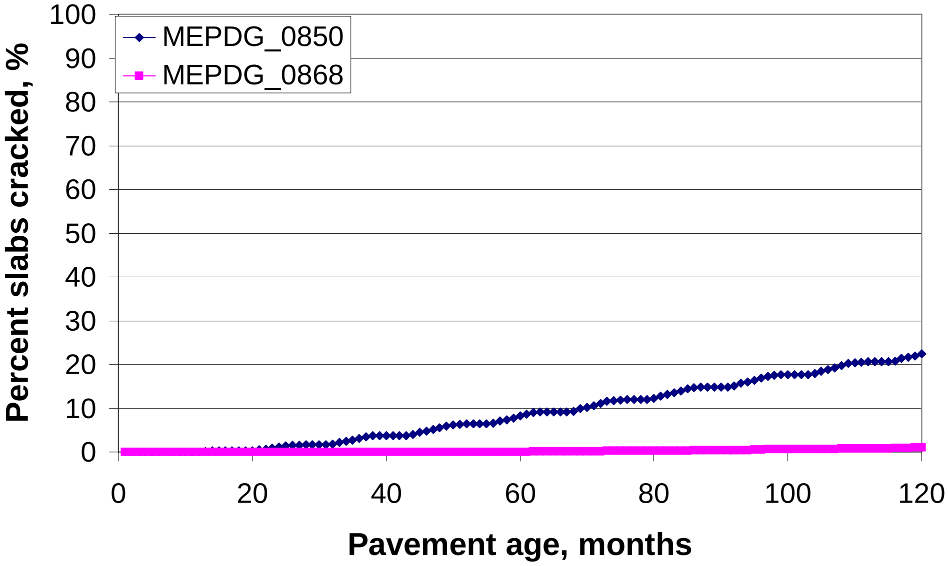


Figure C-4: Predicted cracking - Cell IM37_2, Outside lane, load = 102 Kip, HPCC =6.4, Dowel D=0

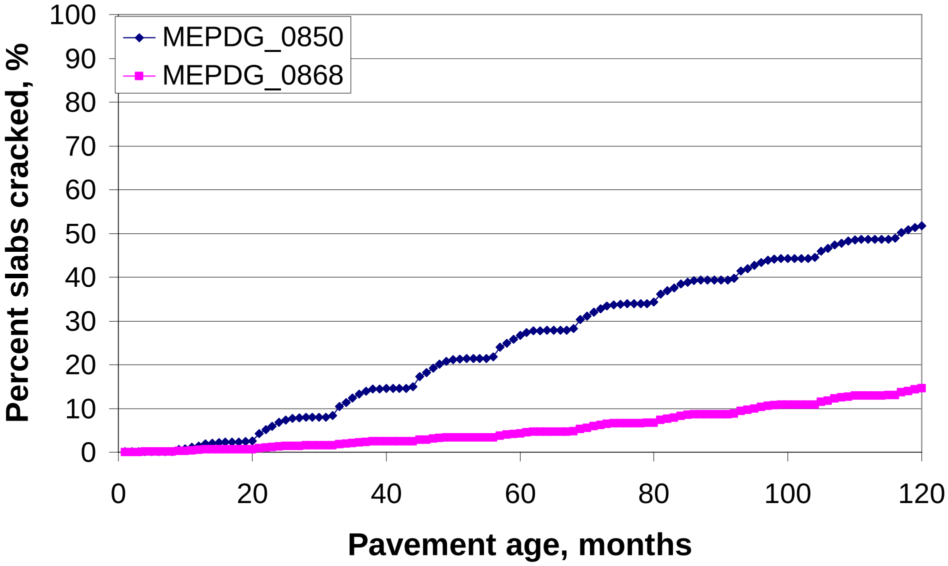


Figure C-5: Predicted cracking - Cell IM38_1, Inside lane, load = 80 Kip, HPCC =6.35, Dowel D = 1

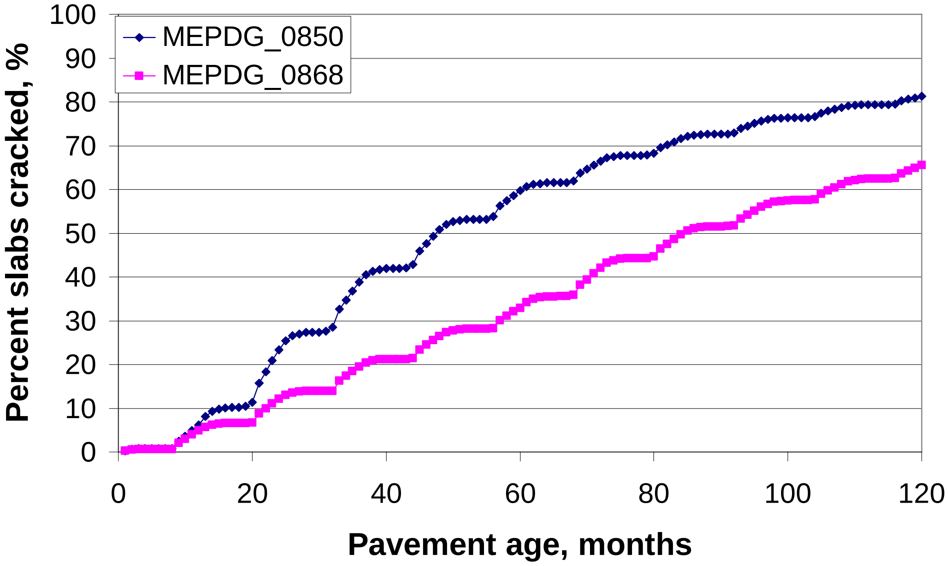


Figure C-6: Predicted cracking - Cell IM38_2, Outside lane, load = 102 Kip, HPCC =6.35, Dowel D=1

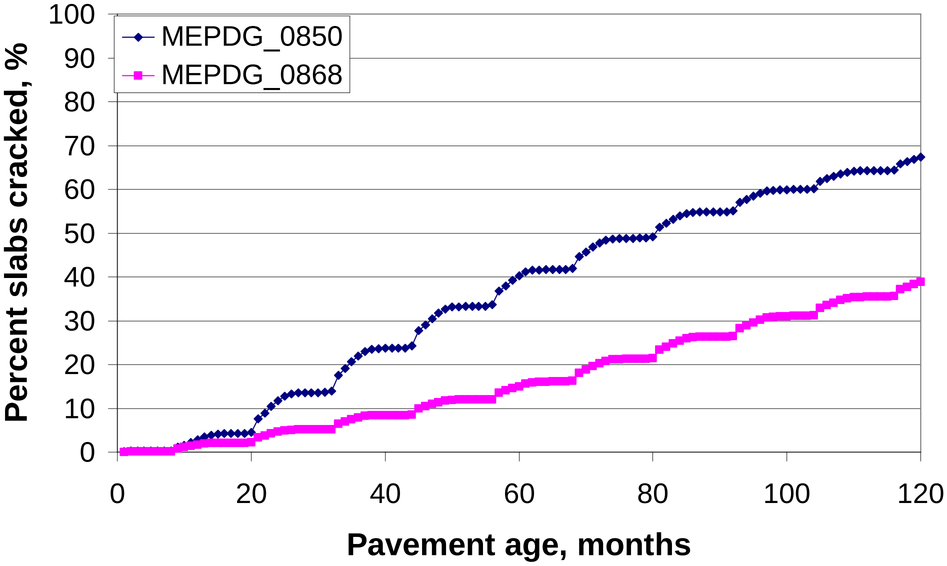


Figure C-7: Predicted cracking - Cell IM39_1, Inside lane, load = 80 Kip, HPCC =6.38, Dowel D = 1

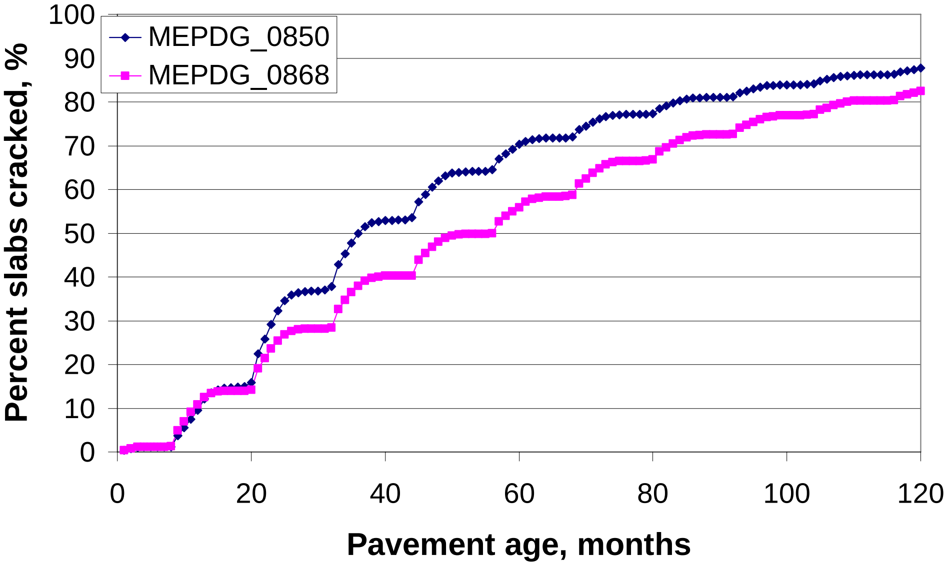


Figure C-8: Predicted cracking - Cell IM39_2, Outside lane, load = 102 Kip, HPCC =6.38, Dowel D=1

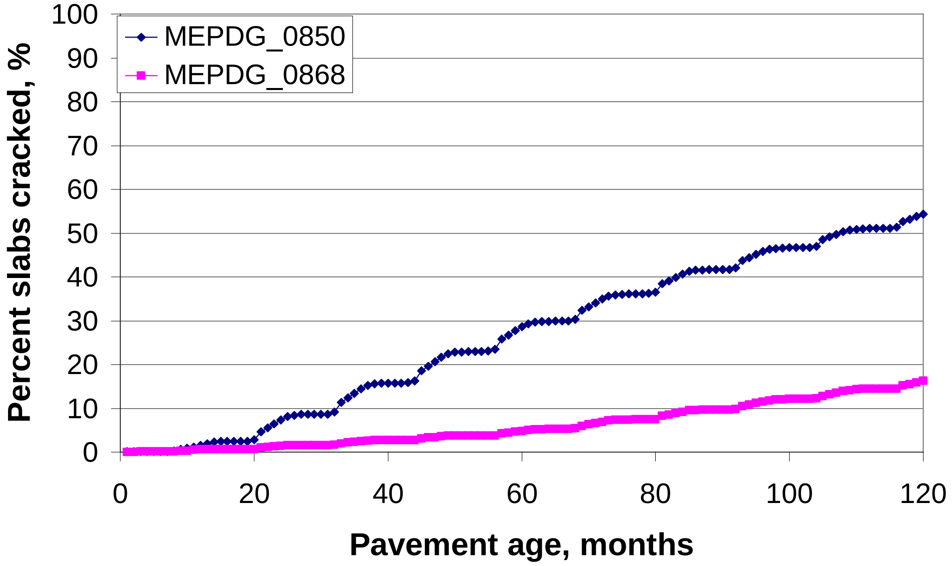


Figure C-9: Predicted cracking - Cell IM40-6.3-1, Inside lane, load = 80 Kip, HPCC =6.3, Dowel D=0

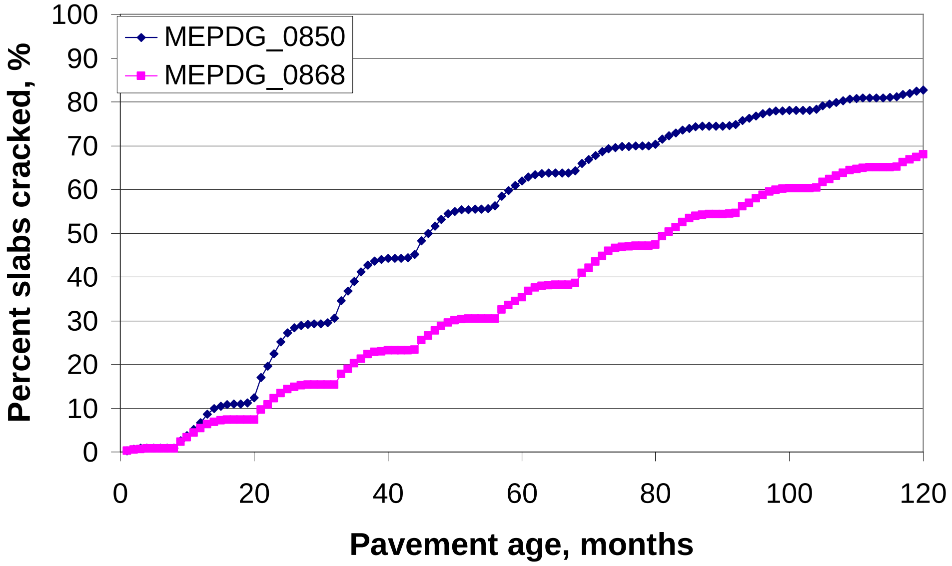


Figure C-10: Predicted cracking - Cell IM40-6.3-2, Outside lane, load = 102 Kip, HPCC =6.3, Dowel D = 0

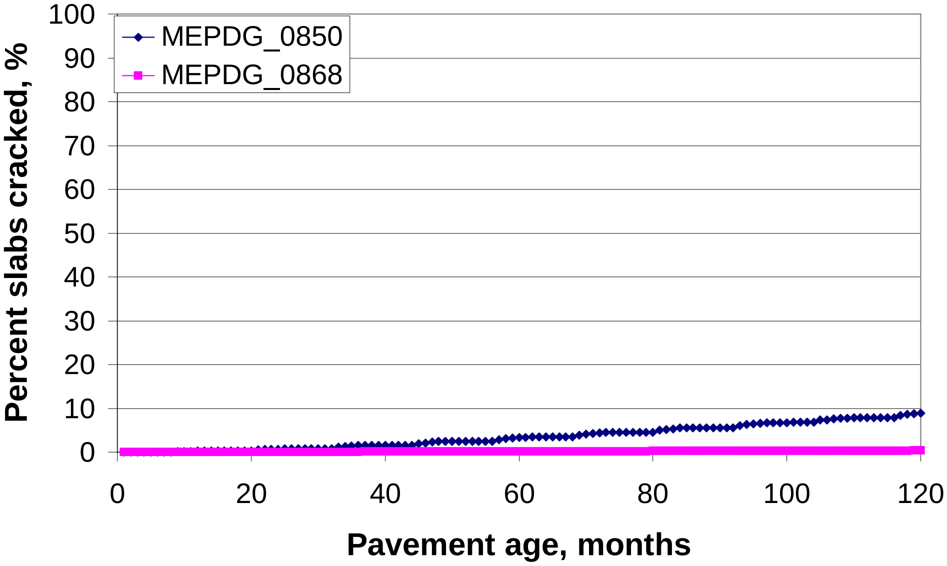


Figure C-11: Predicted cracking - Cell IM40-7.6-1, Inside lane, load = 80 Kip, HPCC =7.6, Dowel D=0

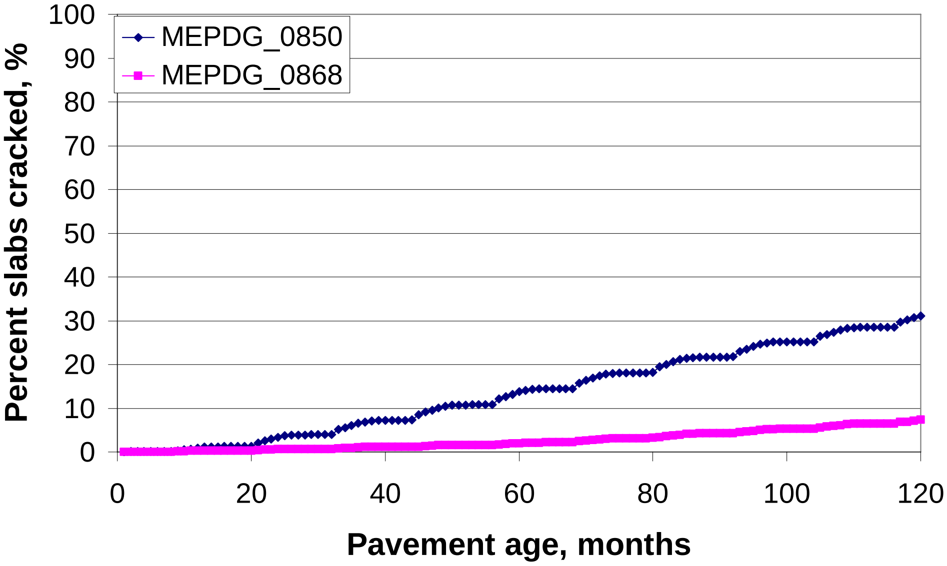


Figure C-12: Predicted cracking - Cell IM40-7.6-2, Outside lane, load = 102 Kip, HPCC =7.6, Dowel D = 0

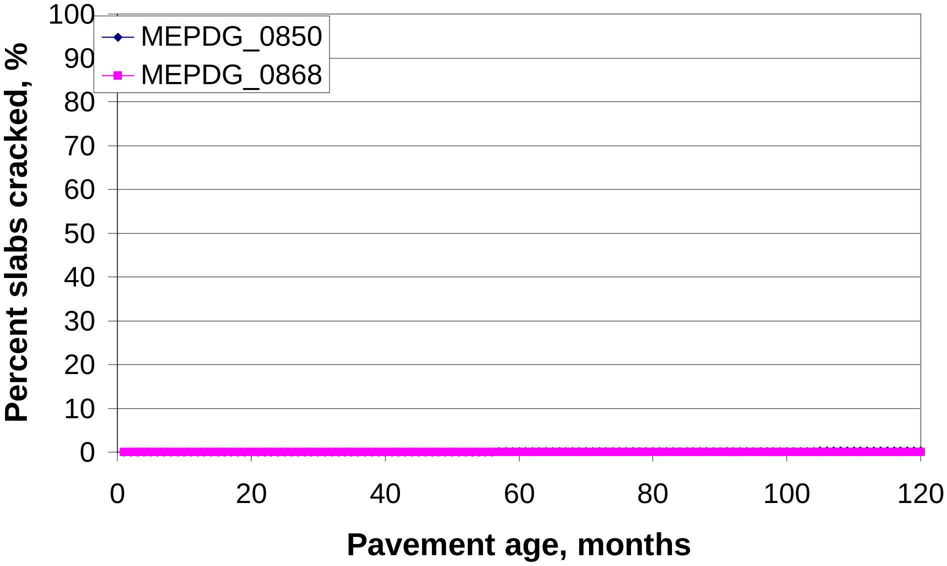


Figure C-13: Predicted cracking - Cell IM52-1.0-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D=1

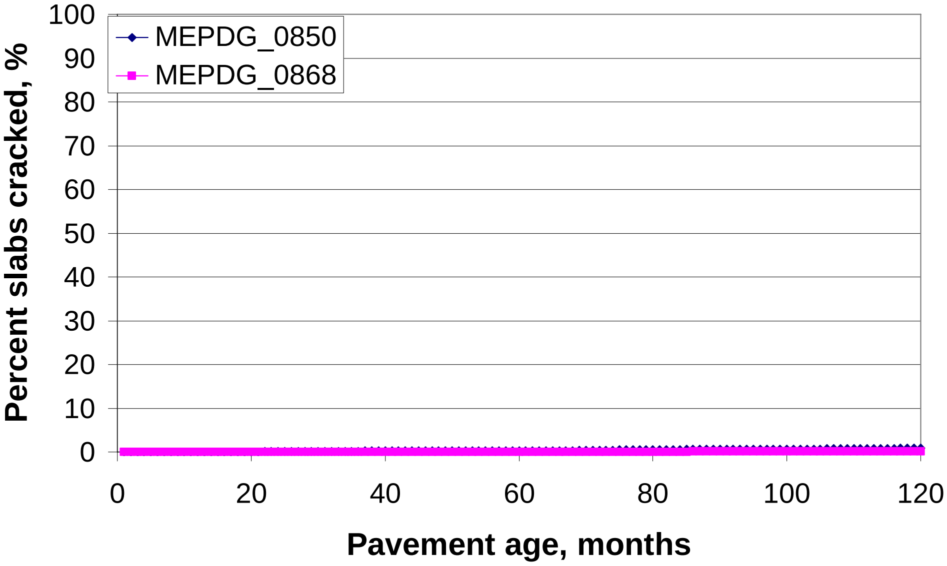


Figure C-14: Predicted cracking - Cell IM52-1.0-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D = 1

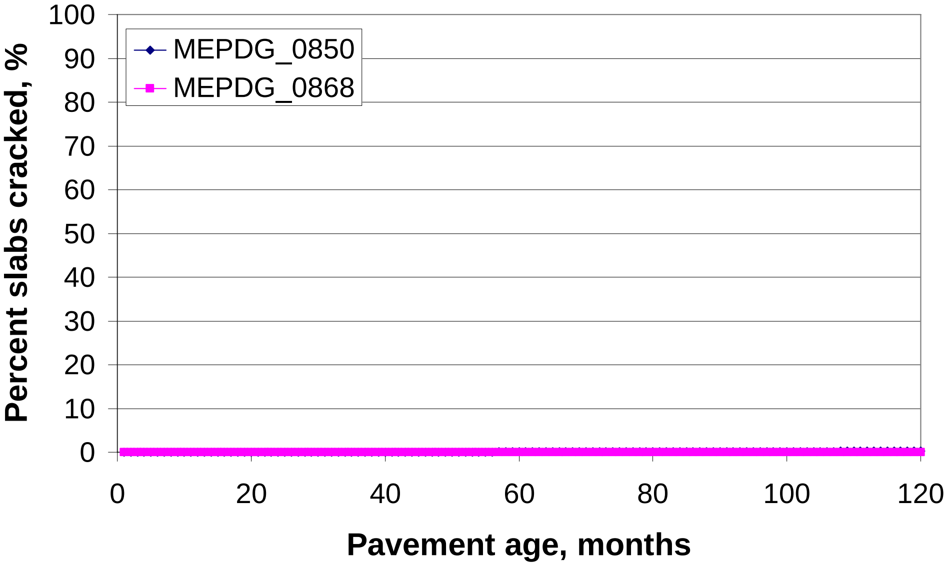


Figure C-15: Predicted cracking - Cell IM52-1.25-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D = 1.25

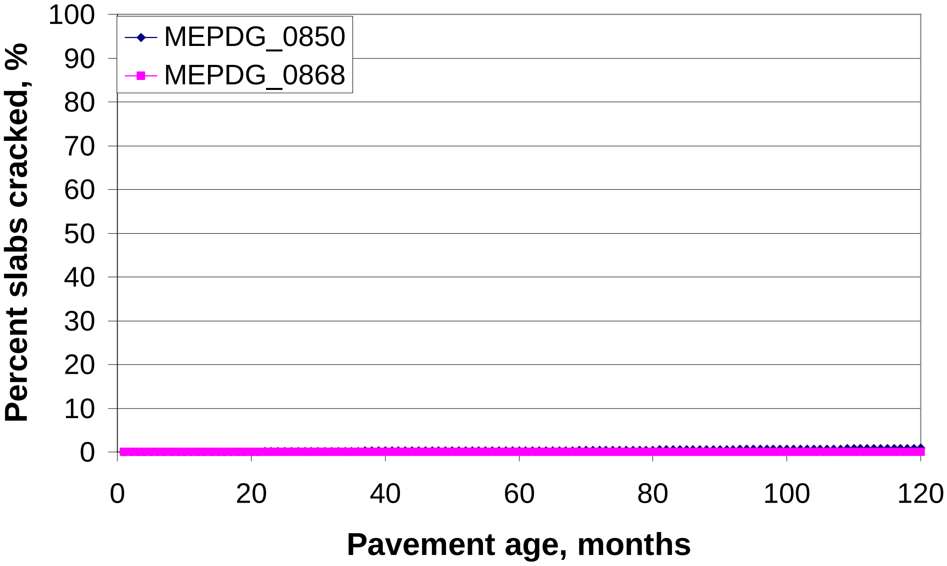


Figure C-16: Predicted cracking - Cell IM52-1.25-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D = 1.25

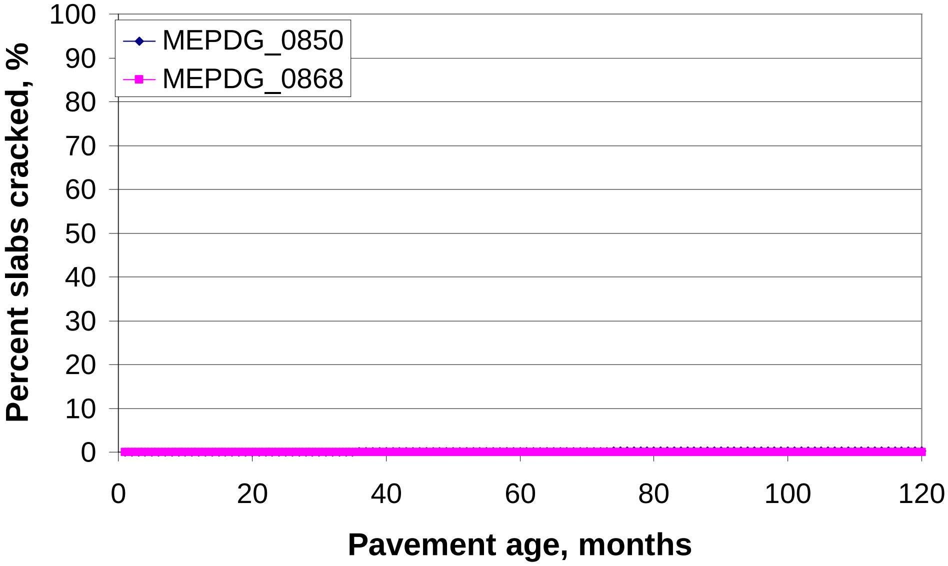


Figure C-17: Predicted cracking - Cell IM53-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D = 0

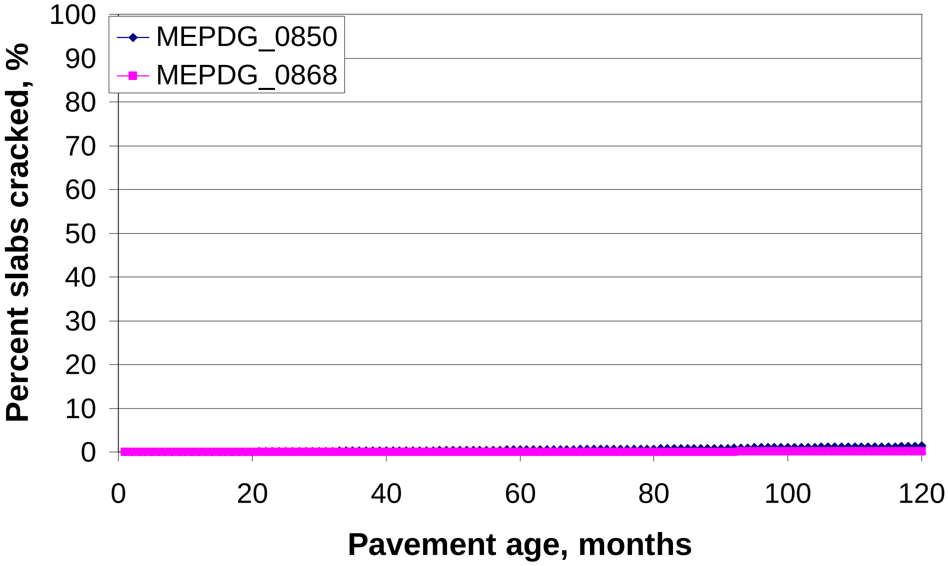


Figure C-18: Predicted cracking - Cell IM53-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D=0

Comparison of Predicted Faulting: MEPDG 0.850 vs. MEPDG 0.868

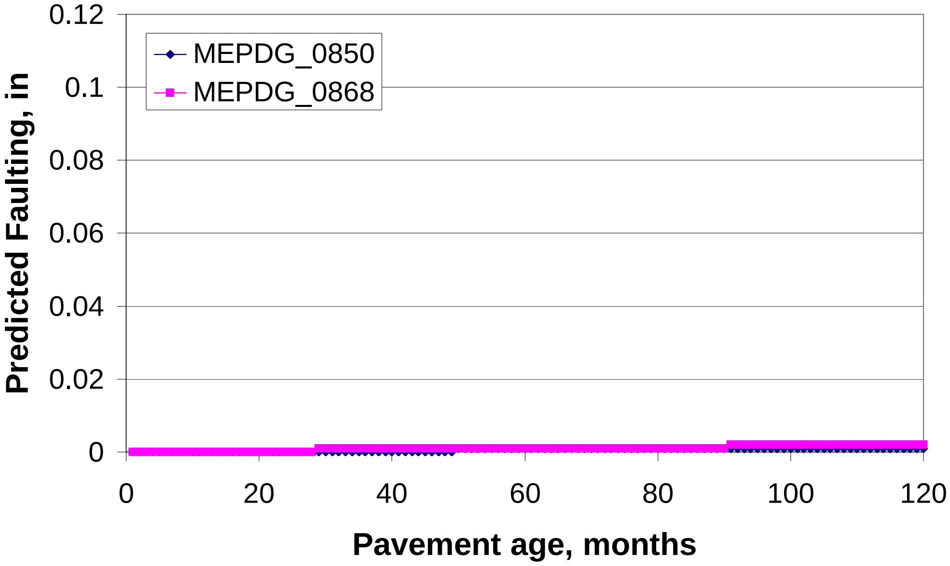


Figure C-19: Predicted faulting - Cell IM36-1, Inside lane, load = 80 Kip, HPCC =6.35, Dowel D = 1

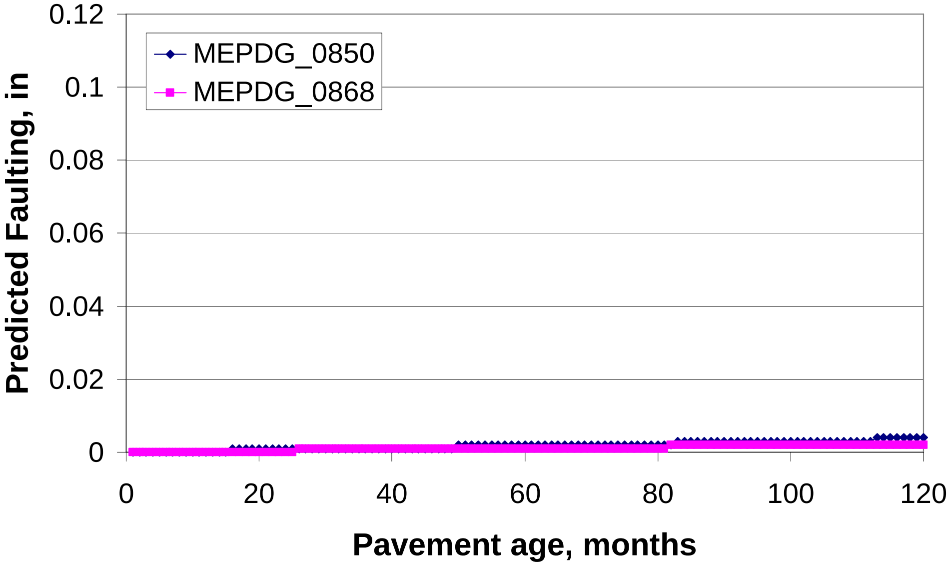


Figure C-20: Predicted faulting - Cell IM36-2, Outside lane, load = 102 Kip, HPCC =6.35, Dowel D=1

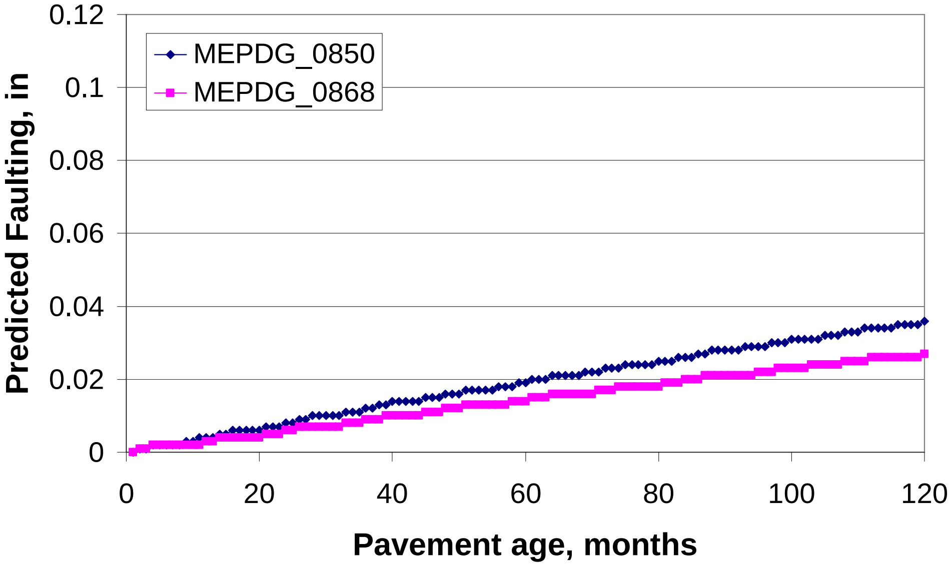


Figure C-21: Predicted faulting - Cell IM37_1, Inside lane, load = 80 Kip, HPCC =6.4, Dowel D = 0

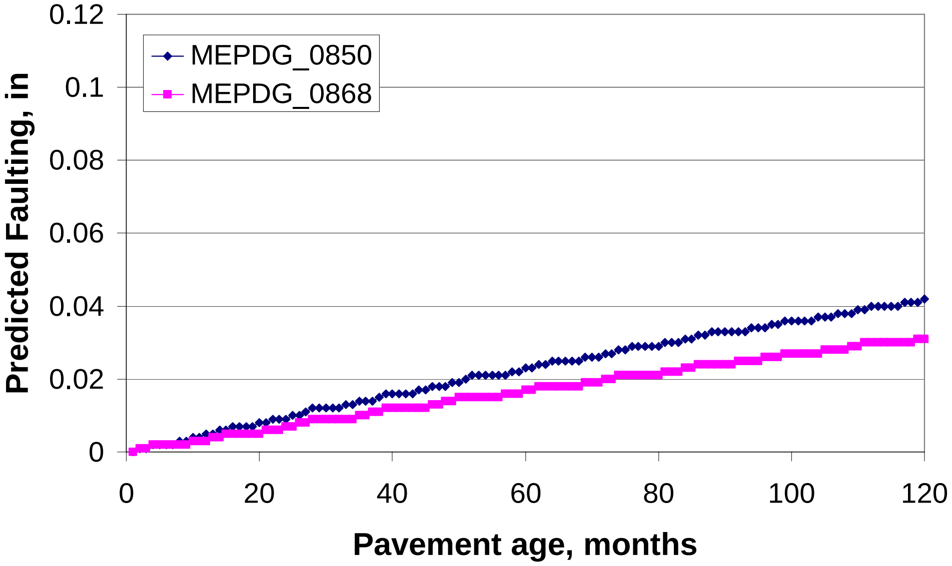


Figure C-22: Predicted faulting - Cell IM37_2, Outside lane, load = 102 Kip, HPCC =6.4, Dowel D=0

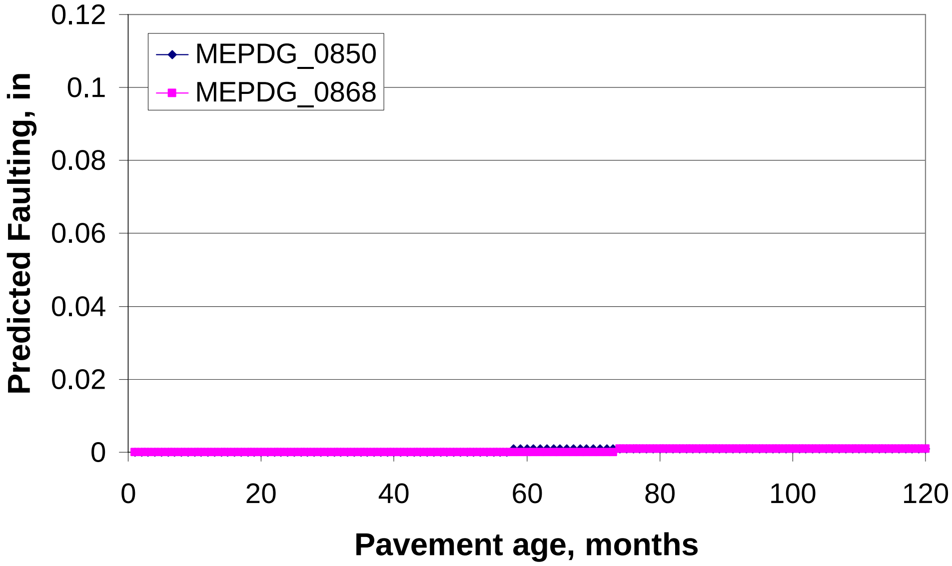


Figure C-23: Predicted faulting - Cell IM38_1, Inside lane, load = 80 Kip, HPCC =6.35, Dowel D = 1

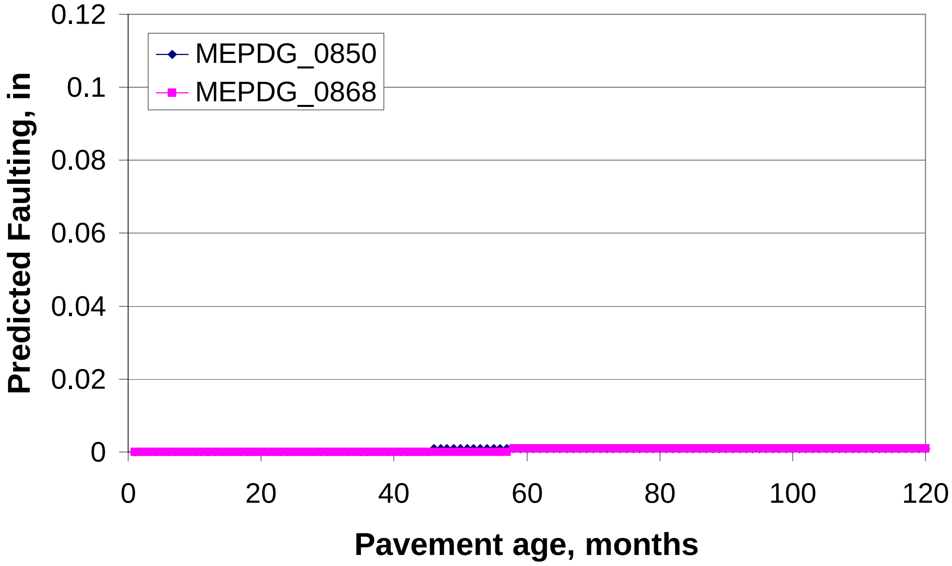


Figure C-24: Predicted faulting - Cell IM38_2, Outside lane, load = 102 Kip, HPCC =6.35, Dowel D=1

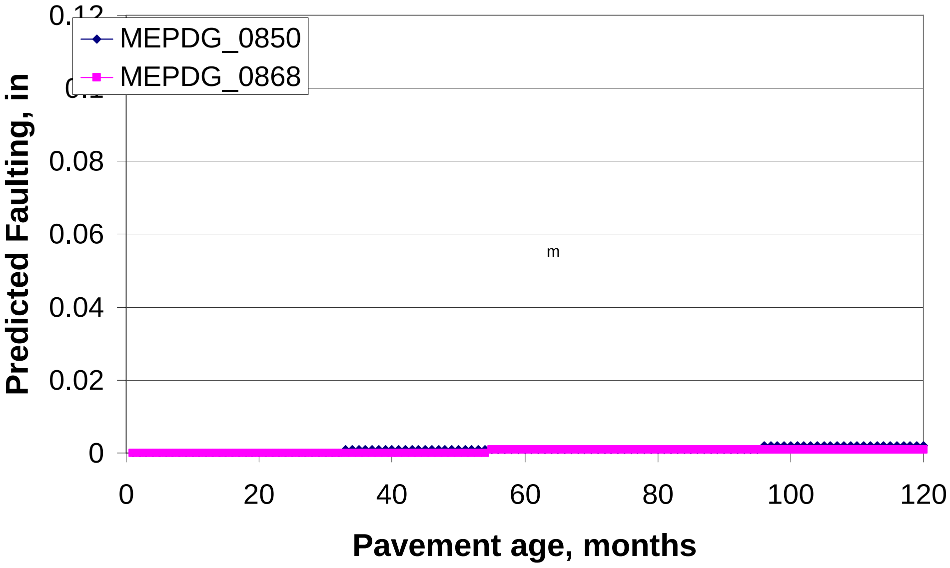


Figure C-25: Predicted faulting - Cell IM39_1, Inside lane, load = 80 Kip, HPCC =6.38, Dowel D = 1

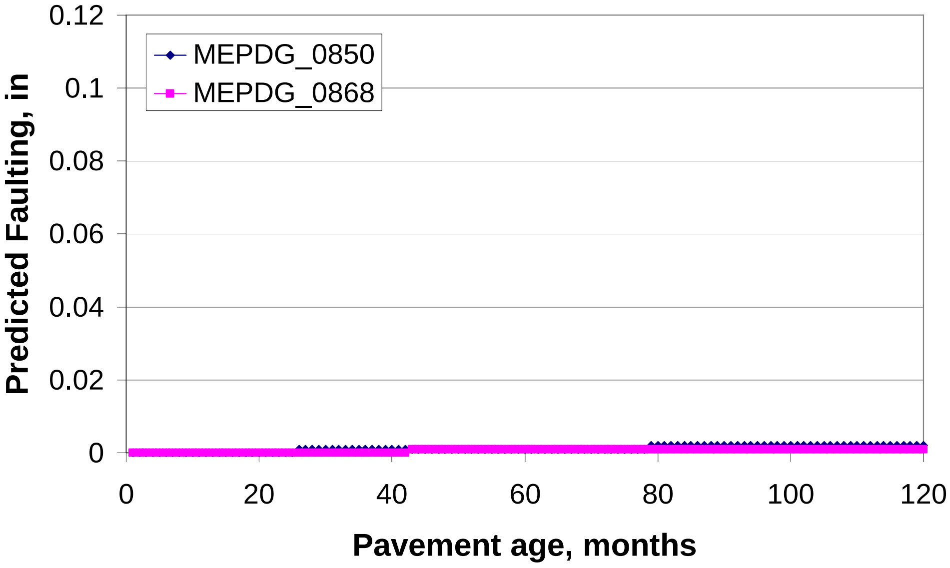


Figure C-26: Predicted faulting - Cell IM39_2, Outside lane, load = 102 Kip, HPCC =6.38, Dowel D=1

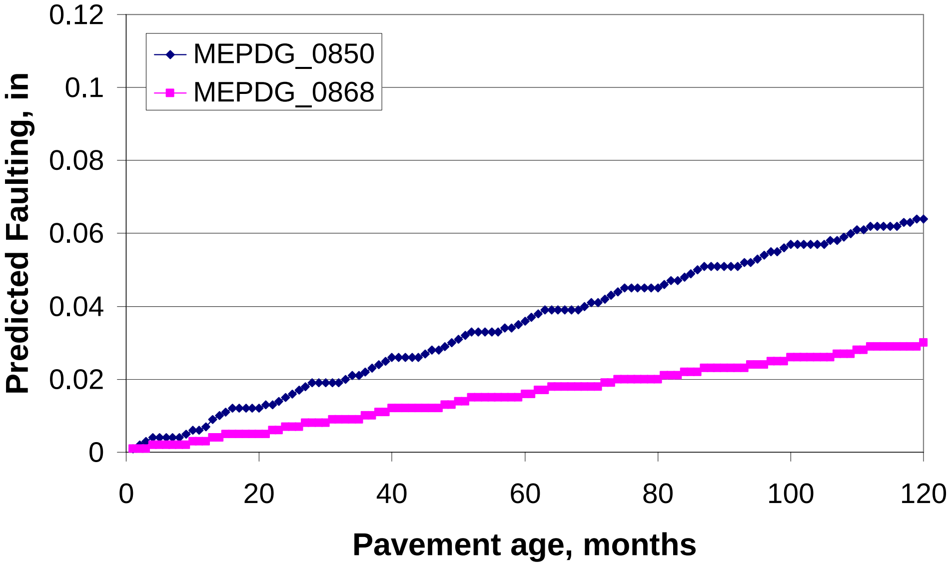


Figure C-27: Predicted faulting - Cell IM40-6.3-1, Inside lane, load = 80 Kip, HPCC =6.3, Dowel D=0

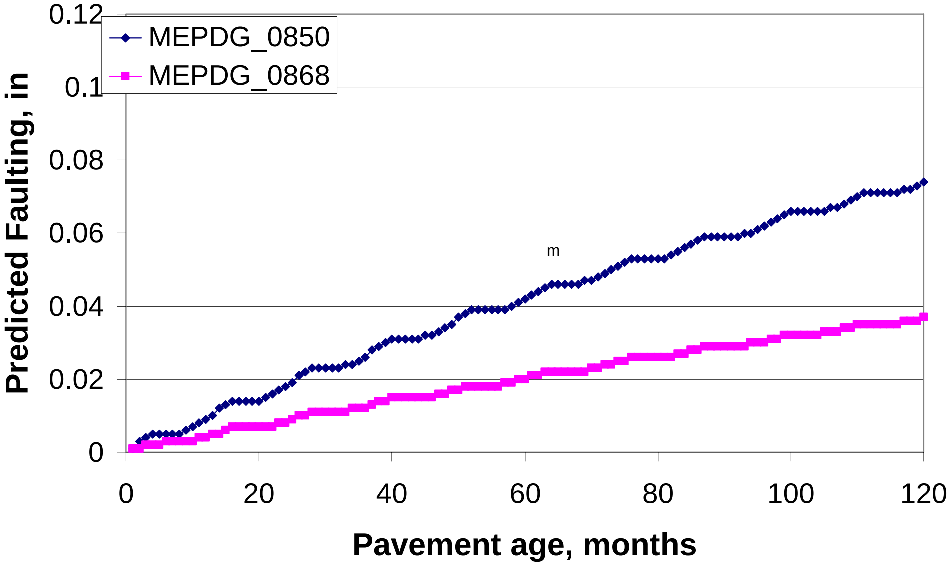


Figure C-28: Predicted faulting - Cell IM40-6.3-2, Outside lane, load = 102 Kip, HPCC =6.3, Dowel D = 0

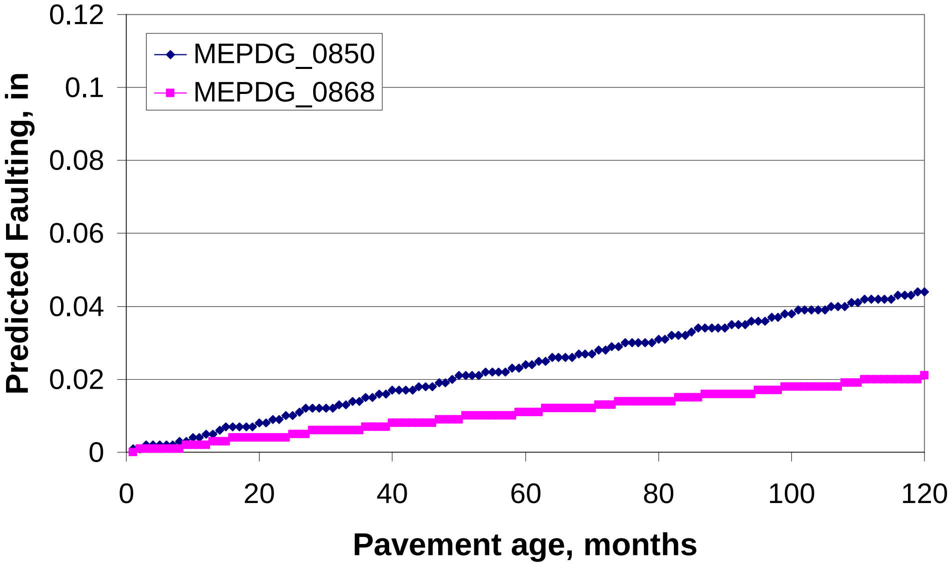


Figure C-29: Predicted faulting - Cell IM40-7.6-1, Inside lane, load = 80 Kip, HPCC =7.6, Dowel D=0

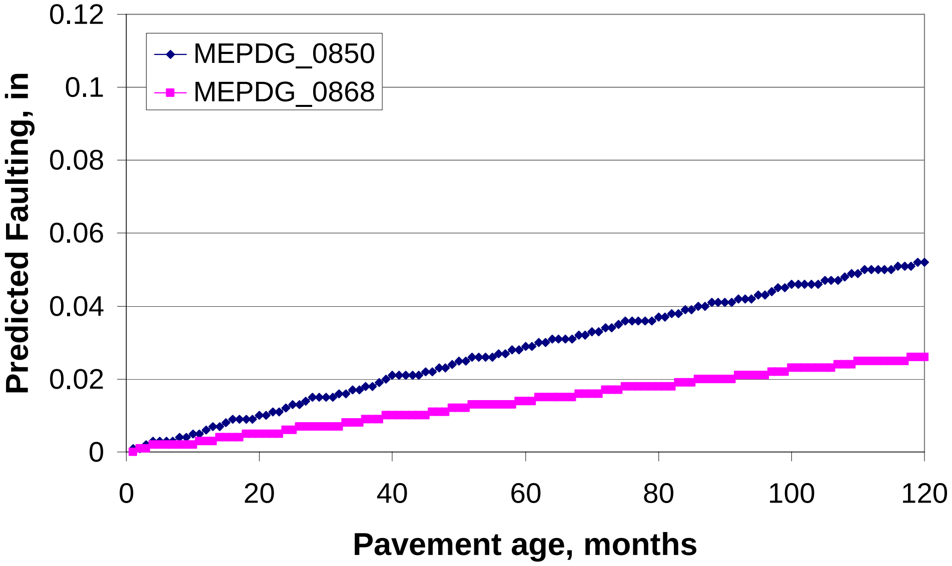


Figure C-30: Predicted faulting - Cell IM40-7.6-2, Outside lane, load = 102 Kip, HPCC =7.6, Dowel D = 0

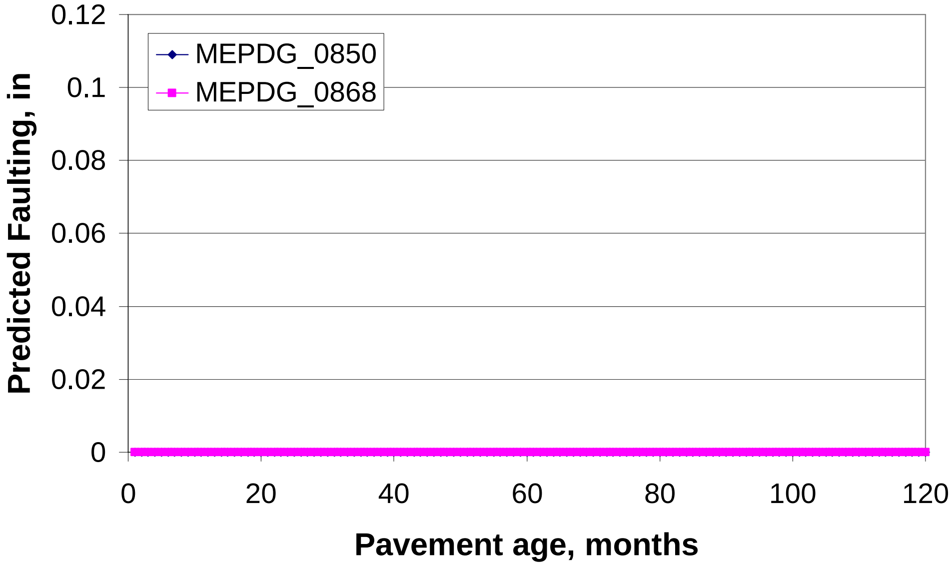


Figure C-31: Predicted faulting - Cell IM52-1.0-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D=1

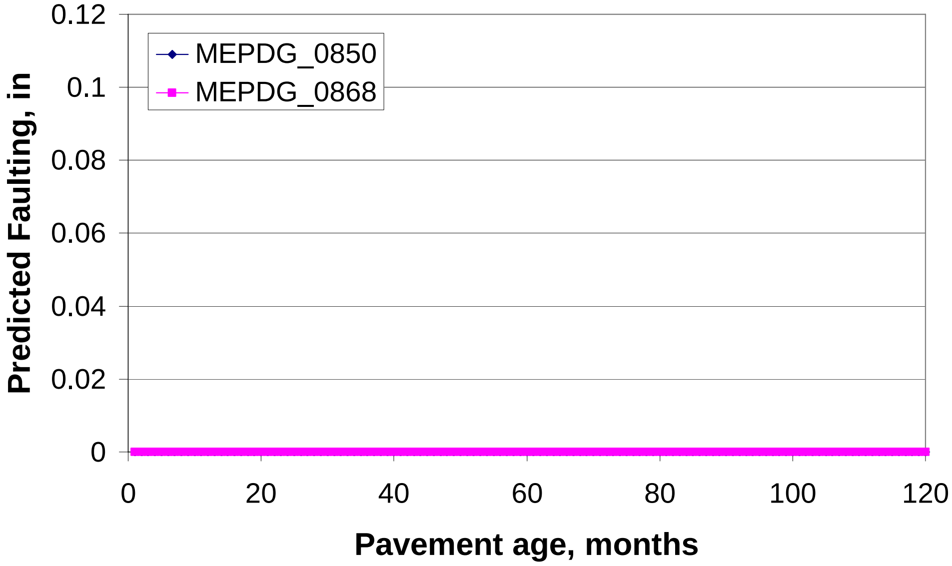


Figure C-32: Predicted faulting - Cell IM52-1.0-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D = 1

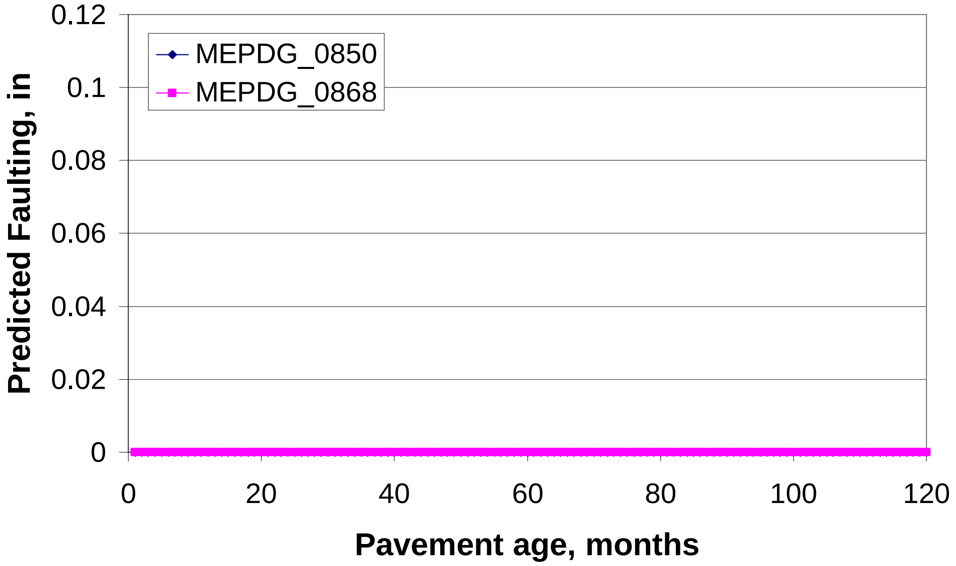


Figure C-33: Predicted faulting - Cell IM52-1.25-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D = 1.25

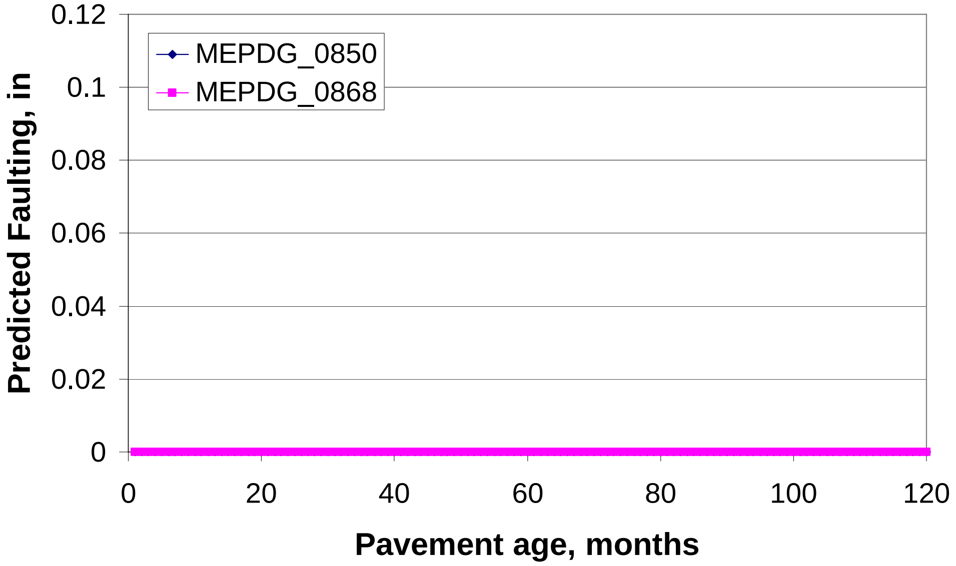


Figure C-34: Predicted faulting - Cell IM52-1.25-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D = 1.25

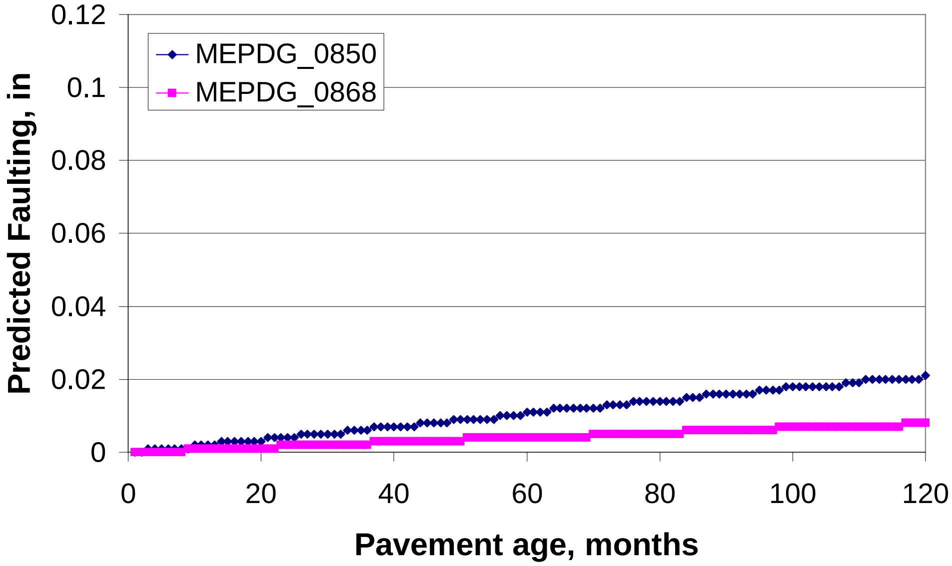


Figure C-35: Predicted faulting - Cell IM53-1, Inside lane, load = 80 Kip, HPCC =7.5, Dowel D = 0

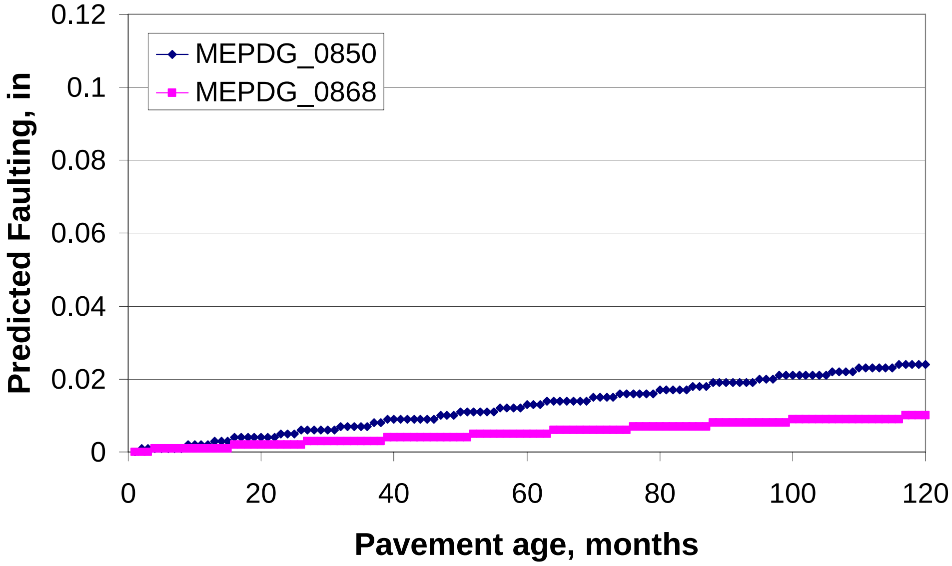


Figure C-36: Predicted faulting - Cell IM53-2, Outside lane, load = 102 Kip, HPCC =7.5, Dowel D=0

Appendix D. Description of the Calibration Dataset

Table D-1. Calibration dataset - Summary of site conditions

Site Conditions					
Section ID	**Location**	**Design Life, years**	**Traffic Open Month**	**ESALs mln**	**Subgrade**
19_0213	Iowa	30	8	27.14	A-6
19_0214	Iowa	30	8	27.14	A-6
19_0215	Iowa	30	8	27.14	A-6
19_0216	Iowa	30	8	27.14	A-6
19_0217	Iowa	30	8	27.14	A-6
19_0218	Iowa	30	8	27.14	A-6
19_0219	Iowa	30	8	27.14	A-6
19_0220	Iowa	30	8	27.14	A-6
19_0221	Iowa	30	8	27.14	A-6
19_0222	Iowa	30	8	27.14	A-6
19_0223	Iowa	30	8	27.14	A-6
19_0224	Iowa	30	8	27.14	A-6
55_3008_L13	Wisconsin	30	12	27.15	A-4
55_3008_L19	Wisconsin	30	12	50	A-4
55_3009_L12	Wisconsin	30	10	6.41	A-6
55_3009_L19	Wisconsin	30	10	2.08	A-6
55_3010_L12	Wisconsin	30	10	3.33	A-4
55_3010_L19	Wisconsin	30	10	7.39	A-4
55_3016_L12	Wisconsin	30	9	3.87	A-2-4
55_3016_L19	Wisconsin	30	9	3.87	A-2-4
55_6351_L12	Wisconsin	30	8	11.79	A-1-b
55_6351_L19	Wisconsin	30	8	29.68	A-1-b
55_6352_L12	Wisconsin	30	8	11.8	A-1-b
55_6352_L19	Wisconsin	30	8	90.3	A-1-b
55_6353_L12	Wisconsin	30	8	11.79	A-1-b
55_6353_L19	Wisconsin	30	8	27.7	A-1-b
55_6354_L12	Wisconsin	30	8	11.81	A-1-b
55_6354_L19	Wisconsin	30	8	27.7	A-1-b
55_6355_L12	Wisconsin	30	8	11.78	A-1-b
55_6355_L19	Wisconsin	30	8	30.24	A-1-b
Loop_4_8	AASHO-IL	14	11	11.77	A-7-6
Loop_4_9.5	AASHO-IL	14	11	11.77	A-7-6
Loop_5_11	AASHO-IL	14	11	16.69	A-7-6
Loop_5_9.5	AASHO-IL	14	11	16.69	A-7-6
Loop_6_11	AASHO-IL	14	11	25.98	A-7-6
Loop_6_12.5	AASHO-IL	14	11	25.98	A-7-6
Loop_6_9.5	AASHO-IL	14	11	25.98	A-7-6

Table D-1. Calibration dataset - Summary of site conditions (cont.)

Site Conditions					
Section ID	**Location**	**Design Life, years**	**Traffic Open Month**	**ESALs mln**	**Subgrade**
IM10	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM11	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM12	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM13	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM5	Mainlane_MnRoad-MN	10	7	7.98	A-6
IM6	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM7	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM8	Mainlane_MnRoad-MN	10	7	7.92	A-6
IM9	Mainlane_MnRoad-MN	10	7	7.92	A-6
27_3003	Minnesota	30	11	3.32	A-6
IM36-1	LVR-MnRoad-MN	10	8	0.76	A-3
IM36-2	LVR-MnRoad-MN	10	8	0.76	A-3
IM37_1	LVR-MnRoad-MN	10	8	0.76	A-3
IM37_2	LVR-MnRoad-MN	10	8	0.76	A-3
IM38_1	LVR-MnRoad-MN	10	8	0.76	A-6
IM38_2	LVR-MnRoad-MN	10	8	0.76	A-6
IM39_1	LVR-MnRoad-MN	10	8	0.76	A-6
IM39_2	LVR-MnRoad-MN	10	8	0.76	A-6
IM40-6.3-1	LVR-MnRoad-MN	10	8	0.76	A-6
IM40-6.3-2	LVR-MnRoad-MN	10	8	0.76	A-6
IM40-7.6-1	LVR-MnRoad-MN	10	8	0.76	A-6
IM40-7.6-2	LVR-MnRoad-MN	10	8	0.76	A-6
IM52-1.0-1	LVR-MnRoad-MN	5	8	0.76	A-6
IM52-1.0-2	LVR-MnRoad-MN	5	8	0.76	A-6
IM52-1.25-1	LVR-MnRoad-MN	5	8	0.76	A-6
IM52-1.25-2	LVR-MnRoad-MN	5	8	0.76	A-6
IM53-1	LVR-MnRoad-MN	5	8	0.76	A-6
IM53-2	LVR-MnRoad-MN	5	8	0.76	A-6

Table D-2. Calibration dataset – Design features inputs

Design Features										
Section ID	H PCC in	H Base in	Base	H Subbase, in	Subbase	Slab Width ft	Joint Spacing, ft	Shoulders	Dowel Diameter in	COTE
19_0213	8.50	6.1	A-1a	24	A-6	14.00	15.00	AC	1.25	5.40E-06
19_0214	8.40	6.3	A-1a	38	A-6	12.00	15.00	AC	1.25	5.40E-06
19_0215	11.80	5.8	A-1a	24	A-6	12.00	15.00	AC	1.50	5.40E-06
19_0216	11.60	5.9	A-1a	24	A-6	12.00	15.00	AC	1.50	5.40E-06
19_0217	8.10	6.5	CTB	24	A-6	14.00	15.00	AC	1.25	5.40E-06
19_0218	8.20	6.4	CTB	24	A-6	12.00	15.00	AC	1.25	5.40E-06
19_0219	11.20	6.8	CTB	24	A-6	14.00	15.00	AC	1.50	5.40E-06
19_0220	11.40	6.9	CTB	24	A-6	14.00	15.00	AC	1.50	5.40E-06
19_0221	9.40	3.6	A-1a	24	A-6	14.00	15.00	AC	1.25	5.40E-06
19_0222	8.30	3.9	A-1a	24	A-6	12.00	15.00	AC	1.25	5.40E-06
19_0223	11.70	3.6	A-1a	24	A-6	12.00	15.00	AC	1.50	5.40E-06
19_0224	11.60	3.8	A-1a	24	A-6	14.00	15.00	AC	1.50	5.40E-06
55_3008_L13	10.70	8.2	A-1-a	none	none	12.00	12.50	AC	1.00	5.89E-06
55_3008_L19	10.70	8.2	A-1-a	none	none	12.00	18.50	AC	1.00	5.89E-06
55_3009_L12	8.20	6.2	A-1-a	none	none	12.00	12.50	AC	0.00	5.83E-06
55_3009_L19	8.20	6.2	A-1-a	none	none	12.00	18.50	AC	0.00	5.83E-06
55_3010_L12	10.80	7.8	A-1-a	none	none	12.00	12.50	PCC	0.00	6.33E-06
55_3010_L19	10.80	7.8	A-1-a	none	none	12.00	18.50	PCC	0.00	6.33E-06
55_3016_L12	8.90	8.9	A-1-b	none	none	12.00	12.50	PCC	0.00	5.83E-06
55_3016_L19	8.90	8.9	A-1-b	none	none	12.00	18.50	PCC	0.00	5.83E-06
55_6351_L12	10.00	3.8	A-1-a	6.6	A-1-b	14.00	12.50	AC	0.00	6.09E-06
55_6351_L19	10.00	3.8	A-1-a	6.6	A-1-b	14.00	18.50	AC	0.00	6.09E-06
55_6352_L12	9.20	6.4	A-1-b	10.6	A-1-b	14.00	12.50	AC	1.13	6.09E-06
55_6352_L19	9.20	6.4	A-1-b	10.6	A-1-b	14.00	18.50	AC	1.13	6.09E-06
55_6353_L12	10.50	3.2	CSB	9.8	A-1-a	14.00	12.50	AC	0.00	6.09E-06
55_6353_L19	10.50	3.2	CSB	9.8	A-1-a	14.00	18.50	AC	0.00	6.09E-06
55_6354_L12	9.60	3.2	PASB	4	A-1-a	14.00	12.50	AC	0.00	6.28E-06
55_6354_L19	9.60	3.2	PASB	4	A-1-a	14.00	18.50	AC	0.00	6.28E-06
55_6355_L12	9.30	3.6	PASB	5.2	A-1-b	14.00	12.50	AC	1.13	5.90E-06
55_6355_L19	9.30	3.6	PASB	5.2	A-1-b	14.00	18.50	AC	1.13	5.90E-06
Loop_4_8	8.00	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.00	5.50E-06
Loop_4_9.5	9.50	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.25	5.50E-06
Loop_5_11	11.00	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.38	5.50E-06
Loop_5_9.5	9.50	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.25	5.50E-06
Loop_6_11	11.00	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.38	5.50E-06
Loop_6_12.5	12.50	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.63	5.50E-06
Loop_6_9.5	9.50	6.0	Crushed gravel	none	none	12.00	15.00	AC	1.25	5.50E-06
IM10	9.86	4.0	PASB	4	A-1-b	12.00	20.00	AC	1.25	4.60E-06
IM11	9.64	5.0	A-1-a	none	none	12.00	24.00	AC	1.25	4.60E-06
IM12	9.91	5.0	A-1-a	none	none	12.00	15.00	AC	1.25	4.60E-06
IM13	9.73	5.0	A-1-a	none	none	12.00	20.00	AC	1.50	4.60E-06
IM5	7.14	3.0	A-1-b	27	A-1-b	14.00	20.00	AC	1.00	4.60E-06
IM6	7.39	5.0	A-1-b	none	none	14.00	15.00	AC	1.00	4.60E-06
IM7	7.55	4.0	PASB	4	A-1-b	14.00	20.00	AC	1.00	4.60E-06
IM8	7.43	4.0	PASB	4	A-1-b	14.00	15.00	AC	1.00	4.60E-06
IM9	7.43	4.0	PASB	4	A-1-b	14.00	15.00	AC	1.00	4.60E-06
27_3003	7.60	5.0	A-1-b	none	none	14.00	15.00	PCC	0.00	6.09E-06

Table D-2. Calibration dataset – Design features inputs (cont.)

Design Features										
Section ID	H PCC in	H Base in	Base	H Subbase, in	Subbase	Slab Width ft	Joint Spacing, ft	Shoulders	Dowel Diameter in	COTE
IM36-1	6.35	5	Class 5	none	none	12	15	AC	1.00	4.60E-06
IM36-2	6.35	5	Class 5	none	none	12	15	AC	1.00	4.60E-06
IM37_1	6.4	12	Class 5	none	none	12	12	AC	0.00	4.60E-06
IM37_2	6.4	12	Class 5	none	none	12	12	AC	0.00	4.60E-06
IM38_1	6.35	5	Class 5	none	none	12	15	AC	1.00	4.60E-06
IM38_2	6.35	5	Class 5	none	none	12	15	AC	1.00	4.60E-06
IM39_1	6.38	5	Class 5	none	none	12	20	AC	1.00	4.60E-06
IM39_2	6.38	5	Class 5	none	none	12	20	AC	1.00	4.60E-06
IM40-6.3-1	6.3	5	Class 5	none	none	12	15	AC	0.00	4.60E-06
IM40-6.3-2	6.3	5	Class 5	none	none	12	15	AC	0.00	4.60E-06
IM40-7.6-1	7.6	5	Class 5	none	none	12	15	AC	0.00	4.60E-06
IM40-7.6-2	7.6	5	Class 5	none	none	12	15	AC	0.00	4.60E-06
IM52-1.0-1	7.5	5	Class 4	none	none	14	15	AC	1.00	4.60E-06
IM52-1.0-2	7.5	5	Class 4	none	none	14	15	AC	1.00	4.60E-06
IM52-1.25-1	7.5	5	Class 4	none	none	14	15	AC	1.25	4.60E-06
IM52-1.25-2	7.5	5	Class 4	none	none	14	15	AC	1.25	4.60E-06
IM53-1	7.5	5	Class 4	none	none	14	15	AC	0.00	4.60E-06
IM53-2	7.5	5	Class 4	none	none	14	15	AC	0.00	4.60E-06

Table D-3. Calibration dataset – Predicted vs. measured cracking values

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
19_0213_Level	Iowa	2	0.0027	0.0058	**0**	**0**
19_0213_Level	Iowa	34	0.0244	0.037	**0.6**	**0**
19_0213_Level	Iowa	58	0.0393	0.0569	**1.2**	**0**
19_0213_Level	Iowa	66	0.0432	0.0642	**1.5**	**0**
19_0213_Level	Iowa	86	0.0576	0.081	**2.3**	**0**
19_0213_Level	Iowa	92	0.0599	0.0847	**2.4**	**0**
19_0213_Level	Iowa	130	0.0858	0.1169	**4.2**	**0**
19_0214_Level	Iowa	2	0.0015	0.0015	**0**	**0**
19_0214_Level	Iowa	58	0.022	0.0124	**0.2**	**0**
19_0214_Level	Iowa	66	0.024	0.0138	**0.3**	**0**
19_0214_Level	Iowa	86	0.0318	0.0172	**0.4**	**0**
19_0214_Level	Iowa	92	0.0332	0.0179	**0.4**	**0**
19_0214_Level	Iowa	130	0.0471	0.0242	**0.8**	**0**
19_0215_Level	Iowa	2	0.0002	0.001	**0**	**0**
19_0215_Level	Iowa	35	0.0012	0.0046	**0**	**0**
19_0215_Level	Iowa	58	0.0019	0.0065	**0**	**0**
19_0215_Level	Iowa	66	0.0021	0.0072	**0**	**0**
19_0215_Level	Iowa	86	0.0027	0.0088	**0**	**0**
19_0215_Level	Iowa	92	0.0028	0.0091	**0**	**0**
19_0215_Level	Iowa	130	0.0039	0.012	**0.1**	**0**
19_0216_Level	Iowa	2	1.00E-06	0.0001	**0**	**0**
19_0216_Level	Iowa	35	1.00E-06	0.0002	**0**	**0**
19_0216_Level	Iowa	58	1.00E-06	0.0003	**0**	**0**
19_0216_Level	Iowa	66	1.00E-06	0.0003	**0**	**0**
19_0216_Level	Iowa	86	0.0001	0.0004	**0**	**0**
19_0216_Level	Iowa	92	0.0001	0.0004	**0**	**0**
19_0217_Level	Iowa	2	1.00E-06	1.00E-06	**0**	**3**

Table D-3. Calibration dataset – Predicted vs. measured cracking values cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
19_0217_Level	Iowa	34	1.00E-06	1.00E-06	**0**	**6**
19_0217_Level	Iowa	56	1.00E-06	1.00E-06	**0**	**6**
19_0217_Level	Iowa	66	0.0022	0.0013	**0**	**6**
19_0217_Level	Iowa	86	0.02	0.0046	**0.2**	**6**
19_0217_Level	Iowa	92	0.0224	0.0056	**0.2**	**6**
19_0217_Level	Iowa	130	0.0551	0.0121	**0.8**	**6**
19_0218_Level	Iowa	2	1.00E-06	1.00E-06	**0**	**0**
19_0218_Level	Iowa	35	1.00E-06	1.00E-06	**0**	**3**
19_0218_Level	Iowa	56	1.00E-06	1.00E-06	**0**	**0**
19_0218_Level	Iowa	66	0.0009	0.0004	**0**	**0**
19_0218_Level	Iowa	86	0.0107	0.0014	**0.1**	**0**
19_0218_Level	Iowa	92	0.0121	0.0016	**0.1**	**0**
19_0218_Level	Iowa	130	0.03	0.0036	**0.3**	**0**
19_0219_Level	Iowa	2	1.00E-06	1.00E-06	**0**	**0**
19_0219_Level	Iowa	35	1.00E-06	1.00E-06	**0**	**0**
19_0219_Level	Iowa	56	1.00E-06	1.00E-06	**0**	**0**
19_0219_Level	Iowa	66	1.00E-06	0.0003	**0**	**0**
19_0219_Level	Iowa	86	0.0001	0.0012	**0**	**0**
19_0219_Level	Iowa	92	0.0001	0.0014	**0**	**0**
19_0219_Level	Iowa	130	0.0003	0.003	**0**	**0**
19_0220_Level	Iowa	2	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	35	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	56	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	66	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	86	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	92	1.00E-06	1.00E-06	**0**	**0**
19_0220_Level	Iowa	130	1.00E-06	0.0001	**0**	**0**
19_0221_Level	Iowa	2	0.0001	0.0001	**0**	**0**
19_0221_Level	Iowa	34	0.0005	0.0002	**0**	**0**
19_0221_Level	Iowa	58	0.0008	0.0003	**0**	**0**
19_0221_Level	Iowa	66	0.0011	0.0016	**0**	**0**
19_0221_Level	Iowa	86	0.003	0.0059	**0**	**0**
19_0221_Level	Iowa	92	0.0032	0.0066	**0**	**0**
19_0221_Level	Iowa	130	0.0067	0.0146	**0.1**	**0**
19_0222_Level	Iowa	2	0.0004	0.0001	**0**	**0**
19_0222_Level	Iowa	58	0.0037	0.0002	**0**	**0**
19_0222_Level	Iowa	66	0.0049	0.001	**0**	**0**
19_0222_Level	Iowa	86	0.0109	0.0038	**0.1**	**0**
19_0222_Level	Iowa	92	0.0117	0.0043	**0.1**	**0**
19_0222_Level	Iowa	130	0.0224	0.0094	**0.2**	**0**
19_0223_Level	Iowa	2	1.00E-06	0.0009	**0**	**0**
19_0223_Level	Iowa	58	0.0002	0.004	**0**	**0**
19_0223_Level	Iowa	62	0.0003	0.0053	**0**	**0**
19_0223_Level	Iowa	66	0.0003	0.006	**0**	**0**
19_0223_Level	Iowa	86	0.0007	0.012	**0.1**	**0**
19_0223_Level	Iowa	92	0.0008	0.0129	**0.1**	**0**
19_0223_Level	Iowa	130	0.0016	0.0236	**0.2**	**0**
19_0224_Level	Iowa	2	1.00E-06	1.00E-06	**0**	**0**
19_0224_Level	Iowa	62	1.00E-06	1.00E-06	**0**	**0**

Table D.3 Calibration dataset – Predicted vs. measured cracking values (cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
19_0224_Level	Iowa	66	1.00E-06	1.00E-06	**0**	**0**
19_0224_Level	Iowa	86	1.00E-06	1.00E-06	**0**	**0**
19_0224_Level	Iowa	92	1.00E-06	1.00E-06	**0**	**0**
19_0224_Level	Iowa	130	1.00E-06	0.0001	**0**	**0**
19_3006_r	Iowa	226	0.2813	0.3143	**21.8**	**16**
19_3006_r	Iowa	282	0.384	0.4407	**33.5**	**20**
19_3006_r	Iowa	296	0.4154	0.4744	**36.7**	**20**
19_3006_r	Iowa	299	0.4197	0.4865	**37.5**	**20**
19_3009	Iowa	214	0.0175	0.1778	**5.3**	**8**
19_3009	Iowa	280	0.0345	0.3437	**14.6**	**8**
19_3009	Iowa	316	0.0446	0.4451	**20.9**	**8**
19_3009	Iowa	342	0.052	0.5231	**25.7**	**8**
19_3028	Iowa	117	1.00E-06	1.00E-06	**0**	**0**
19_3028	Iowa	172	0.0297	0.0508	**0.9**	**0**
19_3028	Iowa	209	0.0537	0.092	**2.5**	**0**
19_3028	Iowa	235	0.0713	0.1227	**4**	**0**
19_3033	Iowa	132	0.0042	0.0037	**0**	**0**
19_3033	Iowa	187	0.0254	0.024	**0.4**	**0**
19_3033	Iowa	230	0.0463	0.0445	**1.1**	**0**
19_3033	Iowa	250	0.059	0.0542	**1.6**	**0**
19_3055	Iowa	299	0.0033	0.0028	**0**	**0**
19_3055	Iowa	371	0.0044	0.0037	**0**	**0**
19_3055	Iowa	400	0.0049	0.0042	**0**	**0**
27_3003	Minnesota	166	0.001	0.0028	**0**	**0**
27_3003	Minnesota	204	0.0012	0.0034	**0**	**0**
27_3007	Minnesota	12	0.0068	0.0002	**0**	**0**
27_3007	Minnesota	63	0.0625	0.0012	**0.9**	**0**
27_3007	Minnesota	87	0.1073	0.0019	**2.3**	**0**
27_3009	Minnesota	12	0.0123	0.0003	**0.1**	**0**
27_3009	Minnesota	63	0.1051	0.0018	**2.2**	**0**
27_3009	Minnesota	87	0.1773	0.0028	**5.2**	**0**
27_3010	Minnesota	12	0.0111	0.0014	**0.1**	**0**
27_3010	Minnesota	63	0.0974	0.0098	**2**	**0**
27_3010	Minnesota	86	0.1654	0.0157	**4.7**	**0**
27_3012	Minnesota	12	0.001	0.0052	**0**	**0**
27_3012	Minnesota	63	0.0067	0.0363	**0.4**	**0**
27_3012	Minnesota	86	0.0103	0.0555	**0.8**	**0**
27_3013	Minnesota	166	0.0013	0.0004	**0**	**0**
27_3013	Minnesota	166	0.0013	0.0004	**0**	**0**
27_3013	Minnesota	204	0.0017	0.0005	**0**	**0**
27_3013	Minnesota	204	0.0017	0.0005	**0**	**0**
55_3008_L13	Wisconsin	227	1.00E-06	0.0002	**0**	**0**
55_3008_L19	Wisconsin	227	0.0025	0.0398	**0.4**	**7.4**
55_3009_L12	Wisconsin	121	0.0002	0.0105	**0**	**0**
55_3009_L12	Wisconsin	127	0.0002	0.0107	**0**	**0**
55_3009_L12	Wisconsin	179	0.0002	0.0141	**0.1**	**0**
55_3009_L19	Wisconsin	121	0.0022	0.4463	**20.5**	**0**

Table D.3 Calibration dataset – Predicted vs. measured cracking values (cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
55_3009_L19	Wisconsin	127	0.0023	0.4581	21.2	0
55_3009_L19	Wisconsin	179	0.0031	0.6252	31.2	0
55_3010_L12	Wisconsin	193	1.00E-06	0.0006	0	0
55_3010_L12	Wisconsin	251	1.00E-06	0.0008	0	0
55_3010_L19	Wisconsin	193	0.001	0.0969	1.9	0
55_3010_L19	Wisconsin	251	0.0013	0.1288	3.1	0
55_3012_12.5	Wisconsin	189	0.1622	0.0004	4.5	0
55_3012_12.5	Wisconsin	263	0.2322	0.0006	7.9	0
55_3012_18.5	Wisconsin	189	0.2201	0.0029	7.3	0
55_3014_12.5	Wisconsin	199	1.00E-06	0.004	0	0
55_3014_12.5	Wisconsin	275	1.00E-06	0.0055	0	0
55_3016_L12	Wisconsin	98	0.0002	0.0002	0	0
55_3016_L19	Wisconsin	98	0.0037	0.0242	0.2	0
55_3019_12	Wisconsin	280	0.0007	0.0002	0	0
55_3019_18	Wisconsin	280	0.0547	0.0246	0.9	0
55_6351_L12	Wisconsin	132	0.0002	0.009	0	0
55_6351_L12	Wisconsin	169	0.0003	0.0121	0.1	0
55_6351_L19_r	Wisconsin	132	0.0569	0.6026	30.5	37
55_6351_L19_r	Wisconsin	169	0.08	0.8377	43.4	37
55_6352_L12	Wisconsin	132	1.00E-06	0.0006	0	0
55_6352_L12	Wisconsin	169	1.00E-06	0.0008	0	0
55_6352_L19	Wisconsin	132	0.0048	0.0954	1.9	0
55_6352_L19	Wisconsin	169	0.0075	0.1474	3.9	0
55_6353_L12	Wisconsin	74	1.00E-06	0.0002	0	0
55_6353_L12	Wisconsin	132	1.00E-06	0.0005	0	0
55_6353_L12	Wisconsin	169	1.00E-06	0.0007	0	0
55_6353_L19	Wisconsin	74	0.0008	0.0202	0.1	0
55_6353_L19	Wisconsin	132	0.0022	0.0751	1.3	0
55_6353_L19	Wisconsin	169	0.0032	0.1184	2.7	0
55_6354_L12	Wisconsin	74	1.00E-06	0.0002	0	0
55_6354_L12	Wisconsin	132	1.00E-06	0.0008	0	0
55_6354_L12	Wisconsin	169	1.00E-06	0.0012	0	0
55_6354_L19	Wisconsin	74	0.0004	0.0382	0.4	0
55_6354_L19	Wisconsin	132	0.0012	0.1336	3.3	0
55_6354_L19	Wisconsin	169	0.0017	0.2093	6.7	0
55_6355_L12	Wisconsin	132	1.00E-06	0.0008	0	0
55_6355_L12	Wisconsin	169	1.00E-06	0.0013	0	0
55_6355_L19	Wisconsin	132	0.0058	0.1182	2.7	0
55_6355_L19	Wisconsin	169	0.0095	0.1962	6.1	0
Loop_4_8	AASHO-Illinois	168	0.7941	0.6601	60.2	40.4
Loop_4_9.5	AASHO-Illinois	168	0.0568	0.2021	7.1	0
Loop_5_11	AASHO-Illinois	168	0.0031	0.0488	0.6	0
Loop_5_9.5	AASHO-Illinois	168	0.0568	0.2021	7.1	0
Loop_6_11	AASHO-Illinois	168	0.0032	0.0488	0.6	0
Loop_6_12.5	AASHO-Illinois	168	0.0001	0.0122	0.1	0
Loop_6_9.5	AASHO-Illinois	168	0.0568	0.2021	7.1	16.1
IM10	Mainlane_MnRoad	78	0.0284	0.0896	2	0

Table D-3. Calibration dataset – Predicted vs. measured cracking values (cont.)

Project	**Location**	**Age months**	**Calculated**			**Measured Total % Crack**
			Total damage		**Total % crack**	
			Bottom-Up	**Top-Down**		
IM11	Mainlane_MnRoad	78	0.2965	0.3242	**23.1**	**0**
IM12	Mainlane_MnRoad	78	0.0102	0.0082	**0.1**	**0**
IM13	Mainlane_MnRoad	78	0.1083	0.3061	**14.1**	**0**
IM5	Mainlane_MnRoad	78	0.106	0.1724	**7.1**	**0**
IM6	Mainlane_MnRoad	78	0.0621	0.0122	**1**	**0**
IM7	Mainlane_MnRoad	78	0.0267	0.0433	**0.7**	**0**
IM8	Mainlane_MnRoad	78	0.0161	0.0041	**0.1**	**0**
IM9	Mainlane_MnRoad	78	0.0162	0.004	**0.1**	**0**
IM36-1	LVR_MnRoad	120	0.0793	0.0003	**1.4**	**0**
IM36-2	LVR_MnRoad	120	0.2866	0.0005	**10.9**	**0**
IM37_1	LVR_MnRoad	120	0.0154	0.000001	**0.1**	**0**
IM37_2	LVR_MnRoad	120	0.0656	0.000001	**1**	**0**
IM38_1	LVR_MnRoad	120	0.3493	0.0004	**14.6**	**0**
IM39_1	LVR_MnRoad	120	0.7633	0.0021	**38.8**	**0**
IM40-6.3-1	LVR_MnRoad	120	0.3757	0.0004	**16.2**	**0**
IM40-7.6-1	LVR_MnRoad	120	0.0357	0.0003	**0.4**	**0**
IM40-7.6-2	LVR_MnRoad	120	0.2205	0.0006	**7.3**	**0**
IM52-1.0-1	LVR_MnRoad	63	0.001	0.000001	**0**	**0**
IM52-1.0-2	LVR_MnRoad	63	0.0072	0.000001	**0**	**0**
IM52-1.25-1	LVR_MnRoad	63	0.001	0.000001	**0**	**0**
IM52-1.25-2	LVR_MnRoad	63	0.0013	0.000001	**0**	**0**
IM53-1	LVR_MnRoad	63	0.001	0.000001	**0**	**0**
IM53-2	LVR_MnRoad	63	0.0071	0.000001	**0**	**0**

Table D-4. Calibrated vs. measured values of cracking

Project	**Location**	**Age months**	**Calculated**			**Measured Total % Crack**
			Total damage		**Total % crack**	
			Bottom-Up	**Top-Down**		
19_0213_Level	Iowa	2	0.0027	0.0058	**0.0**	**0**
19_0213_Level	Iowa	34	0.0244	0.037	**0.1**	**0**
19_0213_Level	Iowa	58	0.0393	0.0569	**0.2**	**0**
19_0213_Level	Iowa	66	0.0432	0.0642	**0.2**	**0**
19_0213_Level	Iowa	86	0.0576	0.081	**0.3**	**0**
19_0213_Level	Iowa	92	0.0599	0.0847	**0.4**	**0**
19_0213_Level	Iowa	130	0.0858	0.1169	**0.8**	**0**
19_0214_Level	Iowa	2	0.0015	0.0015	**0.0**	**0**
19_0214_Level	Iowa	58	0.022	0.0124	**0.0**	**0**
19_0214_Level	Iowa	66	0.024	0.0138	**0.0**	**0**
19_0214_Level	Iowa	86	0.0318	0.0172	**0.0**	**0**
19_0214_Level	Iowa	92	0.0332	0.0179	**0.0**	**0**
19_0214_Level	Iowa	130	0.0471	0.0242	**0.1**	**0**
19_0215_Level	Iowa	2	0.0002	0.001	**0.0**	**0**
19_0215_Level	Iowa	35	0.0012	0.0046	**0.0**	**0**
19_0215_Level	Iowa	58	0.0019	0.0065	**0.0**	**0**
19_0215_Level	Iowa	66	0.0021	0.0072	**0.0**	**0**
19_0215_Level	Iowa	86	0.0027	0.0088	**0.0**	**0**
19_0215_Level	Iowa	92	0.0028	0.0091	**0.0**	**0**
19_0215_Level	Iowa	130	0.0039	0.012	**0.0**	**0**
19_0216_Level	Iowa	2	1.00E-06	0.0001	**0.0**	**0**
19_0216_Level	Iowa	35	1.00E-06	0.0002	**0.0**	**0**
19_0216_Level	Iowa	58	1.00E-06	0.0003	**0.0**	**0**
19_0216_Level	Iowa	66	1.00E-06	0.0003	**0.0**	**0**
19_0216_Level	Iowa	86	0.0001	0.0004	**0.0**	**0**
19_0216_Level	Iowa	92	0.0001	0.0004	**0.0**	**0**
19_0217_Level	Iowa	2	1.00E-06	1.00E-06	**0.0**	**3**

Table D-4. Calibrated vs. measured values of cracking (cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
19_0217_Level	Iowa	34	1.00E-06	1.00E-06	0.0	6
19_0217_Level	Iowa	56	1.00E-06	1.00E-06	0.0	6
19_0217_Level	Iowa	66	0.0022	0.0013	0.0	6
19_0217_Level	Iowa	86	0.02	0.0046	0.0	6
19_0217_Level	Iowa	92	0.0224	0.0056	0.0	6
19_0217_Level	Iowa	130	0.0551	0.0121	0.1	6
19_0218_Level	Iowa	2	1.00E-06	1.00E-06	0.0	0
19_0218_Level	Iowa	35	1.00E-06	1.00E-06	0.0	3
19_0218_Level	Iowa	56	1.00E-06	1.00E-06	0.0	0
19_0218_Level	Iowa	66	0.0009	0.0004	0.0	0
19_0218_Level	Iowa	86	0.0107	0.0014	0.0	0
19_0218_Level	Iowa	92	0.0121	0.0016	0.0	0
19_0218_Level	Iowa	130	0.03	0.0036	0.0	0
19_0219_Level	Iowa	2	1.00E-06	1.00E-06	0.0	0
19_0219_Level	Iowa	35	1.00E-06	1.00E-06	0.0	0
19_0219_Level	Iowa	56	1.00E-06	1.00E-06	0.0	0
19_0219_Level	Iowa	66	1.00E-06	0.0003	0.0	0
19_0219_Level	Iowa	86	0.0001	0.0012	0.0	0
19_0219_Level	Iowa	92	0.0001	0.0014	0.0	0
19_0219_Level	Iowa	130	0.0003	0.003	0.0	0
19_0220_Level	Iowa	2	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	35	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	56	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	66	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	86	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	92	1.00E-06	1.00E-06	0.0	0
19_0220_Level	Iowa	130	1.00E-06	0.0001	0.0	0
19_0221_Level	Iowa	2	0.0001	0.0001	0.0	0
19_0221_Level	Iowa	34	0.0005	0.0002	0.0	0
19_0221_Level	Iowa	58	0.0008	0.0003	0.0	0
19_0221_Level	Iowa	66	0.0011	0.0016	0.0	0
19_0221_Level	Iowa	86	0.003	0.0059	0.0	0
19_0221_Level	Iowa	92	0.0032	0.0066	0.0	0
19_0221_Level	Iowa	130	0.0067	0.0146	0.0	0
19_0222_Level	Iowa	2	0.0004	0.0001	0.0	0
19_0222_Level	Iowa	58	0.0037	0.0002	0.0	0
19_0222_Level	Iowa	66	0.0049	0.001	0.0	0
19_0222_Level	Iowa	86	0.0109	0.0038	0.0	0
19_0222_Level	Iowa	92	0.0117	0.0043	0.0	0
19_0222_Level	Iowa	130	0.0224	0.0094	0.0	0
19_0223_Level	Iowa	2	1.00E-06	0.0009	0.0	0
19_0223_Level	Iowa	58	0.0002	0.004	0.0	0
19_0223_Level	Iowa	62	0.0003	0.0053	0.0	0
19_0223_Level	Iowa	66	0.0003	0.006	0.0	0
19_0223_Level	Iowa	86	0.0007	0.012	0.0	0
19_0223_Level	Iowa	92	0.0008	0.0129	0.0	0
19_0223_Level	Iowa	130	0.0016	0.0236	0.0	0
19_0224_Level	Iowa	2	1.00E-06	1.00E-06	0.0	0
19_0224_Level	Iowa	62	1.00E-06	1.00E-06	0.0	0

Table D-4. Calibrated vs. measured values of cracking (cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
19_0224_Level	Iowa	66	1.00E-06	1.00E-06	0.0	0
19_0224_Level	Iowa	86	1.00E-06	1.00E-06	0.0	0
19_0224_Level	Iowa	92	1.00E-06	1.00E-06	0.0	0
19_0224_Level	Iowa	130	1.00E-06	0.0001	0.0	0
19_3006_r	Iowa	226	0.2813	0.3143	7.1	16
19_3006_r	Iowa	282	0.384	0.4407	13.6	20
19_3006_r	Iowa	296	0.4154	0.4744	15.7	20
19_3006_r	Iowa	299	0.4197	0.4865	16.2	20
19_3009	Iowa	214	0.0175	0.1778	1.2	8
19_3009	Iowa	280	0.0345	0.3437	4.9	8
19_3009	Iowa	316	0.0446	0.4451	8.2	8
19_3009	Iowa	342	0.052	0.5231	11.2	8
19_3028	Iowa	117	1.00E-06	1.00E-06	0.0	0
19_3028	Iowa	172	0.0297	0.0508	0.1	0
19_3028	Iowa	209	0.0537	0.092	0.4	0
19_3028	Iowa	235	0.0713	0.1227	0.7	0
19_3033	Iowa	132	0.0042	0.0037	0.0	0
19_3033	Iowa	187	0.0254	0.024	0.0	0
19_3033	Iowa	230	0.0463	0.0445	0.1	0
19_3033	Iowa	250	0.059	0.0542	0.2	0
19_3055	Iowa	299	0.0033	0.0028	0.0	0
19_3055	Iowa	371	0.0044	0.0037	0.0	0
19_3055	Iowa	400	0.0049	0.0042	0.0	0
27_3003	Minnesota	166	0.001	0.0028	0.0	0
27_3003	Minnesota	204	0.0012	0.0034	0.0	0
27_3007	Minnesota	12	0.0068	0.0002	0.0	0
27_3007	Minnesota	63	0.0625	0.0012	0.1	0
27_3007	Minnesota	87	0.1073	0.0019	0.4	0
27_3009	Minnesota	12	0.0123	0.0003	0.0	0
27_3009	Minnesota	63	0.1051	0.0018	0.4	0
27_3009	Minnesota	87	0.1773	0.0028	1.2	0
27_3010	Minnesota	12	0.0111	0.0014	0.0	0
27_3010	Minnesota	63	0.0974	0.0098	0.3	0
27_3010	Minnesota	86	0.1654	0.0157	1.1	0
27_3012	Minnesota	12	0.001	0.0052	0.0	0
27_3012	Minnesota	63	0.0067	0.0363	0.0	0
27_3012	Minnesota	86	0.0103	0.0555	0.1	0
27_3013	Minnesota	166	0.0013	0.0004	0.0	0
27_3013	Minnesota	166	0.0013	0.0004	0.0	0
27_3013	Minnesota	204	0.0017	0.0005	0.0	0
27_3013	Minnesota	204	0.0017	0.0005	0.0	0
55_3008_L13	Wisconsin	227	1.00E-06	0.0002	0.0	0
55_3008_L19	Wisconsin	227	0.0025	0.0398	0.1	7.4
55_3009_L12	Wisconsin	121	0.0002	0.0105	0.0	0
55_3009_L12	Wisconsin	127	0.0002	0.0107	0.0	0
55_3009_L12	Wisconsin	179	0.0002	0.0141	0.0	0
55_3009_L19	Wisconsin	121	0.0022	0.4463	8.2	0

Table D-4. Calibrated vs. measured values of cracking (cont.)

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
55_3009_L19	Wisconsin	127	0.0023	0.4581	**8.6**	**0**
55_3009_L19	Wisconsin	179	0.0031	0.6252	**15.5**	**0**
55_3010_L12	Wisconsin	193	1.00E-06	0.0006	**0.0**	**0**
55_3010_L12	Wisconsin	251	1.00E-06	0.0008	**0.0**	**0**
55_3010_L19	Wisconsin	193	0.001	0.0969	**0.3**	**0**
55_3010_L19	Wisconsin	251	0.0013	0.1288	**0.6**	**0**
55_3012_12.5	Wisconsin	189	0.1622	0.0004	**1.0**	**0**
55_3012_12.5	Wisconsin	263	0.2322	0.0006	**2.1**	**0**
55_3012_18.5	Wisconsin	189	0.2201	0.0029	**1.9**	**0**
55_3014_12.5	Wisconsin	199	1.00E-06	0.004	**0.0**	**0**
55_3014_12.5	Wisconsin	275	1.00E-06	0.0055	**0.0**	**0**
55_3016_L12	Wisconsin	98	0.0002	0.0002	**0.0**	**0**
55_3016_L19	Wisconsin	98	0.0037	0.0242	**0.0**	**0**
55_3019_12	Wisconsin	280	0.0007	0.0002	**0.0**	**0**
55_3019_18	Wisconsin	280	0.0547	0.0246	**0.1**	**0**
55_6351_L12	Wisconsin	132	0.0002	0.009	**0.0**	**0**
55_6351_L12	Wisconsin	169	0.0003	0.0121	**0.0**	**0**
55_6351_L19_r	Wisconsin	132	0.0569	0.6026	**14.6**	**37**
55_6351_L19_r	Wisconsin	169	0.08	0.8377	**25.8**	**37**
55_6352_L12	Wisconsin	132	1.00E-06	0.0006	**0.0**	**0**
55_6352_L12	Wisconsin	169	1.00E-06	0.0008	**0.0**	**0**
55_6352_L19	Wisconsin	132	0.0048	0.0954	**0.3**	**0**
55_6352_L19	Wisconsin	169	0.0075	0.1474	**0.8**	**0**
55_6353_L12	Wisconsin	74	1.00E-06	0.0002	**0.0**	**0**
55_6353_L12	Wisconsin	132	1.00E-06	0.0005	**0.0**	**0**
55_6353_L12	Wisconsin	169	1.00E-06	0.0007	**0.0**	**0**
55_6353_L19	Wisconsin	74	0.0008	0.0202	**0.0**	**0**
55_6353_L19	Wisconsin	132	0.0022	0.0751	**0.2**	**0**
55_6353_L19	Wisconsin	169	0.0032	0.1184	**0.5**	**0**
55_6354_L12	Wisconsin	74	1.00E-06	0.0002	**0.0**	**0**
55_6354_L12	Wisconsin	132	1.00E-06	0.0008	**0.0**	**0**
55_6354_L12	Wisconsin	169	1.00E-06	0.0012	**0.0**	**0**
55_6354_L19	Wisconsin	74	0.0004	0.0382	**0.0**	**0**
55_6354_L19	Wisconsin	132	0.0012	0.1336	**0.7**	**0**
55_6354_L19	Wisconsin	169	0.0017	0.2093	**1.7**	**0**
55_6355_L12	Wisconsin	132	1.00E-06	0.0008	**0.0**	**0**
55_6355_L12	Wisconsin	169	1.00E-06	0.0013	**0.0**	**0**
55_6355_L19	Wisconsin	132	0.0058	0.1182	**0.5**	**0**
55_6355_L19	Wisconsin	169	0.0095	0.1962	**1.5**	**0**
Loop_4_8	AASHO-Illinois	168	0.7941	0.6601	**36.6**	**40.4**
Loop_4_9.5	AASHO-Illinois	168	0.0568	0.2021	**1.7**	**0**
Loop_5_11	AASHO-Illinois	168	0.0031	0.0488	**0.1**	**0**
Loop_5_9.5	AASHO-Illinois	168	0.0568	0.2021	**1.7**	**0**
Loop_6_11	AASHO-Illinois	168	0.0032	0.0488	**0.1**	**0**
Loop_6_12.5	AASHO-Illinois	168	0.0001	0.0122	**0.0**	**0**
Loop_6_9.5	AASHO-Illinois	168	0.0568	0.2021	**1.7**	**16.1**
IM10	Mainlane_MnRoad	78	0.0284	0.0896	**0.3**	**0**

Table D-4. Calibrated vs. measured values of cracking (cont.).

Project	Location	Age months	Calculated			Measured Total % Crack
			Total damage		Total % crack	
			Bottom-Up	Top-Down		
IM11	Mainlane_MnRoad	78	0.2965	0.3242	7.7	0
IM12	Mainlane_MnRoad	78	0.0102	0.0082	0.0	0
IM13	Mainlane_MnRoad	78	0.1083	0.3061	4.2	0
IM5	Mainlane_MnRoad	78	0.106	0.1724	1.5	0
IM6	Mainlane_MnRoad	78	0.0621	0.0122	0.1	0
IM7	Mainlane_MnRoad	78	0.0267	0.0433	0.1	0
IM8	Mainlane_MnRoad	78	0.0161	0.0041	0.0	0
IM9	Mainlane_MnRoad	78	0.0162	0.004	0.0	0
IM36-1	LVR_MnRoad	120	0.0793	0.0003	0.2	0
IM36-2	LVR_MnRoad	120	0.2866	0.0005	3.3	0
IM37_1	LVR_MnRoad	120	0.0154	0.000001	0.0	0
IM37_2	LVR_MnRoad	120	0.0656	0.000001	0.1	0
IM38_1	LVR_MnRoad	120	0.3493	0.0004	5.0	0
IM39_1	LVR_MnRoad	120	0.7633	0.0021	22.0	0
IM40-6.3-1	LVR_MnRoad	120	0.3757	0.0004	5.8	0
IM40-7.6-1	LVR_MnRoad	120	0.0357	0.0003	0.0	0
IM40-7.6-2	LVR_MnRoad	120	0.2205	0.0006	1.9	0
IM52-1.0-1	LVR_MnRoad	63	0.001	0.000001	0.0	0
IM52-1.0-2	LVR_MnRoad	63	0.0072	0.000001	0.0	0
IM52-1.25-1	LVR_MnRoad	63	0.001	0.000001	0.0	0
IM52-1.25-2	LVR_MnRoad	63	0.0013	0.000001	0.0	0
IM53-1	LVR_MnRoad	63	0.001	0.000001	0.0	0
IM53-2	LVR_MnRoad	63	0.0071	0.000001	0.0	0