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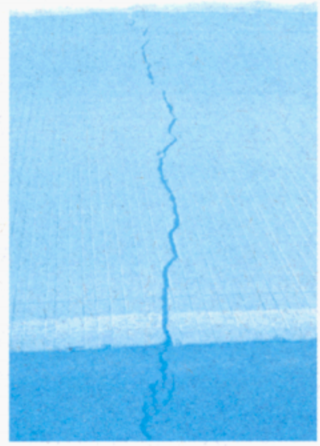
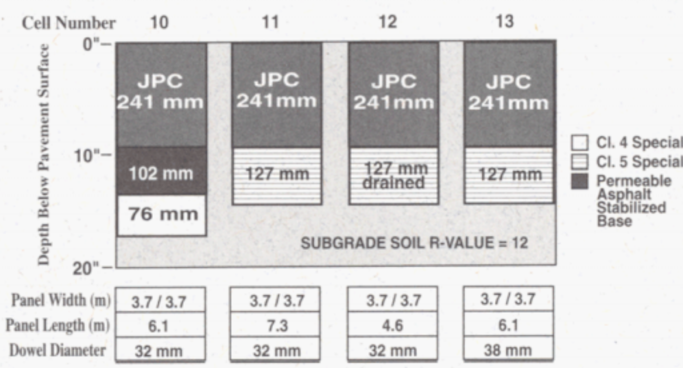


Figure 1.2 Mn/ROAD 10-Year Mainline Concrete Test Sections



Application of Empirical and Mechanistic-Empirical Pavement Design Procedures to Mn/ROAD Concrete Pavement Test Sections

Research

Local Road Research Board

Mn/ROAD
Office of Minnesota Road Research

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Current pavement design procedures are based principally on empirical approaches. The current trend toward developing more mechanistic-empirical type pavement design methods led Minnesota to develop the Minnesota Road Research Project (Mn/ROAD), a long-term pavement testing facility. The project consists of 40 heavily instrumented test sections, 14 of which are jointed plain concrete (JPC) designs.

Mn/ROAD researchers determine the predicted lives of the concrete test sections by applying design and as-built data to three currently accepted concrete pavement design methods: Minnesota Department of Transportation's rigid pavement design guidelines, AASHTO Guide for Design of Pavement Structures 1993, and the PCA Thickness Design for Concrete Highway and Street Pavements (1984).

The analysis began with determining the applicable as-built parameter values for each respective design method. Applying the as-built parameters to the three methods resulted in widely varied predictions of pavement life. For the 1993 AASHTO design method, reliability levels of 50 percent and 95 percent were applied for comparison. An experimental procedure for converting PCA method fatigue and erosion results to AASHTO type CESALS demonstrated unsuitability. Validation of the predictions presented will occur as the test cells reach their terminal serviceability.

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APPLICATION OF EMPIRICAL AND MECHANISTIC-EMPIRICAL PAVEMENT DESIGN PROCEDURES TO Mn/ROAD CONCRETE PAVEMENT TEST SECTIONS

Final Report

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TABLE OF CONTENTS

Contents - Continued

LIST OF TABLES AND FIGURES

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Current pavement design procedures are based principally on empirical approaches. The introduction of new materials and the significant increase in recent traffic volumes have brought uncertainty to their prediction of pavement behavior. The current trend toward developing more mechanistic-empirical type pavement design methods led Minnesota to develop the Minnesota Road Research Project (Mn/ROAD). The project consists of 40 heavily instrumented test sections, 14 of which are jointed plain concrete (JPC) designs.

The predicted service lives of the Mn/ROAD concrete test sections were determined using design and as-built data applied to three currently accepted concrete pavement design methods: Minnesota Department of Transportation's rigid pavement design guidelines, *AASHTO Guide for Design of Pavement Structures 1993*, and the *PCA Thickness Design for Concrete Highway and Street Pavements (1984)*.

The analysis included determination of applicable as-built parameter values for each respective design method. The following observations were made:

- As-built 28 day concrete modulus of rupture values were generally lower than assumed in design.
- As-built modulus of subgrade reaction values were very close to design assumptions for the Mn/DOT method, but were about 40% lower than design for the 1993 AASHTO method.
- Generally, as-built pavement thicknesses were over 2% higher than design.
- Initial serviceability factors were much lower than expected for new concrete pavement construction.

The predicted test cell life (to terminal serviceability) varied widely depending on the design life, pavement design method, and reliability level. The following observations were made:

- As-built information applied to the Mn/DOT design method resulted in test cell life predictions ranging from 2.4 to 5.8 years for the 5 year design cells, and from 12.0 to 13.1 years for the 10 year design cells.
- For a reliability level of 95%, as-built information applied to the 1993 AASHTO design method resulted in test cell life predictions ranging from 0.8 to 2.3 years for the 5 year design cells, and from 3.0 to 5.3 years for the 10 year design cells. For a reliability level of 50%, test cell

life predictions were somewhat closer to design values, but still varied widely.

- With the exception of test cells 6 and 8, the 1984 PCA design method predicted pavement fatigue stress and erosion damage to be less than 15% for the original design lives of the mainline test cells. For the low volume road test cells, only cells 37 and 40 (no dowels)showed predicted erosion damage levels exceeding 4% in 3 years of trafficking.
- The procedure outlined in this study for converting PCA method fatigue and erosion results to AASHTO type CESALs demonstrated unsuitability. The need exists for a reliable procedure which would correlate fatigue and erosion damage to AASHTO serviceability criteria (ride quality).

The significantly different test cell life predictions that were found in this study demonstrate the disagreement on how to best predict concrete pavement life. It also highlights the limitations caused by the assumptions required for each method, and the extent to which the original AASHO Road Test results have been extrapolated beyond their intended application. The results clearly justify the need for a more rational design method, taking into account modern day traffic loads, materials, and construction practices.

With the age of the Mn/ROAD concrete test cells currently at 2.5 years, and CESAL applications at approximately 2.2 million, there is very little visual evidence of surface distress or measurable deterioration of ride quality since construction was completed. Results from this study therefore indicate some discrepancies between field performance and the empirical design methods currently being applied.

The predictions found in this study will be monitored as the Mn/ROAD test cells continue to age. Validation of the predictions presented here will occur as the test cells reach terminal serviceability.

CHAPTER 1
INTRODUCTION

BACKGROUND

Existing pavement design procedures are principally based on either empirical or mechanistic-empirical approaches. An empirical approach is based on observed performance, without consideration of theoretical behavior. Conversely, a mechanistic-empirical design approach ties together the theoretical behavior of a pavement with observed performance.

The Minnesota Department of Transportation's (Mn/DOT) current rigid pavement design procedure is described as "an empirical method which is based on a combination of the modified 1981 AASHTO pavement design procedure and the knowledge gained from performance of rigid pavements in Minnesota.[1]" Application of this method has provided good overall performance over the last 20 years. However, the introduction of new materials and construction methods, as well as the significant increase in traffic volumes and loads, has brought uncertainty to its ability to predict long term pavement behavior in Minnesota.

Recognizing the need to address the situation, Mn/DOT, in cooperation with the University of Minnesota, decided in the late 1980's to join the emerging trend toward developing a mechanistic-empirical type pavement design method. With the large amount of capital investment tied into the state's road network, it was deemed that any decreases in construction costs, or increases in pavement life, would be beneficial. Besides economic benefits, longer lasting roads result in less construction and maintenance, which reduces safety hazards to the road construction industry and the traveling public.

It has been nearly 40 years since the last major road test (AASHO) was constructed. AASHTO's (American Association of State Highway and Transportation Officials) current design method is still based for the most part on test results from that experiment. Unfortunately due to the short time that experiment was run, and the fact that the results only really represented Illinois' climate conditions, many of the findings have out of necessity been extrapolated far beyond reasonableness. In order to better understand the effects the increased traffic loads and volumes are having on pavement performance in Minnesota, Mn/DOT decided to design and construct a new full scale pavement test facility. Known as the Minnesota Road Research Project, or Mn/ROAD, this road test will provide Mn/DOT and other cold region areas the necessary data for developing a new comprehensive mechanistic-empirical pavement design method.

Mn/ROAD TEST FACILITY

Located approximately 40 miles northwest of Minneapolis in Otsego, Minnesota, Mn/ROAD is a full scale cold regions pavement test facility. It contains forty 150 m (500 ft) long instrumented test sections or "cells" arranged into two different groups of traffic loading and three different periods of service life. The groupings are as follows:

1) Nine 5 year design life "mainline" cells, which receive live high volume interstate (I-94) traffic loads,
2) Fourteen 10 year design life "mainline" cells, which also receive live high volume interstate (I-94) traffic loads, and
3) Seventeen 3 year design life "low volume" cells, which receive loading from one calibrated truck driven around a closed loop configuration.

Of the forty test cells, 14 are portland cement concrete surfaced, 22 are bituminous surfaced, and 4 are aggregate surfaced. See Figures 1.1-1.3 for concrete test cell profiles.

Construction of the Mn/ROAD test facility began in 1990. Electronic instrumentation and paving of the test cells occurred in 1992 and 1993. The test cells were opened to traffic loading in August of 1994.

Each Mn/ROAD test cell was designed using current Mn/DOT pavement design guidelines. Designs were checked for reasonableness using the *AASHTO Guide for Design of Pavement Structures 1986*[5], which was current at that time.

FOCUS OF THIS STUDY

Due to the fact the Mn/ROAD test facility was designed to receive "real world" traffic, as well as to be exposed to the natural Minnesota climate (it is not intended to be an "accelerated" test facility), early research results are limited. One area of study that is immediately available for analysis, however, is the comparison between actual or as-built pavement material properties and the assumed values used in design. This study took the result of that type of comparison and examined its effect on Mn/ROAD concrete pavement test cell life predictions using current pavement design procedures.

This study was formulated to address a portion of Mn/ROAD's long term Research Objective #1-C, titled "Verification of Empirical Design Models for New Rigid Pavements.[6]" That objective seeks to determine the effect recent traffic characteristic changes have on existing rigid pavement design methods. This study, however, only examined the effect current materials and construction practices have on different pavement design procedures.

In this study, Mn/ROAD data was applied to three different rigid pavement design methods:

1) Minnesota Department of Transportation's (Mn/DOT) rigid pavement design guidelines[1] (based on modified 1981 *AASHTO Interim Guide for Design of Pavement Structures*[2]).
2) *AASHTO Guide for Design of Pavement Structures 1993*[3].
3) PCA *Thickness Design for Concrete Highway and Street Pavements (1984)*.[4]

As described above, Mn/DOT's rigid pavement design procedure is empirical and based on the 1981 AASHTO design guide. The AASHTO 1993 pavement design guide, also an empirically based method, adds considerations for reliability, environmental effects, and behavior with tied shoulders. Finally, the PCA (Portland Cement Association, 1984) pavement design method is mechanistic-empirical based. It combines slab behavior theories and finite element analyses with experimental pavement testing results from facilities such as the AASHO Road Test.

OBJECTIVES

The objectives of this study included:

1) Verify parameters and assumptions used in original Mn/ROAD concrete test cell design calculations.
2) Determine applicable pavement design method parameters based on available as-built data collected up to December 1996.
3) Determine the predicted service lives of the Mn/ROAD project's concrete test sections using two empirical and one mechanistic-empirical pavement design method.

Figure 1.1 Mn/ROAD 5-Year Mainline Concrete Test Sections

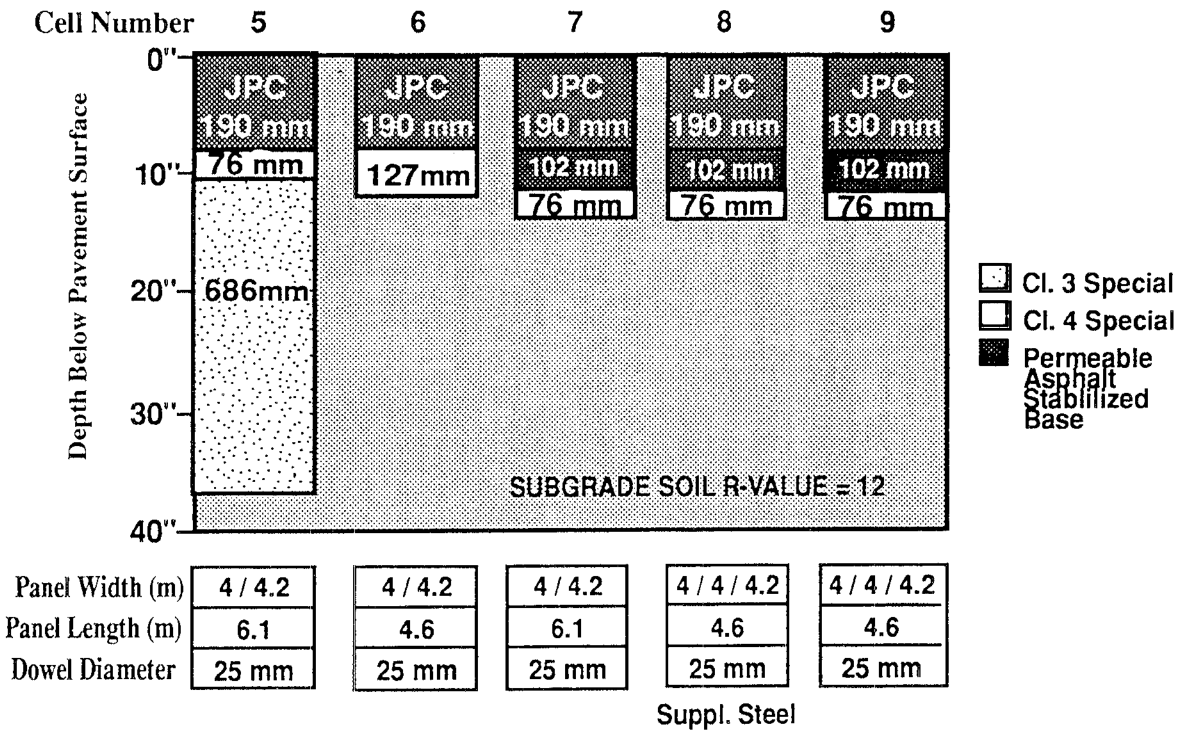


Figure 1.2 Mn/ROAD 10-Year Mainline Concrete Test Sections

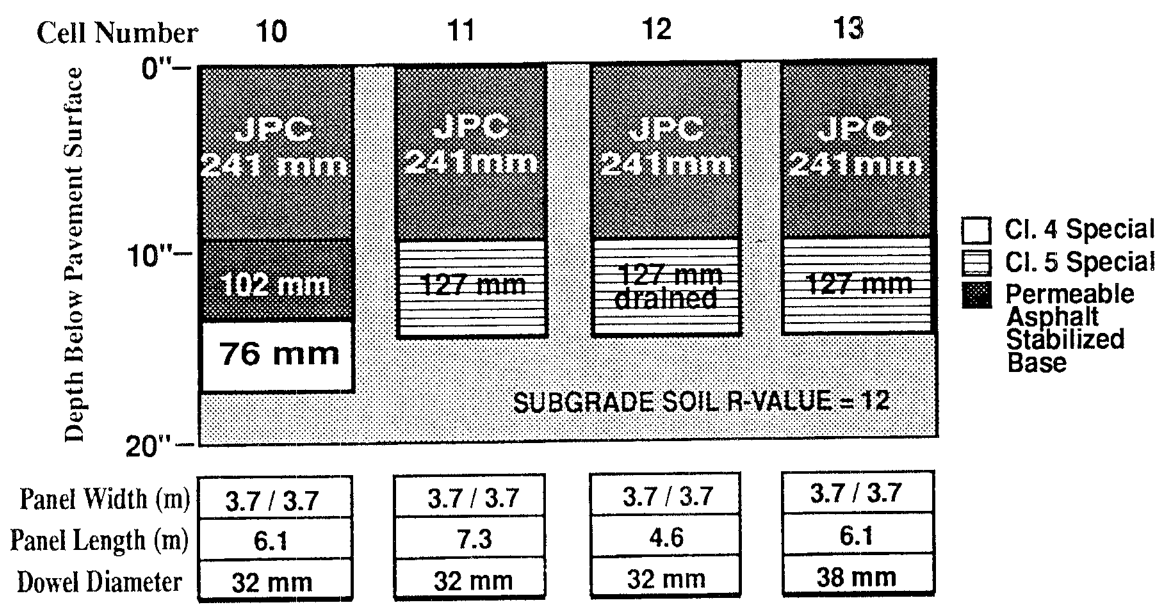
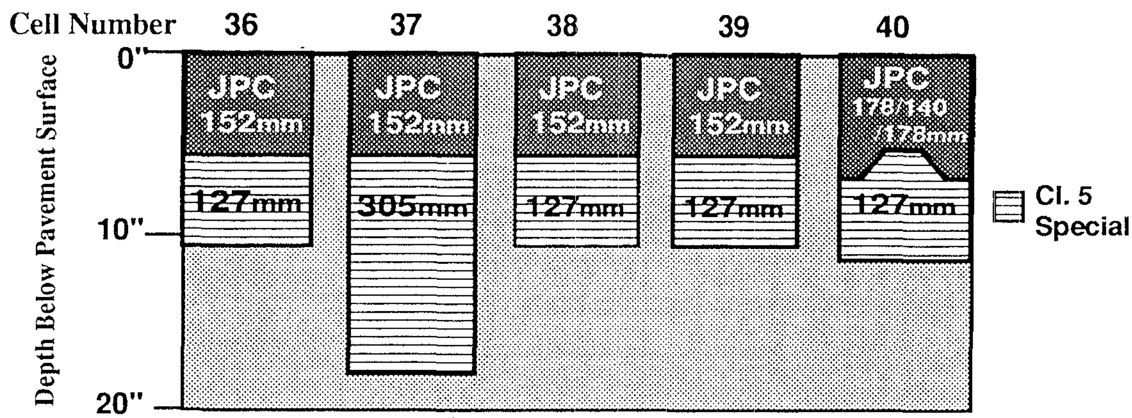


Figure 1.3 Mn/ROAD Low Volume Road Concrete Test Sections



Panel Width (m)	3.7/3.7	3.7/3.7	3.7/3.7	3.7/3.7	3.7/3.7
Panel Length (m)	4.6	3.7	3.7	6.1	4.6
Dowel Diameter	25 mm	none	25 mm	25 mm	none
Soil "R" Value	70	70	12	12	12

SCOPE

This study addressed the properties and behavior of the following Mn/ROAD concrete pavement test cells:

1) "Mainline" 5-year design life cells: #5 - 9.

2) "Mainline" 10-year design life cells: #10 - 13.

3) "Low Volume Road" 3-year design life cells: #36 - 40.

See Figures 1.1 - 1.3 for test cell cross sections and details.

The pavement design parameters considered in this study include:

1) Panel length and width

2) Presence of dowel bars

3) Modulus of subgrade reaction (k-value)

4) Concrete modulus of rupture

5) Concrete modulus of elasticity

6) Joint load transfer effectiveness

7) Pavement serviceability (ride quality)

8) Drainage coefficient

9) Equivalent single axle load (ESALs) applications

10) Pavement layer thickness.

As-built design parameter values were determined from concrete core measurements, soil test results, and falling weight deflectometer (FWD) test results.

APPROACH

This study began with the assembly and summarization of design and as-built information obtained during and following the construction of the Mn/ROAD project. For the "mainline" test sections, traffic loading and volumes from the on-site weigh-in-motion (WIM) equipment were gathered for comparison to original traffic forecasts. For the low volume road test sections, truck loading and loop count information was taken from daily driver information sheets.

Once the necessary as-built information was gathered, it was applied to the three pavement design methods considered in this study. To expedite the analysis, the following computer program versions of each of the design methods were utilized:

1) Mn/DOT method : "PAVE" program[7]

2) 1986 AASHTO method: "DNPS86/PC™" program[8]

3) 1993 AASHTO method: "DARWin™" program[9]

4) 1984 PCA method: PCAPAV program[10].

The analysis process began with the application of original design parameter values to the Mn/DOT design method. This served to highlight the original assumed values, and to verify the original design life predictions. Next, the results of that analysis were compared to those found by applying the same values to the 1986 AASHTO design method, which was current at the time of design. As-built parameter values were next input into all three methods under consideration. This served to determine the effect construction had on each design method's service life predictions.

The final results presented for each design method include:

1) Total CESAL (concrete pavement equivalent single axle load) applications to terminal serviceability predicted for each test cell based on as-built material and section properties.

2) Predicted serviceability life for each test cell based on data gathered from August 1994 to December 1996.

CHAPTER 2

DESIGN PARAMETERS

RIGID PAVEMENT DESIGN PARAMETERS

The three concrete pavement design methods applied in this study utilize several common input parameters. The original assumed values, together with as-built values as determined by various test methods, are outlined in the following sections. Before examining these parameters it should be noted that all of the concrete test cells at Mn/ROAD contain plain jointed portland cement concrete (JPC) slabs. All but two cells (cells 37 and 40) have doweled joints.

Mn/DOT Concrete Pavement Design Method Parameters

Tables 2.1 and 2.2 summarize many of the Mn/ROAD original and as-built design parameter values used for this design method.

Concrete Modulus of Rupture

The concrete modulus of rupture value used for the design of all concrete test cells was 3.450 MPa (500 psi). This value came from the specified application of a safety factor of 1.33 to a state (of Minnesota) historical average modulus of rupture value of 4.655 MPa (675 psi).[1] The as-built values for each test cell were determined from samples taken during construction. All values are based on 28 day third point loading beam tests[11] (ASTM C 78-84). A safety factor of 1.33 was applied to these values for a valid comparison. See Table 2.2.

Concrete Modulus of Elasticity

The concrete modulus of elasticity value used for the design of all concrete test cells was the Mn/DOT standard value of 28960 MPa (4,200,000 psi). This parameter is rarely tested for in practice, since it has little effect on the final pavement design thickness. The as-built values used in this study came from tests on 28 day concrete core samples[11] (ASTM C 469-87a). See Table 2.2.

TABLE 2.1 Mn/ROAD original test cell design parameters for Mn/DOT concrete pavement design method

Test Cell #	k-value using modified R-value (kPa/cm)	Load transfer (J factor)	Calculated pavement thickness[b] (mm)
5	1422	2.6	178
6	720	2.6	193
7	796	2.6	190
8	796	2.6	190
9	796	2.6	190
10	796	3.2	246
11	720	3.2	246
12	720	3.2	246
13	720	3.2	246
36	1422	3.2	107
37	1422	3.8	107
38	720	3.2	107
39	720	3.2	107
40	720	3.2[a]	107

(a) Assumed thickened edge would balance effects of nondoweled joints.
(b) Determined using Mn/DOT's PAVE computer program.

Unit conversions: kPa/cm=0.369pci, mm=0.0394in

TABLE 2.2 **Mn/ROAD as-built test cell design parameters for Mn/DOT concrete pavement design method**

Test Cell #	Concrete modulus of rupture[a,b] (MPa)	Concrete modulus of elasticity[a] (MPa)	k-value using modified R-value (kPa/cm)	Average pavement thickness[c] (mm)
5	3.241	25566	1425	189
6	2.929	31245	780	187
7	2.981	27074	950	199
8	2.643	31211	915	194
9	2.929	29458	930	198
10	3.267	21440	950	253
11	3.733	26083	885	244
12	3.448	28461	830	253
13	3.526	27330	830	250
36	3.267	25615	1425	166
37	3.422	23262	1425	174
38	3.474	31659	850	167
39	3.189	29116	830	165
40	3.215	26206	850	197/182/197

(a) From Reference 11..
(b) Safety factor reduction of 1.33 has been applied.
(c) See Appendix A.

Unit conversions: MPa=145psi, kPa/cm=0.369pci, mm=0.0394in

Modulus of Subgrade Reaction

The modulus of subgrade reaction (k-value) used in the Mn/DOT design method is based upon correlation to the resistance or R-value of the subgrade soil. The relationship was formulated by regression analysis of Hveem Stabilometer R-value and fractional plate bearing tests conducted at various test sites to produce k-values suitable for Minnesota's climate.[1] The correlation equation is as follows:

$$k = -1.17 + 63\sqrt{R} \qquad (1)$$

where k = modulus of subgrade reaction, psi/in, and

R = R-value determined for the subgrade[12].

Design R-values for the subgrade soils were determined by laboratory testing of preliminary field samples following a modified AASHTO T-190 specification. Modifications to the standard procedure are outlined in Mn/DOT's *Geotechnical & Pavement Manual, Part 1.*[12]

Two types of subgrade material were used under the concrete test cells on the Mn/ROAD project. Twelve of the cells (including all of the mainline test cells) have a silty clay subgrade with a design R-value of 12. The other two cells (located on the low volume road loop) have a select granular subgrade material with a design R-value of 70.

While there are various gravel and asphalt-stabilized base layers over the subgrade layers, their contribution to the design k-value is typically neglected in the Mn/DOT pavement design procedure. However, in an effort to better predict the true behavior of the test cells, the designers attempted to account for the increased stiffness provided by the various base layers. This was accomplished by determining each base layer's R-value based on granular equivalency, and then adding it to the subgrade R-value. The procedure used was as follows:

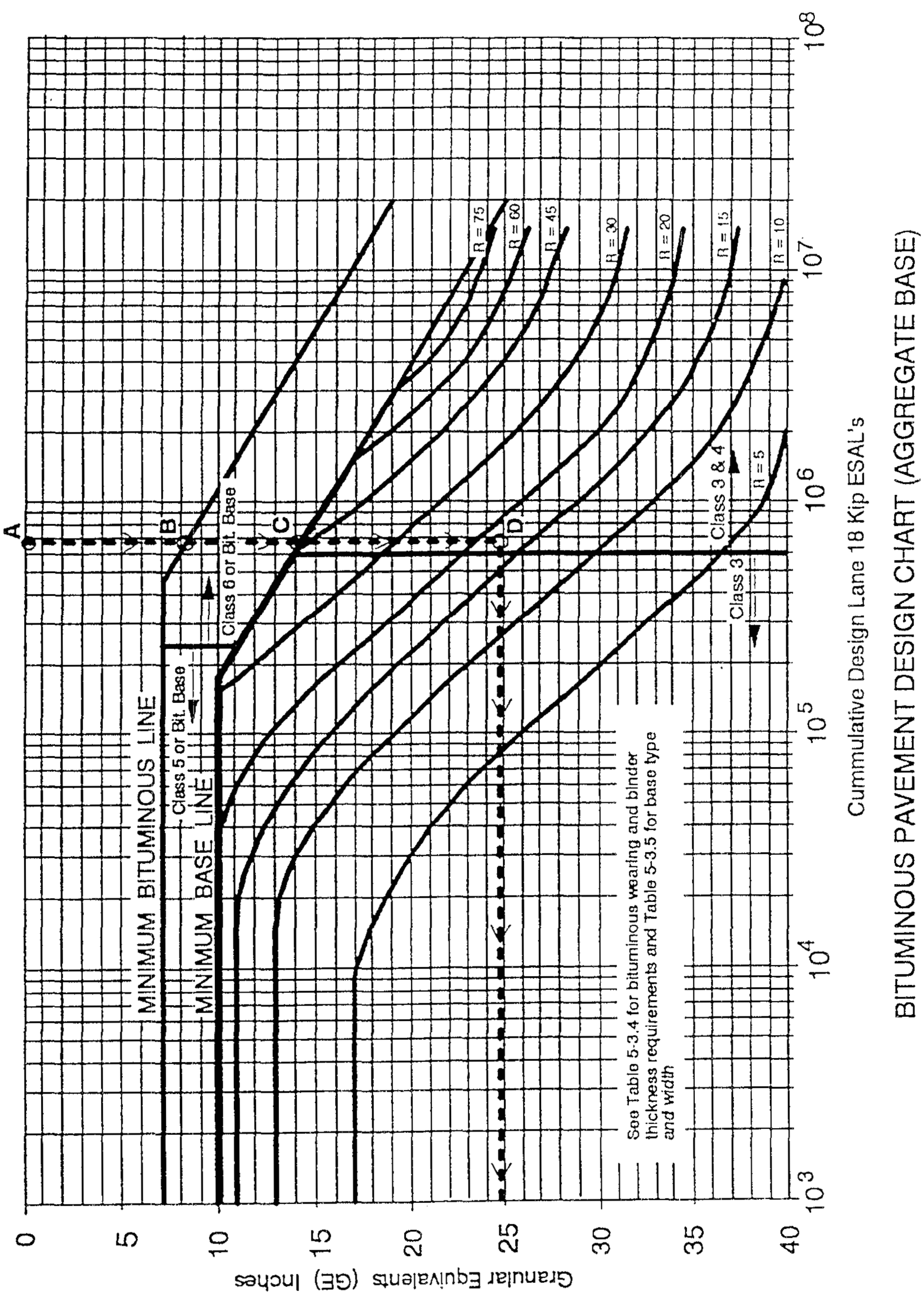
1) Determine the granular equivalent (G.E.) factor based on the type of base from Table 2.3.
2) Multiply the thickness of the base by the granular equivalent factor to obtain the granular equivalents to be used in Figure 2.1[1].
3) Enter Figure 2.1 with the design lane ESALs value until meeting the corresponding subgrade R-value curve.
4) From the point determined in step 3, move up the graph by the number of granular equivalents determined in step 2.

TABLE 2.3 Mn/ROAD Granular Equivalent (G.E.) factors

Material	Specification	G.E. factor[a]
Aggregate Base	Class 3 Sp.	0.75
Aggregate Base	Class 4 Sp.	0.75
Aggregate Base	Class 5 Sp.	1.0
Aggregate Base	Class 6 Sp.	1.0
Permeable Asphalt Stabilized Base	PASB	1.0

(a) Followed recommendations found in reference 1.

FIGURE 2.1 Mn/DOT Bituminous Pavement Design Chart (Aggregate Base)[1]



5) Determine the overall R-value at that point.

The value determined was then correlated to a k-value using equation 1 above. The design k-values are listed in Table 2.1.

As-built subgrade soil R-values were determined from testing soil samples taken during the construction of Mn/ROAD. The same R-value base layer modification procedure as described above was applied. Table 2.4 shows both the as-built R-values and resulting k-values used in this analysis.

Load Transfer Coefficient

Load transfer coefficient values (J-factors) used in the Mn/DOT design method were taken directly from AASHTO recommendations. Table 2.1 lists the values used in the original design of each test cell. The Mn/ROAD 5 year design concrete test cells were constructed with a driving lane width of 4.2 m (14 ft), which was considered to be an extended edge or tied concrete shoulder design. The 10 year design concrete test cells have a 3.6 m (12 ft) driving lane width. Except for test cells 8 and 9, the concrete test cells at Mn/ROAD have bituminous shoulders on both sides. Cells 8 and 9 have a tied 4.0 m (13 ft) concrete shoulder attached to the passing lane and a bituminous shoulder adjacent to the driving lane.

Test cell 40 was assigned a J-factor of 3.2 assuming the thickened edge design would compensate for the lack of dowels.

An attempt was made to determine "as-built J-factors" by utilizing Spangler's stress equation, which was used originally to extend AASHO Road Test results to other soil and concrete properties. In trying to consider all the important variables involved, such as slab warp and curl, extended panel width, and dowel bar presence, it was soon discovered that the analysis would become too involved for this study. Therefore, the same values used in design were also used for the as-built analysis in this study.

A recent publication[14] lists as a deficiency of the AASHTO pavement design methods the use of the Spangler equation for determining critical slab stress. While the Spangler equation focused on the corner of the panel as the location of critical stress, the critical stress location for the AASHO road test sections was actually along the slab edge for panels 165 mm (6.5 in) and

TABLE 2.4 Mn/ROAD k-values as determined from R-values

Test Cell #	Design R-value[a]	Modified design R-value[b]	As-built R-value [a]	Modified as-built R-value[b]	k-value using modified as-built R-value (kPa/cm)
5	12	70	15.5	70	1425
6	12	18	15.0	21	780
7	12	22	15.5	31	950
8	12	22	13.0	29	915
9	12	22	14.3	30	930
10	12	22	15.3	31	950
11	12	18	14.8	27	885
12	12	18	12.7	24	830
13	12	18	13.2	24	830
36	70	70	70.0	70	1425
37	70	70	70.0	70	1425
38	12	18	16.2	25	850
39	12	18	15.4	24	830
40	12	18	16.0	25	850

(a) R-value @ 1.655 MPa (240 psi) water exudation pressure.
(b) Modified using Mn/DOT granular equivalency chart (Fig. 2.1).

Unit conversions: kPa/cm=0.369pci

greater in thickness. The presence of dowel bars resulted in much lower stresses in the slab corners. The authors state "Use of Spangler's corner equation with doweled joints does not model the critical stress and crack initiation location, and thus cannot possibly provide accurate indications of the effect of slab support on cracking, especially when thermal curling and moisture warping are considered." Thus, an in-depth investigation into "as-built J-factors" may not be beneficial.

Traffic loading

An important parameter was the estimated number of AASHTO 18-kip equivalent single-axle loads (ESALs) to be applied before the serviceability level of each test cell would reach a terminal value of 2.5. Since the 5 and 10 year design test cells receive traffic diverted off the existing Interstate Highway 94, original design traffic volumes were estimated in 1987 based on historical data available for that location. Following the 1989 installation of the weigh-in-motion (WIM) device (just preceding the entrance to the project), data was collected and analyzed to validate the original forecast.

Table 2.5 shows a breakdown of traffic data used for the base year design of the Mn/ROAD mainline test sections. Table 2.6 shows the traffic data broken down by vehicle type. Also shown are the concrete pavement ESAL factors (CESALs) assumed for the design. The total two-way annual CESALs were found to be 2,011,798, to which a design lane factor of 0.45 was applied to arrive at the base year design CESAL prediction of 905,309.

The Mn/DOT design method recommends multiplying estimated ESALs by 0.93 to account for the difference between climate conditions in Minnesota and Illinois (AASHO Road Test). This correction was, however, not utilized in the design of Mn/ROAD test sections.

Table 2.7 summarizes the final formulation of the traffic information used for the design of the Mn/ROAD mainline concrete sections. The sections were designed for the HCADT (Heavy Commercial Average Daily Traffic) with an assumed 2.5% annual compound growth rate. At the time of design, the anticipated time to completion of construction (start of traffic application) was estimated to be in 1992. Therefore the 5 year design life cells were designed using CESAL numbers from years 1992 through 1996. Similarly, the 10 year design life cells were designed using CESAL numbers from years 1992 through 2001. Actual trafficking began in August of 1994.

In summary, the design concrete equivalent 18 kip single axle loads (CESALs) for Mn/ROAD mainline test cells were as follows:

1) 5 year design test cells (#5-9): 5,262,400

2) 10 year design test cells (#10-13): 11,225,270.

The Mn/ROAD low volume test cells (cells 36-40) were initially designed for 100,000 CESALs. As stated previously, initial pavement thickness calculations revealed a recommended slab thickness of 107 mm (4.2 in). Given Mn/DOT's minimum concrete pavement thickness requirement of 152 mm (6.0 in), it becomes apparent the low volume road test cells should withstand significantly more CESAL applications than originally intended in the experimental time line of 3 years.

Pavement Thickness

Design pavement thicknesses were determined by inserting all of the necessary parameters into Mn/DOT's PAVE[7] computer program. This program simply solves the AASHTO 1981 concrete pavement design equation. The thicknesses output by the program are shown in Table 2.1. To simplify the installation of the load response instrumentation and the paving of the test cells, uniform thicknesses were chosen for the three different design life segments. Design thicknesses were as follows:

1) 5 year design life cells: 190 mm (7.5 in)

2) 10 year design life cells: 241 mm (9.5 in)

3) Low Volume Road cells: 152 mm (6.0 in) [except cell 40: 178-140-178 mm (7-5.5-7 in)].

While the Mn/DOT method predicted only a 107 mm (4.2 in) thick slab was needed for test cells 36-39 on the Low Volume Road, field slab behavior experience in Minnesota has dictated a minimum concrete pavement design thickness of 152 mm (6.0 in).

As-built pavement thicknesses were determined from core samples taken after construction. See Appendix A, Table A.1. Values used in this study are the average of all core lengths for each particular test cell. See Table 2.2.

TABLE 2.5 Base year[a] I-94 traffic data used for design of Mn/ROAD mainline test cells

Traffic Type		Number of Vehicles
Average Daily Traffic (ADT):	Two-way	24200
	One-way	12110
	Design lane	10899
Heavy Commercial Average Daily Traffic:	Two-way	3599
(HCADT)	Design lane	1620
Single Unit Trucks (S.U.):	Two-way	654
	Design lane	294
Tractor Semi-trailer (TST):	Two-way	2862
	Design lane	1288

(a) Traffic analysis base year=1988. First test cell design life year=1992.

TABLE 2.6 CESAL calculations by vehicle type used for design of Mn/ROAD mainline test cells

Vehicle Type	Concrete Pavement ESAL Factor [(a)]	Average Daily CESALs
Car/Pickup	0.0007	14
2 axle, 6 tire S.U.	0.22	90
3+ axle S.U.	0.59	145
3 axle TST	0.37	10
4 axle TST	0.53	58
5+ axle TST	1.89	4999
Twin trailers	1.60	131
Truck w/trailer, buses	0.74	61
	Total Daily ESALs	5508
	Total (two-way) Annual CESALs	2011798

(a) From reference 12.

TABLE 2.7 Mn/ROAD test cell design annual CESAL applications

Year	Design Lane HCADT	Annual CESALs[(a)]
1988	1620	905309
1989	1657	928146
1990	1695	951646
1991	1734	975814
1992[(b)]	1774	1000653
1993	1814	1025603
1994	1856	1051798
1995	1899	1078677
1996	1942	1105676
1997	1987	1133936
1998	2032	1162322
1999	2079	1191981
2000	2162	1221772
2001	2175	1252848

(a) Assumed 2.5% annual compound growth rate.
(b) 1992 - 1996 = 5 year design life (Total CESALs = 5,262,407)
1992 - 2001 = 10 year design life (Total CESALs = 11,225,266).

1986/1993 AASHTO Concrete Pavement Design Method Parameters

During the original design of the tests cells, the Mn/DOT design method results were checked for reasonableness by using the 1986 AASHTO concrete pavement design method. Due to the small difference between the 1986 AASHTO design method and the 1993 AASHTO design method, this study uses the former for verification of the original design results and the latter for comparison of the as-built design results.

During application of the 1986 AASHTO design method, the low volume road concrete test cells were designed using the low volume road design catalog (Section II, Chapter 4).[5] The assumed parameter values used for this method will be outlined in each section below.

Concrete Modulus of Rupture

A concrete modulus of rupture value of 4.655 MPa (675 psi) was used for all mainline test cells in the original design verification following the 1986 AASHTO design method. This value was based on the Minnesota state historical average modulus of rupture value reported earlier in this report. A value of 4.828 MPa (700 psi) was used for the design check of the low volume road test cells. The as-built values used in the 1993 AASHTO design method application were the same as those used in the Mn/DOT as-built design analysis (Table 2.2), without application of the 1.33 safety factor.

Concrete Modulus of Elasticity

For the 1986 AASHTO design method application, a concrete modulus of elasticity value of 28960 MPa (4,200,000 psi) was used for all mainline test cells. Low volume road test cells used an assigned value of 34480 (5,000,000 psi). For the 1993 AASHTO method application, as-built values were the same as those used in the Mn/DOT as-built design analysis (Table 2.2).

Modulus of Subgrade Reaction

In the Mn/DOT design check using the 1986 AASHTO design method, k-values for the mainline test cells were calculated using assumed seasonal resilient modulus values applied to a worksheet in the "DNPS86/PC™" computer program. Table 2.9 lists seasonal values used for

TABLE 2.8 Mn/ROAD original design parameters for 1986 AASHTO concrete pavement design method

Test Cell #	k-value from resilient modulus (kPa/cm)	Drainage coefficient	Calculated pavement thickness[(a)] (mm)
5	2295	1.00	180
6	1368	1.00	196
7	1401	1.15	178
8	1401	1.15	178
9	1401	1.15	178
10	1453	1.15	234
11	1412	1.00	254
12	1412	1.05	246
13	1412	1.00	254
36	1423[(b)]	1.0[(c)]	127
37	1423	1.0	127
38	583	1.0	152
39	583	1.0	152
40	583	1.0	152

(a) Values for test cells 5-13 from AASHTO's DNPS86/PC™ computer program. Values for test cells 36-40 from AASHTO low volume road design catalog.
(b) k-values for test cells 36-40 based on Mn/DOT R-value correlations.
(c) Value assumed by 1986 AASHTO low volume road design catalog.

Unit conversions: kPa/cm=0.369pci, mm=0.0394in

TABLE 2.9 Mn/ROAD resilient modulus values used for 1986 AASHTO design method k-value determination

Day of Year	Soil Type Clay Loam/Sandy Loam (R=12) Resilient Modulus (MPa)	Soil Type Select Granular (R=70) Resilient Modulus (MPa)
15 - Mid Jan.	345	414
30 - 1st Feb.	345	414
45 - Mid Feb.	310	414
60 - 1st Mar.	310	414
75 - Mid Mar.	97	241
90 - 1st Apr.	41	90
105 - Mid Apr.	34	90
120 - 1st May	34	97
135 - Mid May	34	110
150 - 1st June	38	110
165 - Mid June	38	124
180 - 1st July	41	124
195 - Mid July	41	124
210 - 1st Aug.	45	124
225 - Mid Aug.	45	138
240 - 1st Sept.	48	138
255 - Mid Sept.	48	138
270 - 1st Oct.	55	152
285 - Mid Oct.	55	152
300 - 1st Nov.	55	152
315 - Mid Nov.	69	172
330 - 1st Dec.	138	241
345 - Mid. Dec.	207	241
360 - 1st Jan.	276	414

Unit conversion: MPa=145 psi

each type of subgrade soil. Table 2.8 lists the calculated k-values. The low volume road test cells were designed using only two values for this parameter. Both values were based on unmodified R-values input into the Mn/DOT k-value correlation (equation 1) listed in the previous section.

For the 1993 AASHTO design method application, the k-values were determined following the "AREA" procedure as outlined in section 5.6.5 of the design guide[3]. Data was gathered from center of panel falling weight deflectometer (FWD) tests conducted from 1993 through 1996. To insure reasonable contact between slab and subbase or subgrade, a slab temperature gradient analysis was conducted and only FWD tests conducted during negative or slightly positive gradients were utilized. Table 2.10 lists the resulting as-built k-values from the analysis. Appendix B contains additional details on the calculations carried out.

The loss of support factor for the design and as-built analysis was taken to be 0.0 for all test cells. This assumption is reasonable, since recent research[14] has reported the use of this factor results in over designed pavement sections. Due to the fact that many AASHO road test sections failed in part due to loss of slab support, its effect is already incorporated into the AASHTO thickness design equation.

Load Transfer Coefficient

Load transfer coefficient values (J-factors) used both in the check of the Mn/DOT design method and the as-built analysis were taken to be the same as in Table 2.1.

Serviceability Factors

For the 1986 AASHTO design method, the initial and terminal serviceability factors were taken to be 4.5 and 2.5 (PSR) respectively. For the 1993 AASHTO design method application, as-built initial serviceability factor values were determined through correlation to an International Roughness Index (IRI) number based on measurements gathered utilizing the South Dakota profiler technique. See Table 2.10. Table 2.11 lists the IRI measured immediately following construction, along with the corresponding PSR rating. The concrete pavement correlation equation used by Mn/DOT is: $PSR = 6.204 - 2.299\sqrt{(IRI)}$.

TABLE 2.10 Mn/ROAD as-built design parameters for the 1993 AASHTO concrete pavement design method

Test Cell #	k-value from 1993 AASHTO "AREA" method (kPa/cm)	Initial serviceability factor (PSR)
5	490	3.54
6	450	3.61
7	475	3.86
8	500	3.21[(a)]
9	500	3.61
10	530	3.53
11	515	3.30
12	530	3.54
13	515	3.72
36	515	3.72
37	500	3.87
38	325	3.73
39	345	3.49
40	350	3.37

(a) Paver stalled during construction. Diamond grinding applied to sections of pavement surface in this test cell.

Unit conversion: kPa/cm=0.369pci

Whereas AASHTO refers to the present serviceability index as the correlation of subjective pavement condition rating (ride quality panel) to objective measurements (such as IRI), Mn/DOT chooses the reverse approach. This study adopted the Mn/DOT standard method of using the terms present serviceability index and present serviceability rating interchangeably.

For the as-built application the terminal serviceability factor remained at 2.5.

Drainage Coefficients

Drainage coefficient values for both the 1986 AASHTO and the 1993 AASHTO design method applications can be found in Table 2.8. Based on AASHTO recommendations (Table 2.5, Ref 5), the design values were chosen assuming the pavement structure is exposed to moisture levels approaching saturation between 5 and 25 percent of the time. Investigations into the actual soil moisture conditions are currently underway, but were not considered for this study. Future Mn/ROAD research will include more in-depth determination of representative drainage coefficient values.

Reliability Level

For the 1986 AASHTO method, a reliability level of 95% was used for the mainline test cells. A reliability level of 75% was used in the catalog design method for the low volume road test cells.

For the 1993 AASHTO method application, reliability levels of both 50% and 95% were used for each of the test cells. Two levels were chosen to determine the effect of this variable on the design.

The standard deviation value assumed for both applications was 0.39, as recommended for rigid pavements by the 1986/1993 AASHTO design methods.

Traffic loading

Traffic volumes used for this analysis were the same as for the Mn/DOT design method analysis.

TABLE 2.11 Mn/ROAD test cell initial serviceability ratings for 1993 AASHTO concrete pavement design method

Test Cell #	Traffic Lane	Measured IRI (m/km)	Initial serviceability rating (PSR)
5	Right (Driving)	1.34	3.54
6	Right (Driving)	1.27	3.61
7	Right (Driving)	1.04	3.86
8	Right (Driving)	1.70	3.21
9	Right (Driving)	1.27	3.61
10	Right (Driving)	1.35	3.53
11	Right (Driving)	1.60	3.30
12	Right (Driving)	1.34	3.54
13	Right (Driving)	1.17	3.72
36	Inside Loop (80 k)	1.20	3.69
36	Outside Loop (102 k)	1.14	3.75
37	Inside Loop (80 k)	1.04	3.86
37	Outside Loop (102 k)	1.03	3.87
38	Inside Loop (80 k)	1.20	3.69
38	Outside Loop (102 k)	1.12	3.77
39	Inside Loop (80 k)	1.47	3.42
39	Outside Loop (102 k)	1.31	3.57
40	Inside Loop (80 k)	1.49	3.40
40	Outside Loop (102 k)	1.55	3.34

Pavement Thickness

Mn/DOT method pavement design thicknesses were checked for reasonableness by inserting all of the applicable parameters into the DNPS86/PC™ program (based on 1986 AASHTO Design Method). See Tables 2.1 and 2.8.

As-built pavement thicknesses were taken to be the same as in the Mn/DOT as-built analysis (Table 2.2).

1984 PCA Concrete Pavement Design Method Parameters

The PCA concrete pavement design method was not used in the design of Mn/ROAD concrete test cells. In this study, however, as-built data was applied to this method to provide a comparison between mechanistic-empirical (PCA) and purely empirical (AASHTO) pavement design approaches. The design procedure is different from the AASHTO approach in that several axle load categories are analyzed for their contribution toward fatigue stress and erosion damage.

Concrete Modulus of Rupture

The as-built values used in this method were the same as those used in the Mn/DOT as-built design analysis (Table 2.2), without application of the 1.33 safety factor.

Modulus of Subgrade Reaction

Rather than utilizing the correlation chart provided in the PCA design manual, this study used the same as-built k-values as those determined for the 1993 AASHTO design method (Table 2.10).

Shoulder and Joint Type

Table 2.12 lists the shoulder and joint types used for this analysis. This design method only requires general descriptive information for these two parameters.

TABLE 2.12 Mn/ROAD as-built design parameters for the 1984 PCA concrete pavement design method

Test Cell #	Concrete shoulder considered	Joint type
5	YES	DOWELED
6	YES	DOWELED
7	YES	DOWELED
8	YES	DOWELED
9	YES	DOWELED
10	NO	DOWELED
11	NO	DOWELED
12	NO	DOWELED
13	NO	DOWELED
36	NO	DOWELED
37	NO	NO DOWELS
38	NO	DOWELED
39	NO	DOWELED
40	NO	NO DOWELS

Pavement Thickness

The same as-built pavement thicknesses that were used in the previous two methods were applied (Table 2.2).

Load Safety Factor

This value was chosen to be 1.2 for the mainline test cells, as recommended for interstate type traffic loadings. Due to knowledge of the actual loading applied to the low volume road test cells, a load safety factor 1.0 was deemed appropriate for the analysis.

Axle Load Distribution and Volumes

For the mainline test cells, traffic load and volume information for this design method was provided by Mn/ROAD's on-site weigh-in-motion equipment. For each axle load category, the total truck axle counts per 1000 trucks were determined for the month of October 1994 (shortly after mainline test cells were opened to interstate traffic). Only single and tandem axle group loadings were considered. Table 2.13 shows a typical axle load and count breakdown.

Low volume road test cells only receive traffic load from one calibrated 5-axle tractor semi-trailer truck. This vehicle is driven around the loop of test cells 8 hours per day, 5 days a week. It is loaded to 355 kN (80 kips), with a front single axle weight of 53 kN (12 kips) and two rear tandem axles each 151 kN (34 kips), and driven on the inside lane of the loop 4 days per week. One day a week the truck is loaded to 453 kN (102 kips) and driven on the outside lane of the loop. The goal of this loading scheme is to apply equal amounts of CESALs on each lane. Early analysis demonstrates this to be working well. Daily loop revolutions are logged by the truck driver.

TABLE 2.13 Mn/ROAD typical axle load and count breakdown

Axle Group Weight Range (kN)	Axle Count[a]	
	Single Axles	Tandem Axles
214-231		13
196-214		58
178-196		387
160-178		2194
142-160		10162
125-142	8	12114
107-125	52	7517
89-107	708	7607
71-89	4649	8504
53-71	6947	9150
36-53	42185	10922
18-36	15484	4342
0-18	12437	647

(a) Mn/ROAD (I-94) right lane WIM data for month of October 1994.

Unit conversion: kN=0.225kips

CHAPTER 3

SERVICE LIFE PREDICTIONS

APPLICATION OF PARAMETERS TO DESIGN METHODS

Parameters defined in the previous chapter were applied to their respective concrete pavement design methods to determine the predicted service lives for the Mn/ROAD concrete test cells. For the Mn/DOT and 1986/1993 AASHTO design analyses, two applications of the design parameters were carried out. The first application used original design parameters, the second used as-built data. For the PCA design method, only as-built data was applied. The following information summarizes the resulting prediction of number of CESALs to terminal serviceability found from each respective design method.

Mn/DOT Concrete Pavement Design Method

Application of Original Design Parameters

Tables 3.1 and 3.2 summarize the application of original design parameters to the Mn/DOT concrete pavement design method. The test cell design thicknesses were found using Mn/DOT's PAVE program[7], which solves the 1981 AASHTO concrete pavement thickness design equation. Results are shown for both applications of the original R-value and the base layer modified R-value.

Also shown in Table 3.1 are the parameters used in the verification of the Mn/DOT design results using the 1986 AASHTO concrete pavement design method. Mainline test cell design thicknesses for this method were found using the DNPS86/PC™ program[8]. The reliability level was chosen to be 95%. These results generally show lower thicknesses for the 5 year design life cells, and slightly higher thicknesses for the 10 year design life test cells.

The low volume road test cells where originally designed using the 1986 AASHTO low volume road design catalog (Part II, Chapter 4).[5] The reliability level was chosen to be 75%. Table 3.2 contains the results of the application of design data to that method. It should be noted that the AASHTO low volume road design catalog assumes a terminal serviceability of 1.5.

TABLE 3.1 Application of original Mn/ROAD mainline test cell design parameters to the Mn/DOT concrete pavement design method

Test Cell #	Design CESALs	k-value using modified R-value (kPa/cm)	k-value[a] used for 1986 AASHTO (kPa/cm)	Load transfer (J factor)	Drainage coefficient	Slab thickness using Mn/DOT method (mm)		Slab thickness using 1986 AASHTO method[b] (mm)	Chosen design thickness (mm)
						Using original R-values	Using modified R-values		
5	5,262,400	1422	2295	2.6	1.00	195	178	180	190
6	5,262,400	720	1369	2.6	1.00	195	193	195	190
7	5,262,400	796	1401	2.6	1.15	195	190	178	190
8	5,262,400	796	1401	2.6	1.15	195	190	178	190
9	5,262,400	796	1401	2.6	1.15	195	190	178	190
10	11,225,270	796	1453	3.2	1.15	249	246	234	241
11	11,225,270	720	1412	3.2	1.00	249	246	254	241
12	11,225,270	720	1412	3.2	1.05	249	246	246	241
13	11,225,270	720	1412	3.2	1.00	249	246	254	241

(a) Effective modulus of subgrade reaction as determined by AASHTO "DNPS 86/PC™" program.
(b) Reliability level = 95%.

Unit conversions: kPa/cm=0.369pci, mm=0.0394in

TABLE 3.2 Application of original Mn/ROAD Low Volume Road test cell design parameters to the Mn/DOT and 1986 AASHTO concrete pavement design methods

Test Cell #	Design CESALs	k-value using modified R-value (kPa/cm)	k-value[a] used for 1986 AASHTO (kPa/cm)	Load transfer (J factor)	Drainage coefficient	Slab thickness using Mn/DOT method[b] (mm)		Slab thickness using 1986 AASHTO method[d] (mm)	Chosen design thickness (mm)
						Using original R-values	Using modified R-values		
36	100,000	1422	1422	3.2	1.00	107[c]	107	127	152[e]
37	100,000	1422	1422	3.8	1.00	107	107	127	152
38	100,000	720	583	3.2	1.00	107	107	152	152
39	100,000	720	583	3.2	1.00	107	107	152	152
40	100,000	720	583	3.2	1.00	107	107	152	178/140/178[f]

(a) Assumed for use in AASHTO low volume road design catalog.
(b) Terminal serviceability = 2.5.
(c) Minimum slab thickness allowed in PAVE program.
(d) Reliability level = 75%. Terminal serviceability = 1.5.
(e) Minimum slab thickness permitted by Mn/DOT design method.
(f) Tapered or "thickened edge" design.

Unit conversions: kPa/cm=0.369pci, mm=0.0394in

As a means of comparison, the low volume road test cell design parameters were input into Mn/DOT's PAVE program. In all cases, the results showed a required thickness of less than the minimum thickness allowed by the program [107 mm (4.2 in)]. As stated previously, Mn/DOT's minimum slab thickness at the time of Mn/ROAD test cell design was 152 mm (6.0 in). Therefore the final design thicknesses were increased to 152 mm (6.0 in) (except test cell 40).

In an effort to see the effect the increased low volume road test cell slab thicknesses had on service life, another set of PAVE program runs were conducted. Table 3.3 lists the results from that analysis. The Mn/DOT standard terminal serviceability rating (PSR) of 2.5 was used for this analysis. Use of a terminal serviceability of 1.5 would result in only an approximate [illegible]% increase in predicted life.

Test cell 40 was designed to assess the life and behavior of a tapered or "thickened edge" design. Unfortunately, neither the Mn/DOT or 1986 AASHTO design methods could account for this unique section geometry. Therefore, the average section thickness at the outer wheelpath was used in this analysis.

Application of As-built Design Parameters

Table 3.4 summarizes the application of as-built design parameters to the Mn/DOT concrete pavement design method. For this analysis, as-built slab thicknesses and other parameters were input into the PAVE program to determine the CESALs to terminal serviceability (PSR=2.5). See Chapter 2 for parameter considerations.

1993 AASHTO Concrete Pavement Design Method

Application of Original Design Parameters

Application of the 1986 AASHTO design method was described in the previous section. Tables 3.1 and 3.2 summarize that analysis. Some additional parameters that had to be considered in that analysis were the initial serviceability index (PSR) and the level of reliability. Reliability levels of 95% and 75% were chosen for the mainline and low volume road test cells respectively.

TABLE 3.3 Application of the chosen Low Volume Road test cell design thicknesses to the Mn/DOT PAVE Program

Test Cell #	k-value using modified R-value (kPa/cm)	Load transfer (J factor)	Chosen design thickness (mm)	Design CESALs	Total CESALs [a] predicted by PAVE program
36	1422	3.2	152	100,000	1,330,000
37	1422	3.8	152	100,000	740,000
38	720	3.2	152	100,000	790,000
39	720	3.2	152	100,000	790,000
40	720	3.2	178/140/178	100,000	1,350,000 [b]

(a) Terminal serviceability level, PSR=2.5.
(b) Based on slab thickness of 170 mm at outer wheelpath (offset from centerline = 2.90 m).

Unit conversions: kPa/cm=0.369pci, mm=0.0394in, m=3.28ft

TABLE 3.4 Application of as-built test cell design parameters to the Mn/DOT concrete pavement design method

Test Cell #	k-value using modified R-value (kPa/cm)	Drainage coefficient	Load transfer (J factor)	Design slab thickness (mm)	As-built slab thickness (mm)	Design CESALs	Predicted CESALs to terminal serviceability (PSR=2.5)
5	1425	1.00	2.6	190	189	5,262,400	6,190,000
6	780	1.00	2.6	190	187	5,262,400	2,630,000
7	950	1.15	2.6	190	199	5,262,400	4,540,000
8	915	1.15	2.6	190	194	5,262,400	2,450,000
9	930	1.15	2.6	190	198	5,262,400	4,030,000
10	950	1.15	3.2	241	253	11,225,270	13,800,000
11	885	1.00	3.2	241	244	11,225,270	15,260,000
12	830	1.05	3.2	241	253	11,225,270	13,840,000
13	830	1.00	3.2	241	250	11,225,270	13,970,000
36	1425	1.00	3.2	152	166	100,000	1,740,000
37	1425	1.00	3.8	152	174	100,000	1,500,000
38	850	1.00	3.2	152	167	100,000	1,340,000
39	830	1.00	3.2	152	165	100,000	980,000
40	850	1.00	3.2	178/140/178	197/182/197[a]	100,000	2,440,000

(a) Used slab thickness of 194 mm at outer wheelpath (offset from centerline = 2.90 m) for analysis.

Unit conversions: kPa/cm=0.369pci, mm=0.0394in

Application of As-built Design Parameters

Table 3.5 summarizes the application of as-built design parameters to the 1993 AASHTO concrete pavement design method. For this analysis, as-built slab thicknesses and other parameters were input into the DARWin™ program[9] to determine the CESALs to terminal serviceability (PSR=2.5).

Reliability levels of 95% and 50% were applied to the mainline test cell data in order to assess the effect of design reliability on their lives. Levels of 75% and 50% were applied to the low volume road test cell data.

1984 PCA Concrete Pavement Design Method

Application of Original Design Parameters

This method was not utilized during the design phase. Original design parameters were not applied to this method for this study.

Application of As-built Data Design Parameters

Since the PCA method does not describe pavement terminal serviceability in CESAL applications, two types of analysis were carried out. The first analysis used the method as intended, with the results giving the percentage of fatigue stress or erosion damage for the expected traffic over the original design lives of the test cells. As-built parameters were input into the PCAPAV™ program[10] with the results summarized in Table 3.6. Since the program does not accommodate a traffic growth input, the analysis was carried out assuming a zero traffic growth rate for all of the test cells.

The second analysis using the PCA design method involved an attempt to correlate axle loads to failure with CESALs. The process involved using axle load equivalency factors (ALEF) found in Appendix D of the 1993 AASHTO design guide. While it is not defined in the PCA method what terminal serviceability level would be expected at 100% fatigue or erosion damage, a terminal serviceability of PSR=2.5 was chosen for this exercise. Table 3.7 summarizes the results.

TABLE 3.5 Application of as-built test cell design parameters to the 1993 AASHTO concrete pavement design method

Test Cell #	As-built concrete modulus of rupture (MPa)	Drainage coefficient	Load transfer (J factor)	Design slab thickness (mm)	As-built slab thickness (mm)	Design CESALs	Predicted CESALs[a] to terminal serviceability at 95%[b] reliability	Predicted CESALs[a] to terminal serviceability at 50% reliability
5	4.310	1.00	2.6	190	189	5,262,400	1,220,675	5,348,515
6	3.897	1.00	2.6	190	187	5,262,400	777,475	3,406,585
7	3.966	1.15	2.6	190	199	5,262,400	2,352,225	10,306,500
8	3.517	1.15	2.6	190	194	5,262,400	755,810	3,311,655
9	3.897	1.15	2.6	190	198	5,262,400	1,788,960	7,838,505
10	4.345	1.15	3.2	241	253	11,225,270	5,557,275	24,349,755
11	4.966	1.00	3.2	241	244	11,225,270	3,138,195	13,750,310
12	4.586	1.05	3.2	241	253	11,225,270	4,468,495	19,579,140
13	4.690	1.00	3.2	241	250	11,225,270	4,445,615	19,478,900
36	4.345	1.00	3.2	152	166	100,000	947,390	1,735,645
37	4.552	1.00	3.8	152	174	100,000	858,150	1,572,160
38	4.621	1.00	3.2	152	167	100,000	892,320	1,634,765
39	4.241	1.00	3.2	152	165	100,000	590,270	1,081,395
40	4.276	1.00	3.2	178/140/178	197/182/197[c]	100,000	1,192,580	2,184,850

(a) Determined using DARWin™ program. Assumed standard deviation= 0.39. Terminal serviceability, PSR=2.5.
(b) Reliability level = 75% for test cells 36-40.
(c) Used slab thickness of 194 mm at outer wheelpath (offset from centerline = 2.90 m) for analysis.

Unit conversion: MPa=145 psi

TABLE 3.6 Application of as-built test cell design parameters to the PCA concrete pavement design method for the original design lives

Test Cell #	As-built concrete modulus of rupture (Mpa)	k-value from 1993 AASHTO "AREA" method (kPa/cm)	Load Safety Factor	As-built slab thickness (mm)	One-way ADTT[a]	Percent damage predicted[b]	
						Fatigue analysis	Erosion analysis
5	4.310	490	1.2	189	2210	8	7
6	3.897	450	1.2	187	2210	85	10
7	3.966	475	1.2	199	2210	11	3
8	3.517	500	1.2	194	2210	171	4
9	3.897	500	1.2	198	2210	15	3
10	4.345	530	1.2	253	2210	0	8
11	4.966	515	1.2	244	2210	0	14
12	4.586	530	1.2	253	2210	0	9
13	4.690	515	1.2	250	2210	0	10
36	4.345	515	1.0	166	80	0	3
37	4.552	500	1.0	174	80	0	10
38	4.621	325	1.0	167	80	0	4
39	4.241	345	1.0	165	80	0	4
40	4.276	350	1.0	197/182/197[c]	80	0	7

(a) Traffic growth assumed to be zero for this analysis.
(b) Determined by PCAPAV™ program.
(c) Used slab thickness of 194 mm at outer wheelpath (offset from centerline= 2.90 m) for analysis.

Unit conversions: Mpa=145psi, kPa/cm=0.369pci, mm=0.0394in

The process used to determine the axle repetitions (CESALs) to failure was as follows:

1) Axle load counts (for one month) for both single and tandem axles were broken into 10 load categories each, and normalized to the number of axle events per 1000 trucks.
2) As-built parameters were input into the PCAPAV™ program.
3) The average daily truck traffic (ADTT) value was altered until either the total flexural stress fatigue or erosion damage was predicted to be 100%.
4) For each axle load category which contributed toward the controlling damage mode (fatigue or erosion), the expected repetitions were converted to CESALs using AASHTO axle load equivalency factors (ALEF) for rigid pavements, with a terminal serviceability of 2.5 (Ref. 3,Table D.14).
5) Calculated CESALs were combined from both single and tandem axles to find the predicted CESALs to terminal serviceability. See Table 3.8.

As described before, the PCAPAV™ program does not accommodate a traffic growth input. Therefore, the design versus predicted CESALs analysis was carried out assuming a zero traffic growth rate for all test cells. Adjustments to the design CESALs are reflected in Table 3.7.

TEST CELL LIFE PREDICTION SUMMARY

Due to the uncertainty in predicting future traffic levels and growth, the original traffic growth rate of 2.5% (compounded annually) was used to forecast the service lives of the mainline test cells given by each design method in this study. Recent data indicates the mainline test cells received approximately 2.2 million CESALs from August 1994 to November 1996. Therefore, a first year assumption of 1,000,000 CESALs was a good estimate. The low volume road loop received approximately 80,000 CESALs for the same period of time. An estimated 40,000 CESALs per year, with no growth rate, was used for determining the life span of these test cells. Tables 3.9 and 3.10 show the predicted service life for each test cell based on as-built data applied to the three design methods.

TABLE 3.7 Application of as-built test cell design parameters to the PCA concrete pavement design method to determine terminal serviceability

Test Cell #	As-built concrete modulus of rupture (Mpa)	k-value from 1993 AASHTO "AREA" method (kPa/cm)	Load Safety Factor	As-built slab thickness (mm)	Design CESALs[a]	Predicted CESALs[b] to Terminal Serviceability
5	4.310	490	1.2	189	5,003,265	2,921,600
6	3.897	450	1.2	187	5,003,265	637,200
7	3.966	475	1.2	199	5,003,265	2,159,720
8	3.517	500	1.2	194	5,003,265	514,560
9	3.897	500	1.2	198	5,003,265	1,614,820
10	4.345	530	1.2	253	10,006,530	223,528,890
11	4.966	515	1.2	244	10,006,530	137,017,270
12	4.586	530	1.2	253	10,006,530	220,579,580
13	4.690	515	1.2	250	10,006,530	182,106,130
36	4.345	515	1.0	166	100,000	5,033,440
37	4.552	500	1.0	174	100,000	1,666,590
38	4.621	325	1.0	167	100,000	4,077,510
39	4.241	345	1.0	165	100,000	3,882,870
40	4.276	350	1.0	197/182/197[c]	100,000	2,629,095

(a) Traffic growth assumed to be zero for this analysis.
(b) Determined by PCAPAV™ program. Converted to CESALs using AASHTO load equivalency factors.
(c) Used slab thickness of 194 mm at outer wheelpath (offset from centerline= 2.90 m) for analysis.

Unit conversions: Mpa=145psi, kPa/cm=0.369pci, mm=0.0394in

TABLE 3.8 CESAL calculations for the PCA concrete pavement design method[a]

Test Cell #	Controlling distress mode	Axle type	Axle load with LSF (kN)	AASHTO ALEF[b]	Expected axle repetitions[c]	Predicted CESALs to Terminal Serviceability
5	Fatigue	Single	139	8.99	13156	118,272
		Single	128	6.48	34913	226,236
		Single	117	4.57	153312	700,636
		Single	107	3.14	503451	1,580,836
		Tandem	256	14.25	20745	295,616
		Total				**2,921,597**
6	Fatigue	Single	139	8.99	1232	11,076
		Single	128	6.47	3270	21,157
		Single	117	4.56	14361	65,486
		Single	107	3.13	47158	147,605
		Single	96	2.07	135408	280,295
		Tandem	256	14.22	1943	27,629
		Tandem	235	9.84	8531	83,945
		Total				**637,192**
7	Fatigue	Single	139	9.07	9552	86,637
		Single	128	6.57	25349	166,543
		Single	117	4.66	111314	518,723
		Single	107	3.2	365536	1,169,715
		Tandem	256	14.48	15062	218,098
		Total				**2,159,716**
8	Fatigue	Single	139	9.01	615	5,541
		Single	128	6.52	1632	10,641
		Single	117	4.61	7167	33,040
		Single	107	3.17	23534	74,603
		Single	96	2.09	67574	141,230
		Tandem	256	14.35	970	13,920
		Tandem	235	9.97	4257	42,442
		Tandem	213	6.76	28572	193,147
		Total				**514,563**
9	Fatigue	Single	139	9.05	7164	64,834
		Single	128	6.56	19012	124,719
		Single	117	4.64	83485	387,370
		Single	107	3.19	274152	874,545
		Tandem	256	14.46	11297	163,355
		Total				**1,614,823**

(a) Data from month of October, 1994.
(b) For a terminal serviceability (PSR)=2.5.
(c) Determined by PCAPAV™ program.
Unit conversion: kN=0.225kips

TABLE 3.8 CESAL calculations for the PCA concrete pavement design method[a] - Continued

Test Cell #	Controlling distress mode	Axle type	Axle load with LSF (kN)	AASHTO ALEF[b]	Expected axle repetitions[c]	Predicted CESALs to Terminal Serviceability
10	Erosion	Single	139	10.30	25009	257,593
		Single	128	7.42	66369	492,458
		Single	117	5.17	291445	1,506,771
		Single	107	3.45	957057	3,301,847
		Single	96	2.20	2748052	6,045,714
		Tandem	256	16.82	39437	663,330
		Tandem	235	11.91	173136	2,062,050
		Tandem	213	8.12	1161934	9,434,904
		Tandem	192	5.28	6583013	34,758,309
		Tandem	171	3.23	30493084	98,492,661
		Tandem	149	1.83	36346040	66,513,253
		Total				**223,528,890**
11	Erosion	Single	139	10.07	15023	151,282
		Single	128	7.29	39868	290,638
		Single	117	5.10	175072	892,867
		Single	107	3.42	574906	1,966,179
		Single	96	2.19	1650760	3,615,164
		Single	85	1.32	3273786	4,321,398
		Tandem	256	16.34	23690	387,095
		Tandem	235	11.59	104003	1,205,395
		Tandem	213	7.93	697976	5,534,950
		Tandem	192	5.18	3954429	20,483,942
		Tandem	171	3.19	18317257	58,432,050
		Tandem	149	1.82	21833140	39,736,315
		Total				**137,017,273**
12	Erosion	Single	139	10.30	24679	254,194
		Single	128	7.42	65494	485,965
		Single	117	5.17	287602	1,486,902
		Single	107	3.45	944437	3,258,308
		Single	96	2.20	2711814	5,965,991
		Tandem	256	16.82	38916	654,567
		Tandem	235	11.90	170853	2,033,151
		Tandem	213	8.12	1146612	9,310,489
		Tandem	192	5.28	6496205	34,299,962
		Tandem	171	3.23	30090984	97,193,878
		Tandem	149	1.83	35866759	65,636,169
		Total				**220,579,577**

Unit conversion: kN=0.225kips

TABLE 3.8 CESAL calculations for the PCA concrete pavement design method[a] - Continued

Test Cell #	Controlling distress mode	Axle type	Axle load with LSF (kN)	AASHTO ALEF[b]	Expected axle repetitions[c]	Predicted CESALs to Terminal Serviceability13
13	Erosion	Single	139	10.23	20431	209,009
		Single	128	7.38	54220	400,144
		Single	117	5.15	238094	1,226,184
		Single	107	3.44	781861	2,689,602
		Single	96	2.20	2245003	4,939,007
		Tandem	256	16.66	32217	536,735
		Tandem	235	11.80	141442	1,669,016
		Tandem	213	8.06	949235	7,650,834
		Tandem	192	5.25	5377948	28,234,227
		Tandem	171	3.22	24911123	80,213,816
		Tandem	149	1.83	29692656	54,337,560
		Total				**182,106,134**
36	Erosion	Single	53	0.20	1864238	372,848
		Tandem	142	1.25	3728475	4,660,594
		Total				**5,033,442**
37	Erosion	Single	53	0.19	601657	114,315
		Tandem	142	1.29	1203314	1,552,275
		Total				**1,666,590**
38	Erosion	Single	53	0.20	1510188	302,038
		Tandem	142	1.25	3020375	3,775,469
		Total				**4,077,507**
39	Erosion	Single	53	0.20	1438100	287,620
		Tandem	142	1.25	2876200	3,595,250
		Total				**3,882,870**
40	Erosion	Single	53	0.18	894250	160,965
		Tandem	142	1.38	1,788,500	2,468,130
		Total				**2,629,095**

(a) Data from month of October, 1994.
(b) For a terminal serviceability (PSR)=2.5.
(c) Determined by PCAPAV™ program.

Unit conversion: kN=0.225kips

TABLE 3.9 Service life predicted for Mn/ROAD mainline concrete test cells

Test Cell #	Test cell service life predicted (years)[a]			
	Mn/DOT Method	1993 AASHTO Method		1984 PCA Method
		95% Reliability	50% Reliability	
5	5.8	1.2	5.1	2.9
6	2.6	0.8	3.3	0.7
7	4.4	2.3	9.3	2.2
8	2.4	0.8	3.2	0.6
9	3.9	1.8	7.2	1.6
10	12.0	5.3	19.2	76.4
11	13.1	3.0	12.0	60.2
12	12.0	4.3	16.1	75.9
13	12.1	4.2	16.1	69.4

(a) Based on initial year CESALs estimated at 1,000,000. Terminal serviceability (PSR)=2.5. Assumes 2.5% growth rate in annual CESALs.

TABLE 3.10 Service life predicted for Mn/ROAD low volume road concrete test cells

Test Cell #	Test cell service life predicted (years)[a]			
	Mn/DOT Method	1993 AASHTO Method		1984 PCA Method
		75% Reliability	50% Reliability	
36	43.5	23.7	43.4	125.8
37	37.5	21.4	39.3	41.7
38	33.5	22.3	40.9	101.9
39	24.5	14.8	27.0	97.1
40	50	29.8	54.6	65.7

(a) Based on annual CESALs estimated at 40,000. Terminal serviceability (PSR)=2.5. Assumes zero growth rate in annual CESALs.

CHAPTER 4

DISCUSSION AND SUMMARY

OBSERVATIONS AND DISCUSSION

Mn/DOT Concrete Pavement Design Method

Mainline Test Cells

When the as-built design parameters were applied to this method, slight to moderate decreases in predicted pavement service life were found for the 5 year design life cells, while slight increases were found for the 10 year cells. Several factors account for these differences. By far the greatest contribution came from applying the as-built values for the modulus of rupture. Even though the concrete mixture design was the same for all of the mainline concrete test cells, the 28 day average modulus of rupture values varied (after applying the 1.33 safety factor) from 2.64 MPa (385 psi) to 3.73 MPa (540 psi), with a standard deviation of 0.34 MPa (50 psi). Test cells 11 and 13 were the only mainline cells with 28 day values greater than the original design value of 3.45 MPa (500 psi).

The second significant parameter was the as-built slab thicknesses. Measured thicknesses after construction exceeded design values enough that in many cases they compensated for low concrete modulus of ruptures values. The increase was particularly noticeable in the 10 year design life test cells, where pavement thicknesses were as much as 20 mm (0.8 in) thicker than design. These results are not unexpected, since a recent report [13] pointed out that several state DOTs routinely measure as-built slab thicknesses greater than design. While many times this is caused by disincentives to contractors for paving too thin, in the case of construction of the Mn/ROAD test cells, heavily instrumented areas caused several starts and stops for the slip-form paving equipment. Interrupted paver progress often leads not only to inconsistent pavement thicknesses, but a deterioration of the pavement surface ride quality, which was clearly experienced at Mn/ROAD.

Low Volume Road Test Cells

While the low volume road test cells were initially designed using the AASHTO low volume road design catalog, this study examined the results from application of the as-built parameter values to the standard Mn/DOT concrete pavement thickness design equation. As shown in Table 3.4, the predicted CESALs to terminal serviceability were very excessive compared to design. In fact at the current traffic application rate of 40,000 CESALs per year, it would take well over 20 years to achieve a critically poor ride quality on these test cells.

As described before, based on empirical field experience Mn/DOT mandated a minimum slab thickness of 152 mm (6 in) at the time of test cell design (the 1993 AASHTO minimum is 127 mm). Even the minimum thickness of 107 mm (4.2 in) allowed in the Mn/DOT PAVE program results in predicted CESALs to terminal serviceability of 170,000. Mn/DOT's minimum thickness criteria, coupled with as-built thicknesses at least 13 mm (0.5 in) greater than design, contributed to the prediction of much longer test cell lives.

1993 AASHTO Concrete Pavement Design Method

Mainline Test Cells

For this method, the predicted test cell service lives depended greatly on the reliability level chosen. Choosing a reliability level of 95%, as recommended by AASHTO for the design of interstate pavements, resulted in predicted service lives of at least 50% of the original design assumptions. However, choosing a reliability level of 50% resulted in predicted service lives close to design for the 5 year design cells, but over 100% greater than the design life for many 10 year cells. See Table 3.9.

As in the Mn/DOT method analysis, one of the important parameters affecting the results from this method was the modulus of rupture. The assumed design value of 4.655 MPa (675 psi) was generally greater than most of the 28 day as-built values found through material testing.

During this analysis, a major difference was noticed between the k-values determined for the various design methods. The values found using the 1993 AASHTO "AREA" method were approximately 50% less than the values found using modified R-value correlation in the Mn/DOT method. They were also up to 79% less than the design values found using the originally assumed resilient modulus values in the 1986 AASHTO design method. See Tables 2.4,2.8, and 2.10 for comparison. Such large differences, as demonstrated by this comparison, clearly indicate the limitations and assumptions involved in determining a representative k-value.

This method was significantly affected by the low values measured for the initial serviceability factor. While very well constructed concrete pavements might have an initial serviceability factor exceeding 4.0, Mn/ROAD concrete test cells had an average value near 3.5. These significantly lower values essentially "used up" much of the available service life CESALs predicted by this method.

Low Volume Road Test Cells

Low volume road as-built parameters were also applied to this method. Table 3.5 shows the predicted CESALs to terminal serviceability again very excessive compared to design. Going from a reliability level of 75% to 50% essentially doubled the predicted CESALs to terminal serviceability.

1984 PCA Concrete Pavement Design Method

Mainline Test Cells

The results obtained from applying this method indicate very little damage is predicted for the respective design lives. See Table 3.6. The exceptions were test cell 6 (lower than average k-value) and test cell 8 (low modulus of rupture value).

The design life prediction procedure outlined in chapter 3 (based on AASHTO ALEFs) resulted in predicting service lives lower than design for the 5 year cells, and extremely higher than design for the 10 year cells. The major aspect causing the disparity between the two was the mode of failure predicted. For the 5 year design cells, the fatigue stress failure mode dominated the analysis. For the 10 year cells, the base layer erosion damage was controlling. Comments given in the PCA method indicate this to be the normal failure modes for medium and heavy trafficked pavements respectively.

The extent to which the predicted service lives were much less or greater than the design life of the test cells indicates the procedure used in this study (utilizing AASHTO load equivalency factors) is likely not suitable as presented. In speaking with the author of the design method[4], he stated 100% fatigue stress failure indicates significant slab cracking would have occurred, but that an equivalent ride quality measure has not been equated to this condition. At the same time, a 100% erosion damage condition indicates transverse joint faulting of 3.8 mm (0.15 in). Due to other variables necessary to determine ride quality, knowledge of the amount of cracking or joint faulting is not enough. While several ride quality models were presented in the development of the PCA method,[15,16,17] none of them were applicable to this study. The intent of this study did not warrant further investigation into determining a suitable model.

Low Volume Road Test Cells

Except for the test cells with no dowels (cells 37 and 40), the results of the analysis showed extremely high predictions for test cell life. As expected, the presence of dowels has a marked effect on the level of predicted erosion damage.

SUMMARY AND RECOMMENDATIONS

This study examined the results from the application of Mn/ROAD concrete test cell data to three common concrete pavement design methods. The differences between the design and as-built parameters for each of the methods was also highlighted during the analysis process.

The following general observations were discovered during this study:

1) As-built 28 day concrete modulus of rupture values were generally lower than assumed in design.
2) As-built modulus of subgrade reaction values were very close to design assumptions for the Mn/DOT method, but were about 40% lower than design for the 1993 AASHTO method (note: different methods were used to calculate each).
3) Generally, as-built pavement thicknesses were over 2% higher than design.
4) Initial serviceability factors were much lower than expected for new concrete pavement construction. The presence of load response instrumentation most likely had detrimental effects on the slip form paving operation.

The predicted test cell life (to terminal serviceability) varied widely depending on the design life, pavement design method, and reliability level. The following observations were made:

1) As-built information applied to the Mn/DOT design method resulted in test cell life predictions ranging from 2.4 to 5.8 years for the 5 year design cells, and from 12.0 to 13.1 years for the 10 year design cells.
2) For a reliability level of 95%, as-built information applied to the 1993 AASHTO design method resulted in test cell life predictions ranging from 0.8 to 2.3 years for the 5 year design cells, and from 3.0 to 5.3 years for the 10 year design cells. For a reliability level of 50%, test cell life predictions were somewhat closer to design values, but still varied widely.
3) With the exception of test cells 6 and 8, the 1984 PCA design method predicted pavement fatigue stress and erosion damage to be less than 15% for the original design lives of the mainline test cells. For the low volume road test cells, only cells 37 and 40 (no dowels) showed predicted erosion damage levels exceeding 4% in 3 years of trafficking.
4) The procedure outlined in this study for converting PCA method fatigue and erosion results to AASHTO type CESALs demonstrated unsuitability. The need exists for a reliable procedure which would correlate fatigue and erosion damage to AASHTO serviceability criteria (ride quality).

The focus of this study was to examine, through comparison of current concrete pavement design procedures, the effects current materials and construction practices have on predicted pavement service life. While many as-built input parameters could be measured or calculated, several others were not addressed. Two such parameters are the load transfer coefficient (J-factor) and the drainage coefficient. Future research will focus on determination of suitable values for these and other factors related to concrete pavement behavior.

The significantly different test cell life predictions that were found in this study demonstrate the disagreement on how to best predict concrete pavement life. It also highlights the limitations caused by the assumptions required for each method, and the extent to which the original AASHO Road Test results have been extrapolated beyond their intended application. The results clearly justify the need for a more rational design method, taking into account modern day traffic loads, materials, and construction practices.

With the age of Mn/ROAD concrete test cells currently at 2.5 years, and mainline CESAL applications at approximately 2.2 million, there is very little visual evidence of surface distress or measurable deterioration of ride quality since construction was completed. Results from this study therefore indicate some discrepancies between field performance and the empirical design methods currently being applied.

The predictions found in this study will be monitored as the Mn/ROAD test cells continue to age. Validation of the predictions presented here will occur as the test cells reach terminal serviceability.

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APPENDIX A

Mn/ROAD CONCRETE CORE LENGTHS

Mn/ROAD Concrete Core Lengths

Mn/ROAD concrete core lengths came from two sources. One source was core length measurements recorded during laboratory compressive strength testing[11]. The second source was length measurements of cores extracted during installation of the pavement response instrumentation. Since two of the sensor types installed in the concrete test cells required wood blockouts during paving, length measurements of cores extracted from these locations were increased by the following amounts:

Linear Variable Differential Tranducer (LVDT) sensors: +41 mm (1.625 in)
Horizontal Clip Gauges (HC) sensors: +16 mm (0.625 in).

Table A.1
Mn/ROAD Test Cell 5 Core Lengths

Test Cell	Core location Station (ft)	Core location Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
5	112618	-3	9/15/92		153200 A	7.5	7.53
5	112624	-9	9/15/92		152700 A	7.5	7.39
5	112626	3	9/15/92		153100 A	7.5	6.34
5	112827	-9.78	9/22/92	05-DT-04	54903 A	7.5	7.625
5	112829	-9.79	9/22/92	05-DT-02	54905 A	7.5	7.275
5	112829	-3.76	9/22/92	05-DT-03	54904 A	7.5	7.675
5	112830	-3.79	9/22/92	05-DT-01	54906 A	7.5	7.625
5	112844	-6.1		05-NP-01	54907 A	7.5	8.1
5	112860	-9.97	9/22/92	05-TC-01	54908 A	7.5	8.175
5	113136	-3	9/15/92		153700 A	7.5	7.08
5	113140	9	9/15/92		154100 A	7.5	7.03
5	113148	7	9/15/92		154200 A	7.5	7.48
5				05-HC	54909 A	7.5	7.825
5				05-HC	54910 A	7.5	7.375
					Average length =		7.47

Table A.1 - Continued
Mn/ROAD Test Cell 6 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
6	113199	5	9/15/92		153101 A	7.5	7.19
6	113208	-3	9/15/92		153201 A	7.5	7.46
6	113209	9	9/15/92		152701 A	7.5	7.17
6	113305	-9.94	9/22/92	06-TC-65	54911 A	7.5	7.74
6	113307	-6.06		06-NP-05	54912 A	7.5	7.567
6	113406	-9.58		06-TC-12	54913 A	7.5	7.417
6	113408	-0.05	9/22/92	06-TC-01	54914 A	7.5	7.4
6	113410	-6	9/22/92	06-NP-01	54915 A	7.5	7.175
6	113417	-9.88	9/22/92	06-DT-02	54916 A	7.5	6.75
6	113418	-6.88	9/22/92	06-DT-01	54917 A	7.5	6.875
6	113419	-9.91	9/22/92	06-DT-04	54918 A	7.5	6.9
6	113420	-6.89	9/22/92	06-DT-03	54919 A	7.5	7.175
6	113450	-5.95		06#4 FP	54925 A	7.5	7.775
6	113452	-6.01		06#3 FP	54927 A	7.5	7.6
6	113454	-6.14		06#2 FP	54928 A	7.5	7.65
6	113456	-5.93		06#1 FP	54926 A	7.5	7.625
6	113499	-9.77	9/22/92	06-TC-48	54920 A	7.5	7.2
6	113502	-6.07	9/22/92	06-NP-03	54921 A	7.5	7.3
6	113604	-9.98	9/22/92	06-TC-54	54922 A	7.5	7.725
6	113607	-6.01	9/22/92	06-NP-04	54923 A	7.5	7.8
6	113696	9	9/15/92		154101 A	7.5	7.33
6	113701	-3	9/15/92		153701 A	7.5	6.98
6	113704	7	9/15/92		154201 A	7.5	7.94
6		-9.8		06-HC	54924 A	7.5	7.575
6				06-HC	54929 A	7.5	7.725
					Average length =		7.40

Table A.1 - Continued
Mn/ROAD Test Cell 7 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
7	113729	-9	9/16/92		152702 A	7.5	7.4
7	113731	5	9/16/92		153102 A	7.5	7.59
7	113732	-6	9/16/92		153202 A	7.5	7.85
7	113849	-9.65	9/23/92	07-TC-43	54930 A	7.5	8.15
7	113851	-5.96	9/23/92	07-NP-03	54931 A	7.5	8
7	113963	-10.01	9/23/92	07-TC-12	54932 A	7.5	7.9
7	113965	0.01		07-TC-01	54933 A	7.5	8.15
7	113967	-5.98	9/23/92	07-NP-01	54934 A	7.5	8.05
7	113974		9/23/92	07-DT	54935 A	7.5	7.825
7	113974		9/23/92	07-DT	54937 A	7.5	7.825
7	113974		9/23/92	07-DT	54938 A	7.5	7.75
7	113974		9/23/92	07-DT	54936 A	7.5	7.75
7	114049	-9.9	9/23/92	07-TC-54	54939 A	7.5	7.95
7	114051	-6.11	9/23/92	07-NP-04	54940 A	7.5	8.075
7	114149	-9.81	9/23/92	07-TC-65	54941 A	7.5	7.825
7	114951	-6.06	9/23/92	07-NP-05	54942 A	7.5	8.825
7	114241	-3	9/16/92		153702 A	7.5	7.47
7	114241	9	9/16/92		154102 A	7.5	7.27
7	114245	7	9/16/92		154202 A	7.5	7.57
7		-9.8		07-HC	54944 A	7.5	7.525
7		-4		07-HC	54943 A	7.5	7.375
					Average length =		7.82

Table A.1 - Continued
Mn/ROAD Test Cell 8 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
8	114260	-6	9/16/92		153203 A	7.5	7.65
8	114261	5	9/16/92		153103 A	7.5	7.01
8	114267	-9	9/16/92		152703 A	7.5	7.48
8	114668	-9.78	9/23/92	08-TC-01	54945 A	7.5	8.15
8	114677	-6	9/23/92	08-NP-01	54946 A	7.5	7.9
8	114689		9/23/92	08-DT	54947 A	7.5	7.825
8	114689		9/23/92	08-DT	54948 A	7.5	7.8
8	114689		9/23/92	08-DT	54950 A	7.5	7.975
8	114689		9/23/92	08-DT	54949 A	7.5	7.525
8	114781	-3	9/16/92		153703 A	7.5	7.6
8	114792	7	9/16/92		154203 A	7.5	7.44
8	114793	-2	9/16/92		154103 A	7.5	7.27
8				08-HC	54951 A	7.5	7.275
8				08-HC	54952 A	7.5	7.725
					Average length =		7.62

Table A.1 - Continued
Mn/ROAD Test Cell 9 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
9	114805	-2	9/16/92		153104 A	7.5	7.33
9	114807	3	9/16/92		153204 A	7.5	7.2
9	114809	-9	9/16/92		152704 A	7.5	7.59
9	114938	-9.88	9/23/92	09-TC-01	54953 A	7.5	8.15
9	114950	-5.88		09-NP-01	54954 A	7.5	8.2
9	114957	-9.88	9/23/92	09-DT-02	54955 A	7.5	8.825
9	114958	-3.87	9/23/92	09-DT-01	54956 A	7.5	8.25
9	114959	-9.92	9/23/92	09-DT-04	54957 A	7.5	8.225
9	114960	-3.88	9/23/92	09-DT-03	54958 A	7.5	8.275
9	115321	-3	9/16/92		153704 A	7.5	7.58
9	115325	7	9/16/92		154204 A	7.5	7.94
9	115330	9	9/16/92		154104 A	7.5	6.17
9				09-HC	54959 A	7.5	7.8
9				09-HC	54960 A	7.5	7.5
					Average length =		7.79

Table A.1 - Continued
Mn/ROAD Test Cell 10 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
10	116760	-9	6/14/93		152705 A	9.5	9.88
10	116764	-6	6/14/93		153205 A	9.5	10.11
10	116772	5	6/14/93		153105 A	9.5	9.6
10	117034	-3.84		10-DT-01	55401 A	9.5	10.875
10	117036	-3.81		10-DT-03	55402 A	9.5	10.775
10	117045	-9.55		10-TC-12	55409 A	9.5	10.25
10	117047	0.01		10-TC-01	55408 A	9.5	9.35
10	117052	-5.93		10-NP-01	55407 A	9.5	9.75
10	117054	-10.01		10-HC-02	55404 A	9.5	9.925
10	117055	-3.83		10-HC-01	55403 A	9.5	9.725
10	117097	3.82		10-HC-03	55405 A	9.5	9.975
10	117098	9.89		10-HC-04	55406 A	9.5	9.925
10	117277	-3	6/14/93		153705 A	9.5	9.74
10	117281	-5	6/14/93		154105 A	9.5	9.8
10	117281	7	6/14/93		154205 A	9.5	10.04
					Average length =		9.98

Table A.1 - Continued
Mn/ROAD Test Cell 11 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
11	117321	-9	6/14/93		152706 A	9.5	9.49
11	117323	5	6/14/93		153106 A	9.5	9.6
11	117324	-6	6/14/93		153206 A	9.5	8.89
11	117545	-9.81		11-HC-02	55411 A	9.5	9.375
11	117546	-3.82		11-HC-01	55410 A	9.5	9.225
11	117581	-9.8		11-TC-01	55415 A	9.5	9.725
11	117584	-6.02		11-NP-01	55414 A	9.5	9.8
11	117596	3.84		11-HC-03	55412 A	9.5	9.575
11	117597	9.79		11-HC-04	55413 A	9.5	9.725
11	117823	-3	6/14/93		153706 A	9.5	9.95
11	117829	-2	6/14/93		154106 A	9.5	9.9
11	117829	7	6/14/93		154206 A	9.5	10.12
					Average length =		9.61

Table A.1 - Continued
Mn/ROAD Test Cell 12 Core Lengths

Test Cell	Core location Station (ft)	Core location Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
12	117841	-6	6/14/93		153207 A	9.5	9.84
12	117845	-3	6/14/93		152707 A	9.5	9.93
12	117845	5	6/14/93		153107 A	9.5	10.3
12	118163	-9.61		12-HC-02	55418 A	9.5	9.875
12	118164	-3.87		12-HC-01	55417 A	9.5	9.875
12	118186	-9.91		12-TC-12	55423 A	9.5	9.7
12	118188	-0.03		12-TC-01	55422 A	9.5	9.55
12	118188	-6.07		12-NP-01	55421 A	9.5	10
12	118192	-9.8		12-DT-02	55416 A	9.5	11.325
12	118196	3.88		12-HC-03	55419 A	9.5	9.825
12	118197	9.81		12-HC-04	55420 A	9.5	9.925
12	118336	-5	6/14/93		154107 A	9.5	9.7
12	118341	-3	6/14/93		153707 A	9.5	9.81
12	118344	7	6/14/93		154207 A	9.5	9.86
					Average length =		9.97

Table A.1 - Continued
Mn/ROAD Test Cell 13 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
13	118354	-9	6/14/93		152708 A	9.5	9.92
13	118361	5	6/14/93		153108 A	9.5	9.9
13	118362	-5	6/14/93		153208 A	9.5	9.89
13	118566	-9.84		13-TC-01	55427 A	9.5	10
13	118566	4.05		13-HC-03	55424 A	9.5	9.825
13	118567	10.08		13-HC-04	55425 A	9.5	9.725
13	118569	-5.99		13-NP-01	55426 A	9.5	9.9
13	118871	-7	6/14/93		153708 A	9.5	9.69
13	118875	3	6/14/93		154108 A	9.5	10
13	118879	7	6/14/93		154208 A	9.5	9.62
					Average length =		9.85

Table A.1 - Continued
Mn/ROAD Test Cell 36 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
36	8114	-4	7/19/93		153209 A	6	6.5
36	8122	5	7/19/93		153109 A	6	6.1
36	8124	-9	7/19/93		152709 A	6	6.62
36	8309	-9.89		36-TC-01	55467 A	6	6.35
36	8313	-6.01		36-NP-01	55466 A	6	6.15
36	8319	-9.5		36-DT-03	55464 A	6	6.725
36	8320	-6.48		36-DT-01	55462 A	6	6.575
36	8321	-9.49		36-DT-04	55465 A	6	6.875
36	8322	-6.46		36-DT-02	55463 A	6	6.7
36	8611	-3	7/19/93		153709 A	6	6.31
36	8614	3	7/19/93		154109 A	6	6.8
36	8621	7	7/19/93		154209 A	6	6.71
					Average length =		6.53

Table A.1 - Continued
Mn/ROAD Test Cell 37 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
37	8638	-9	7/19/93		152710 A	6	6.36
37	8640	-6	7/19/93		153210 A	6	6.64
37	8644	5	7/19/93		153110 A	6	6.3
37	8942	-9.45		37-TC-01	55473 A	6	7.375
37	8942	-6.48		37-NP-01	55472 A	6	6.6
37	8946	-9.6		37-DT-02	55469 A	6	7.325
37	8947	-3.54		37-DT-01	55468 A	6	7.325
37	8948	-9.56		37-DT-04	55471 A	6	7.475
37	8949	-3.53		37-DT-03	55470 A	6	7.325
37	9159	6	7/19/93		153710 A	6	6.35
37	9162	6	7/19/93		154110 A	6	6.5
37	9163	-2	7/19/93		154210 A	6	6.7
					Average length =		6.86

Table A.1 - Continued
Mn/ROAD Test Cell 38 Core Lengths

	Core location					Specified	As-built
Test Cell	Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Core Length (in)	Core Length (in)
38	9183	-6	7/19/93		153211 A	6	6.27
38	9190	5	7/19/93		153111 A	6	6.5
38	9191	-9	7/19/93		152711 A	6	6.56
38	9404	-3.5		38-HC-03	55478 A	6	6.375
38	9418	-9.5		38-HC-06	55480 A	6	6.375
38	9419	-3.55		38-HC-05	55479 A	6	6.425
38	9435	3.49		38-HC-09	55481 A	6	6.35
38	9448	-6.5		38-DT-02	55475 A	6	7.05
38	9449	-3.51		38-DT-01	55474 A	6	7.025
38	9450	-6.49		38-DT-04	55477 A	6	7.225
38	9450	-3.51		38-DT-03	55476 A	6	7.075
38	9455	-9.3		38-TC-01	55483 A	6	6.275
38	9456	-6.16		38-NP-01	55482 A	6	6.5
38	9679	-3	7/19/93		153711 A	6	6.56
38	9683	7	7/19/93		154211 A	6	6.41
38	9689	-5	7/19/93		154111 A	6	6.3
					Average length =		6.58

Table A.1 - Continued
Mn/ROAD Test Cell 39 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length (in)	As-built Core Length (in)
39	9700	-9	7/19/93		152712 A	6	6.22
39	9707	-5	7/19/93		153112 A	6	6.4
39	9707	6	7/19/93		153212 A	6	6.52
39	10029	-3.46		39-HC-03	55490 A	6	6.275
39	10031	3.48		39-HC-01	55488 A	6	6.475
39	10032	9.47		39-HC-02	55489 A	6	6.075
39	10049	-9.53		39-HC-08	55494 A	6	6.525
39	10049	-9.53		39-HC-06	55492 A	6	6.075
39	10050	-3.51		39-HC-07	55493 A	6	6.475
39	10050	-3.51		39-HC-05	55491 A	6	6.325
39	10054	-9.6		39-TC-12	55496 A	6	6.325
39	10064	-6.01		39-NP-01	55495 A	6	6.2
39	10067	-9.5		39-DT-02	55485 A	6	6.975
39	10068	-6.46		39-DT-01	55484 A	6	7.075
39	10069	-9.49		39-DT-04	55487 A	6	7.225
39	10070	-6.5		39-DT-03	55486 A	6	6.925
39	10211	-4	7/19/93		154212 A	6	6.49
39	10220	6	7/19/93		154112 A	6	6.7
39	10227	-3	7/19/93		153712 A	6	6.49
					Average length =		6.51

Table A.1 - Continued
Mn/ROAD Test Cell 40 Core Lengths

Test Cell	Core location Station (ft)	Offset (ft)	Core Date	Core Field ID	Mn/ROAD ID #	Specified Core Length[a] (in)	As-built Core Length (in)
40	10245	5	7/19/93		153113 A	6.12	6.8
40	10247	-6	7/19/93		153213 A	6.25	6.48
40	10249	7	7/19/93		152713 A	6.38	6.58
40	10521	3.6		40-HC-01	55501 A	5.95	6.925
40	10522	9.49		40-HC-02	55502 A	6.7	7.375
40	10525	-9.37		40-TC-01	55506 A	6.7	7.7
40	10526	-6.07		40-NP-01	55505 A	6.25	7.325
40	10548	-9.5		40-HC-04	55504 A	6.7	7.775
40	10550	-3.56		40-HC-03	55503 A	5.94	7.125
40	10550	3.57		40-DT-03	55499 A	5.94	7.325
40	10551	9.53		40-DT-04	55500 A	6.7	8.125
40	10552	3.54		40-DT-01	55497 A	5.94	7.625
40	10553	9.51		40-DT-02	55498 A	6.7	7.925
40	10731	-3	7/19/93		153713 A	5.88	6.92
40	10737	7	7/19/93		154113 A	6.38	7
40	10743	7	7/19/93		154213 A	6.38	7.91
					Average @ 3' Offset =		7.18
					Average @ 9' Offset =		7.78

(a) Variable due to tapered cross section. Thickness listed based on offset from centerline.

APPENDIX B

CALCULATION OF k-VALUES USING AASHTO AREA METHOD

Calculation of k-Values Using AASHTO "AREA" Method

One method for determining the modulus of subgrade reaction to an applied load is the "AREA" method found in the 1993 AASHTO guide.[3] This method utilizes measured deflections of a pavement from a known load. For this study, deflections measurements were gathered from FWD testing conducted in the center of the concrete panels for each test cell. Data was compiled for tests conducted from 1993 through 1996.

FWD testing is not typically conducted at Mn/ROAD during the winter, however for this study a special testing event was conducted during January of 1997 to determine representative values for frozen soil conditions. Due to the lack of available information, results from that testing were utilized for all concrete test cells for all months with frozen subgrade conditions.

The k-value resulting from the "AREA" method is an effective dynamic value. This value is divided by two to reach an effective static k-value which is used in design. To account for the effect of changing seasons on the subgrade strength, a damage factor (u_r) was calculated and averaged for each test cell. This factor was subsequently correlated back to the final design effective k-value using:

$$k_{eff} = \frac{E_c}{\left[\dfrac{18.42}{\left(D^{0.75} - (u_r)^{\frac{1}{b}}\right)}\right]^4}$$

where: $b = [4.22 - 0.32p_t]$
$p_t = 2.5$

To minimize slab curling effects (attempt to insure reasonable slab contact with the subgrade), pavement temperature gradients were calculated (assuming a linear profile) for times when the FWD tests were conducted. Only data from tests conducted during gradients ranging from +0.5 to -3.5°F/in were considered. All other k-values were derived using reasonable estimates.

Values from the "AREA" method are typically adjusted by a loss of support factor. This value was taken to be zero for all test cells based on recent findings. See Chapter 2 for more details on this.

The following tables summarize the k-value calculations found for this study using the AASHTO "AREA" method.

Mn/ROAD Test Cell 5 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
5	Jan	8-Jan-97	0.1	25	1220
5	Jan	8-Jan-97		25	1220
5	Feb	8-Jan-97		25	1220
5	Feb	8-Jan-97		25	1220
5	Mar	14-Mar-94	0.0	32	815
5	Mar			35	675
5	Apr			51	285
5	Apr			50	310
5	May	10-May-94	-0.4	55	235
5	May	15-May-96	-2.4	62	160
5	Jun			51	285
5	Jun			51	285
5	Jul			50	300
5	Jul			50	300
5	Aug	14-Aug-96	-0.8	46	380
5	Aug			46	380
5	Sep			50	300
5	Sep			50	300
5	Oct			45	405
5	Oct			45	405
5	Nov			35	675
5	Nov			35	675
5	Dec	8-Jan-97	0.1	25	1220
5	Dec	8-Jan-97		25	1220
			Average U_r:	41	
			Effective Modulus of Subgrade:		490

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 6 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
6	Jan	8-Jan-97	0.1	28	1220
6	Jan	8-Jan-97		28	1220
6	Feb	8-Jan-97		28	1220
6	Feb	8-Jan-97		28	1220
6	Mar	14-Mar-94	0.0	35	815
6	Mar			38	675
6	Apr	20-Apr-94	-0.7	53	285
6	Apr	10-Apr-96	-1.2	52	310
6	May	1-May-96	-1.9	58	225
6	May	15-May-96	-2.3	65	150
6	Jun			53	285
6	Jun			53	285
6	Jul			53	300
6	Jul			53	300
6	Aug	14-Aug-96	-1.1	54	270
6	Aug			54	270
6	Sep			54	270
6	Sep	28-Sep-94	-2.2	61	190
6	Oct			54	270
6	Oct			54	270
6	Nov			38	675
6	Nov			38	675
6	Dec	8-Jan-97	0.1	28	1220
6	Dec	8-Jan-97		28	1220
			Average U_r:	45	
				Effective Modulus of Subgrade:	450

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 7 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
7	Jan	8-Jan-97	0.1	33	1220
7	Jan	8-Jan-97		33	1220
7	Feb	8-Jan-97		33	1220
7	Feb	8-Jan-97		33	1220
7	Mar	14-Mar-94	0.1	33	1220
7	Mar			45	675
7	Apr	10-Apr-96	-2.5	67	240
7	Apr			65	270
7	May	10-May-94	-2.2	71	205
7	May	15-May-96	-1.8	67	240
7	Jun	12-Jun-95	-1.7	67	240
7	Jun	13-Jun-95	-1.4	65	270
7	Jul	10-Jul-96	-3.5	72	190
7	Jul			65	270
7	Aug	14-Aug-96	-0.7	61	320
7	Aug	15-Aug-96	-2.4	65	270
7	Sep	28-Sep-94	-2.6	64	280
7	Sep			64	280
7	Oct			56	405
7	Oct			56	405
7	Nov			45	675
7	Nov			45	675
7	Dec	8-Jan-97	0.1	33	1220
7	Dec	8-Jan-97		33	1220
			Average U_r:	53	
				Effective Modulus of Subgrade:	470

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 8 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
8	Jan	8-Jan-97	0.1	32	1220
8	Jan	8-Jan-97		32	1220
8	Feb	8-Jan-97		32	1220
8	Feb	8-Jan-97		32	1220
8	Mar	14-Mar-94	-2.1	32	1255
8	Mar			43	675
8	Apr	10-Apr-96	-3.4	60	300
8	Apr			56	350
8	May	10-May-94	-3.1	62	260
8	May	15-May-96	-3.1	64	245
8	Jun			60	165
8	Jun			61	270
8	Jul			65	225
8	Jul			61	270
8	Aug	14-Aug-96	-1.4	59	310
8	Aug			59	310
8	Sep	28-Sep-94	-2.3	61	280
8	Sep			61	280
8	Oct			53	405
8	Oct			53	405
8	Nov			43	675
8	Nov			43	675
8	Dec	8-Jan-97	0.1	32	1220
8	Dec	8-Jan-97		32	1220
			Average U_r:	50	
				Effective Modulus of Subgrade:	490

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 9 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
9	Jan	8-Jan-97	0.1	34	1220
9	Jan	8-Jan-97		34	1220
9	Feb	8-Jan-97		34	1220
9	Feb	8-Jan-97		34	1220
9	Mar	14-Mar-94	-2.4	36	1100
9	Mar			46	675
9	Apr	10-Apr-96	-3.2	65	275
9	Apr			60	350
9	May	1-May-96	-2.6	63	305
9	May	10-May-94	-1.9	67	245
9	Jun	12-Jun-95	-3.1	64	285
9	Jun	13-Jun-95	-3.1	63	300
9	Jul	10-Jul-96	-3.5	69	230
9	Jul			65	270
9	Aug	14-Aug-96	-1.3	60	350
9	Aug	15-Aug-96	-3.0	63	305
9	Sep	28-Sep-94	-2.9	64	290
9	Sep			64	290
9	Oct			57	405
9	Oct			57	405
9	Nov			46	675
9	Nov			46	675
9	Dec	8-Jan-97	0.1	34	1220
9	Dec	8-Jan-97		34	1220
			Average U_r:	52	
			Effective Modulus of Subgrade:		500

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 10 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
10	Jan	8-Jan-97	0.1	80	1220
10	Jan	8-Jan-97		80	1220
10	Feb	8-Jan-97		80	1220
10	Feb	8-Jan-97		80	1220
10	Mar			80	1220
10	Mar			102	675
10	Apr	20-Apr-94	-1.1	128	350
10	Apr	10-Apr-96	-2.5	125	380
10	May	1-May-96	-1.4	127	365
10	May	15-May-96	-2.4	135	300
10	Jun			137	285
10	Jun			135	300
10	Jul			152	190
10	Jul			139	270
10	Aug	14-Aug-96	-0.8	123	405
10	Aug	15-Aug-96	-1.8	123	405
10	Sep			136	290
10	Sep			136	290
10	Oct			123	405
10	Oct			123	405
10	Nov			102	675
10	Nov			102	675
10	Dec	8-Jan-97	0.1	80	1220
10	Dec	8-Jan-97		80	1220
			Average U_r:	113	
				Effective Modulus of Subgrade:	525

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 11 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
11	Jan	8-Jan-97	0.1	75	1220
11	Jan	8-Jan-97		75	1220
11	Feb	8-Jan-97		75	1220
11	Feb	8-Jan-97		75	1220
11	Mar			75	1220
11	Mar			96	675
11	Apr	20-Apr-94	-0.9	129	270
11	Apr			127	285
11	May	1-May-96	-1.1	122	325
11	May	15-May-96	-2.5	139	205
11	Jun			127	285
11	Jun			127	285
11	Jul			125	300
11	Jul			125	300
11	Aug	14-Aug-96	-1.0	122	325
11	Aug	15-Aug-96	-1.6	117	375
11	Sep			125	300
11	Sep			125	300
11	Oct			114	405
11	Oct			114	405
11	Nov			96	675
11	Nov			96	675
11	Dec	8-Jan-97	0.1	75	1220
11	Dec	8-Jan-97		75	1220
			Average U_r:	106	
			Effective Modulus of Subgrade:		510

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 12 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
12	Jan	8-Jan-97	0.1	90	1220
12	Jan	8-Jan-97		90	1220
12	Feb	8-Jan-97		90	1220
12	Feb	8-Jan-97		90	1220
12	Mar			90	1220
12	Mar			113	675
12	Apr	10-Apr-96	-1.9	139	325
12	Apr	20-Apr-94	-0.7	142	350
12	May	1-May-96	-1.1	144	310
12	May	15-May-96	-2.3	145	300
12	Jun			147	285
12	Jun			147	285
12	Jul			145	300
12	Jul			145	300
12	Aug	14-Aug-96	-0.4	137	365
12	Aug	15-Aug-96	-0.5	135	395
12	Sep			145	300
12	Sep			145	300
12	Oct			133	405
12	Oct			133	405
12	Nov			113	675
12	Nov			113	675
12	Dec	8-Jan-97	0.1	90	1220
12	Dec	8-Jan-97		90	1220
			Average U_r:	123	
			Effective Modulus of Subgrade:		530

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 13 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
13	Jan	8-Jan-97	0.1	84	1220
13	Jan	8-Jan-97		84	1220
13	Feb	8-Jan-97		84	1220
13	Feb	8-Jan-97		84	1220
13	Mar			84	1220
13	Mar			107	675
13	Apr	10-Apr-96	-1.2	136	285
13	Apr	20-Apr-94	-0.7	140	310
13	May	1-May-96	-1.2	138	300
13	May	15-May-96	-2.5	153	200
13	Jun			140	285
13	Jun			140	285
13	Jul			138	300
13	Jul			138	300
13	Aug	14-Aug-96	-1.1	135	325
13	Aug	15-Aug-96	-1.1	128	385
13	Sep			138	300
13	Sep			138	300
13	Oct			126	405
13	Oct			126	405
13	Nov			107	675
13	Nov			107	675
13	Dec	8-Jan-97	0.1	84	1220
13	Dec	8-Jan-97		84	1220
			Average U_r:	118	
				Effective Modulus of Subgrade:	510

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 36 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
36	Jan	8-Jan-97	0.1	14	1220
36	Jan	8-Jan-97		14	1220
36	Feb	8-Jan-97		14	1220
36	Feb	8-Jan-97		14	1220
36	Mar	15-Mar-96		22	575
36	Mar	31-Mar-94	-0.5	22	575
36	Apr	3-Apr-95	-0.9	30	310
36	Apr	26-Apr-94	-0.6	27	395
36	May	6-May-96	-0.7	28	360
36	May	10-May-96	-0.6	29	340
36	Jun	3-Jun-96	-0.6	28	380
36	Jun	20-Jun-95	-0.6	25	460
36	Jul	11-Jul-94	-0.6	27	405
36	Jul	11-Jul-94	-0.7	22	610
36	Aug	10-Aug-94	0.2	27	395
36	Aug	18-Aug-95	-1.5	28	365
36	Sep	23-Sep-96	-1.7	31	300
36	Sep			31	300
36	Oct	22-Oct-96	0.4	27	395
36	Oct	22-Oct-96	0.4	27	400
36	Nov	13-Nov-95	-1.1	31	305
36	Nov	15-Nov-95	-0.5	31	305
36	Dec	8-Jan-97	0.1	14	1220
36	Dec	8-Jan-97		14	1220
			Average U_r:	24	
				Effective Modulus of Subgrade:	510

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 37 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
37	Jan	8-Jan-97	0.1	16	1220
37	Jan	8-Jan-97		16	1220
37	Feb	8-Jan-97		16	1220
37	Feb	8-Jan-97		16	1220
37	Mar			16	1220
37	Mar	31-Mar-94	-0.5	26	600
37	Apr	14-Apr-94	-0.6	28	515
37	Apr	29-Apr-96	0.6	32	395
37	May	6-May-96	0.8	35	325
37	May	10-May-96	0.9	37	285
37	Jun	3-Jun-96	0.9	35	310
37	Jun	20-Jun-95	0.9	31	420
37	Jul	11-Jul-94	0.4	30	440
37	Jul	11-Jul-94	0.7	29	460
37	Aug	10-Aug-94	-0.4	32	380
37	Aug			32	380
37	Sep	22-Sep-94	-1.0	32	395
37	Sep			32	395
37	Oct	22-Oct-96	-0.3	35	310
37	Oct	22-Oct-96	-0.2	36	285
37	Nov	15-Nov-95	0.2	36	290
37	Nov			36	300
37	Dec			24	680
37	Dec	8-Jan-97	0.1	16	1220
			Average U_r:	28	
				Effective Modulus of Subgrade:	505

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 38 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
38	Jan	8-Jan-97	0.1	17	1220
38	Jan	8-Jan-97		17	1220
38	Feb	8-Jan-97		17	1220
38	Feb	8-Jan-97		17	1220
38	Mar	13-Mar-95	-1.7	25	610
38	Mar	31-Mar-94	0.5	26	555
38	Apr	1-Apr-94	0.5	29	460
38	Apr	29-Apr-96	-0.4	41	185
38	May	6-May-96	-0.7	42	170
38	May	31-May-96	-2.3	42	175
38	Jun	3-Jun-96	-0.9	42	175
38	Jun	20-Jun-95	-0.8	43	165
38	Jul	11-Jul-94	-0.7	41	185
38	Jul	20-Jul-95	-1.2	41	190
38	Aug	10-Aug-94	0.3	41	190
38	Aug	28-Aug-96	-1.9	42	170
38	Sep	23-Sep-96	-1.7	44	150
38	Sep			42	175
38	Oct	22-Oct-96	0.4	40	205
38	Oct	22-Oct-96	0.3	40	205
38	Nov	15-Nov-95	0.3	37	245
38	Nov			37	245
38	Dec			24	680
38	Dec	8-Jan-97	0.1	17	1220
			Average U_r:	34	
			Effective Modulus of Subgrade:		325

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 39 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
39	Jan	8-Jan-97	0.1	15	1220
39	Jan	8-Jan-97		15	1220
39	Feb	8-Jan-97		15	1220
39	Feb	8-Jan-97		15	1220
39	Mar	13-Mar-95	-1.9	22	680
39	Mar	31-Mar-94	0.7	23	625
39	Apr			37	205
39	Apr	29-Apr-96	-0.3	37	205
39	May	6-May-96	-0.5	37	205
39	May	31-May-96	-2.2	39	185
39	Jun	3-Jun-96	-0.7	39	185
39	Jun	20-Jun-95	-0.4	38	195
39	Jul	11-Jul-94	-0.4	36	215
39	Jul	20-Jul-95	-0.9	37	205
39	Aug	10-Aug-94	0.4	36	225
39	Aug	28-Aug-96	-1.5	38	190
39	Sep			38	190
39	Sep	23-Sep-96	-1.0	38	195
39	Oct	22-Oct-96	0.5	35	245
39	Oct	22-Oct-96	0.4	35	235
39	Nov	13-Nov-95	-0.8	31	325
39	Nov	15-Nov-95	-0.1	33	270
39	Dec			22	680
39	Dec	8-Jan-97	0.1	15	1220
			Average U_r:	30	
			Effective Modulus of Subgrade:		345

Unit conversion: kPa/cm=0.369 pci

Table B.1 - Continued
Mn/ROAD Test Cell 40 Modulus of Subgrade Reaction Values

Test Cell	Month	Date	Temperature Gradient (°F/in)	Relative Damage, U_r	Composite k-Value (kPa/cm)
40	Jan	8-Jan-97	0.1	22	1220
40	Jan	8-Jan-97		22	1220
40	Feb	8-Jan-97		22	1220
40	Feb	8-Jan-97		22	1220
40	Mar	13-Mar-95	-1.7	27	845
40	Mar	28-Mar-95	-1.6	50	215
40	Apr	3-Apr-95	-0.6	51	205
40	Apr	29-Apr-96	-0.3	50	215
40	May	10-May-96	-0.2	52	190
40	May	31-May-96	-2.1	52	195
40	Jun	3-Jun-96	-0.7	51	205
40	Jun	25-Jun-96	-3.1	53	185
40	Jul	20-Jul-95	-0.9	48	245
40	Jul	20-Jul-95	-2.9	54	175
40	Aug	18-Aug-95	-1.2	48	245
40	Aug	28-Aug-96	-1.5	50	225
40	Sep			49	230
40	Sep	23-Sep-96	-0.6	49	230
40	Oct	23-Oct-95	0.7	46	270
40	Oct			46	270
40	Nov	13-Nov-95	-1.0	43	320
40	Nov	15-Nov-95	-0.3	44	305
40	Dec			31	680
40	Dec	8-Jan-97	0.1	22	1220
			Average U_r:	42	
				Effective Modulus of Subgrade:	350

Unit conversion: kPa/cm=0.369 pci

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