Selection of Flexible Pavement Backcalculation Software for the Minnesota Road Research Project
This report presents the results of an evaluation process of several different flexible pavement backcalculation programs. The objective of this study was to compare the performance of the candidate programs in terms of usability and accuracy of backcalculation results. This was accomplished by evaluating the selected programs using both field and simulated data. The results of the analysis were used as the basis for selecting a program for routine analysis of MnROAD pavement deflection data.

In situ pavement strains were measured during falling-weight deflectometer tests. The measured strains were then compared to backcalculated strain values from each program. In addition to the field tests, a series of hypothetical pavement structures with a range of prescribed layer thicknesses and moduli were analyzed to obtain surface deflection data. These surface deflections were then used as input for each program involved in the study. The output from each program was compared to the expected values.

Four different programs were evaluated in the study: EVERCALC v. 3.3, EVERCALC v. 4.1, WESDEF, and MODCOMP3. Based on results from the analyses, the program recommended for routine research of the MnROAD test sections is EVERCALC v. 4.1. Recommendations and general guidelines for performing backcalculation analysis are provided.
SELECTION OF FLEXIBLE PAVEMENT BACKCALCULATION SOFTWARE FOR THE MINNESOTA ROAD RESEARCH PROJECT

Final Report

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EXECUTIVE SUMMARY

In many current pavement management strategies, bearing capacity is determined using a falling-weight deflectometer (FWD). The deflection data can be used to obtain information regarding the relative strengths of the various layers within the pavement structure by doing a backcalculation analysis.

Estimating critical pavement responses to traffic loads is a crucial part of a mechanistic design procedure for newly constructed or rehabilitated pavements. One of the features of the Minnesota Road Research Project (Mn/ROAD), a full-scale test facility constructed by the Minnesota Department of Transportation (Mn/DOT), are the in-situ pavement response sensors. Measurements from these sensors will be used to verify and calibrate pavement response models. The calibrated models will in turn be used as the basis for the mechanistic-empirical design procedure that will be developed, in part, from Mn/ROAD data.

The scope of this report deals the evaluation of backcalculation analysis software leading to the selection of a program for routine use on both Mn/ROAD research and general Mn/DOT projects. It is hoped that the recommendations made in this report will be implemented statewide in light of the oncoming mechanistic design procedure.

The main objective of this study was to compare the performance of several different backcalculation programs in terms of usability and accuracy of backcalculation results. This was accomplished by evaluating the selected programs using two approaches. In the first approach the programs were used to analyze data from field deflection testing that was conducted on five
Mn/ROAD flexible pavement test sections. These tests were conducted over the locations of in-situ strain sensors so that the measured strains could be compared against values obtained from the backcalculation results. In the second approach an experiment was conducted in which the programs were run on theoretical deflection data; the moduli predicted from each program were compared to the expected values and the percent error was calculated.

Based upon the results presented in this report it is reasonable to conclude the following:

➢ For the field testing data the agreement between the WESDEF and EVERCALC v. 3.3 was the best among the programs investigated.

➢ The output of the MODCOMP3 program frequently became unstable during the analysis of the field data. Large RMS percent errors, unreasonable results, and long computation times were observed.

➢ When using the WESDEF program to model a semi-infinite subgrade the minimum recommended subgrade thickness is 30 m.

➢ For the simulated deflection study the agreement between expected and backcalculated stress and strain was good for all of the programs, especially for the horizontal strain in the surface (AC) layer. The agreement between stresses and strains in the underlying layers was also good.

➢ The use of EVERCALC v. 4.1 as a "standard" backcalculation program should be implemented (at least for Mn/ROAD and research work).
General comments regarding pavement layer modulus backcalculation and the various programs evaluated in this study are as follows:

- Backcalculation analysis using static, linear elastic theory on deflection data obtained during the spring thaw period is highly problematic. This is due to the contrast in stiffness between shallow frozen/unfrozen zones and thus deviations from the real (field) situation and assumptions implicit in the theory.

- It is not recommended that backcalculation analyses of deflection data from sections having surface layer thicknesses less that 100 mm be done. This is consistent with observations and recommendations found in the literature. An alternative approach would be to use AC moduli-temperature data from thicker test sections with similar mix characteristics to fix the thin layer moduli at a known value. The moduli of the underlying layers could then be backcalculated. Another approach might involve the use of some other parameter as the primary response transfer function input, e.g., curvature or deflection obtained directly from FWD data.

- Assumed surface layer thickness can have a dramatic effect on the backcalculation results. The effects of uncertainty of surface layer thickness on estimated strains should be investigated more formally. This could be done by performing a sensitivity analysis to determine the range of effect of assumed pavement thickness on the magnitude of backcalculated strain, for a variety of structures.
# TABLE OF CONTENTS

**CHAPTER 1**<br>INTRODUCTION .................................................................................................................... 1

**CHAPTER 2**<br>BPIKGROUN1D  
- Deflection Analysis ............................................................................................................ 3  
- Pavement Response Analysis ........................................................................................... 5  
- Description of Programs .................................................................................................. 6

**CHAPTER 3**<br>OBJECTIVES .................................................................................................................... 9

**CHAPTER 4**<br>RESEARCH APPROACH .............................................................................................. 11

**CHAPTER 5**<br>SELECTION STUDY ..................................................................................................... 15 
- Field Deflection Data ........................................................................................................ 15 
- Simulated Deflection Data ................................................................................................ 18

**CHAPTER 6**<br>DISCUSSION ................................................................................................................... 19 
- Field Testing .................................................................................................................... 19 
- Simulation Study ............................................................................................................... 21 
- Program Selection .......................................................................................................... 22
TABLE OF CONTENTS

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS .................................................. 23

REFERENCES ................................................................................................. 25

APPENDIX A - Summary of results from pavement simulation study

APPENDIX B - Comparison of moduli results from MODCOMP3 program

NOTE: Copies of the appendices may be obtained from the author or the Mn/DOT Office of Research Administration.
LIST OF TABLES

Table 4.1 - Mn/ROAD test sections selected for the deflection study........................................27
Table 4.2 - Structural data used for hypothetical sections in simulation study ......................27
Table 6.1 - Summary of modulus percent prediction errors from backcalculation program performance study..................................................................................................................28
Table A.1 - Summary of simulated structures and deflection basins........................................A1
Table A.2 - Summary of simulated structures and subsurface responses.........................A23
LIST OF FIGURES

Fig. 4.1 - Mn/ROAD test sections selected for the deflection study ........................................29

Fig. 4.2 - Locations of calculation points for simulated deflection basins and subsurface responses ...........................................................................................................30

Fig. 5.1 - Comparison of AC pavement thickness determined by coring and GPR ..........31

Fig. 5.2 - Example of experimental relationship between AC strain and modulus ..........32

Fig. 6.1 - Comparison of backcalculated and measured transverse AC strains from TS 4: EVERCALC v. 3.3 .................................................................33

Fig. 6.2 - Comparison of backcalculated and measured transverse AC strains from TS 4: WESDEF .................................................................................34

Fig. 6.3 - Comparison of backcalculated AC strains showing effects of thickness assumption and program .................................................................35

Fig. 6.4 - Comparison of backcalculated and measured transverse AC strains from TS 17: EVERCALC v. 3.3 .................................................................36

Fig. 6.5 - Comparison of backcalculated and measured longitudinal AC strains from TS 22: EVERCALC v. 3.3 .................................................................37

Fig. 6.6 - Comparison of backcalculated and measured transverse AC strains from TS 22: EVERCALC v. 3.3 .................................................................38

Fig. 6.7 - Comparison of backcalculated and measured transverse AC strains from TS 25: EVERCALC v. 3.3 .................................................................39

Fig. 6.8 - Comparison of backcalculated and measured transverse AC strains from TS 27: EVERCALC v. 3.3 .................................................................40

Fig. 6.9 - Comparison of backcalculated and measured longitudinal AC strains from TS 27: EVERCALC v. 3.3 .................................................................41

Fig. 6.10 - Comparison of AC moduli for TS 4: WESDEF vs. EVERCALC v. 3.3 .........42

Fig. 6.11 - Comparison of intermediate subgrade layer moduli for TS 4: WESDEF vs. EVERCALC v. 3.3 .................................................................43
Fig. 6.12 - Comparison of subgrade layer moduli for TS 4: WESDEF vs.
EVERCALC v. 3.3 .................................................................44

Fig. 6.13 - Comparison of RMS error for TS 4: WESDEF vs.
EVERCALC v. 3.3 .................................................................45

Fig. 6.14 - Comparison of backcalculated AC strain for TS 4: WESDEF vs.
EVERCALC v. 3.3 .................................................................46

Fig. 6.15 - Comparison of AC moduli for TS 17: WESDEF vs.
EVERCALC v. 3.3 .................................................................47

Fig. 6.16 - Comparison of base layer moduli for TS 17: WESDEF vs.
EVERCALC v. 3.3 .................................................................48

Fig. 6.17 - Comparison of subgrade layer moduli for TS 17: WESDEF vs.
EVERCALC v. 3.3 .................................................................49

Fig. 6.18 - Comparison of RMS error for TS 17: WESDEF vs.
EVERCALC v. 3.3 .................................................................50

Fig. 6.19 - Comparison of AC strain for TS 17: WESDEF vs.
EVERCALC v. 3.3 .................................................................51

Fig. 6.20 - Comparison of AC moduli for TS 22: WESDEF vs.
EVERCALC v. 3.3 .................................................................52

Fig. 6.21 - Comparison of base layer moduli for TS 22: WESDEF vs.
EVERCALC v. 3.3 .................................................................53

Fig. 6.22 - Comparison of subgrade layer moduli for TS 22: WESDEF vs.
EVERCALC v. 3.3 .................................................................54

Fig. 6.23 - Comparison of RMS error for TS 22: WESDEF vs.
EVERCALC v. 3.3 .................................................................55

Fig. 6.24 - Comparison of AC strain for TS 22: WESDEF vs.
EVERCALC v. 3.3 .................................................................56

Fig. 6.25 - Comparison of AC moduli for TS 25: WESDEF vs.
EVERCALC v. 3.3 .................................................................57

Fig. 6.26 - Comparison of intermediate subgrade layer moduli for TS 25: WESDEF vs.
EVERCALC v. 3.3 .................................................................58

Fig. 6.27 - Comparison of subgrade layer moduli for TS 25: WESDEF vs.
EVERCALC v. 3.3 .................................................................59

Fig. 6.28 - Comparison of RMS error for TS 25: WESDEF vs.
EVERCALC v. 3.3 .................................................................60

Fig. 6.29 - Comparison of AC strain for TS 25: WESDEF vs.
EVERCALC v. 3.3 .................................................................61
Fig. 6.30 - Comparison of AC moduli for TS 27: WESDEF vs. EVERCALC v. 3.3 ........62
Fig. 6.31 - Comparison of base layer moduli for TS 27: WESDEF vs. EVERCALC v. 3.3 63
Fig. 6.32 - Comparison of subgrade layer moduli for TS 27: WESDEF vs. EVERCALC v. 3.3 ..................................................64
Fig. 6.33 - Comparison of RMS error for TS 27: WESDEF vs. EVERCALC v. 3.3 ........65
Fig. 6.34 - Comparison of AC strain for TS 27: WESDEF vs. EVERCALC v. 3.3 ..........66
Fig. 6.35 - Backcalculated vs. expected AC strains for simulated pavement sections ..........67
Fig. 6.36 - Backcalculated vs. expected vertical stress in base for simulated pavement sections ........................................................................68
Fig. 6.37 - Backcalculated vs. expected horizontal stress in base for simulated pavement sections ........................................................................69
Fig. 6.38 - Backcalculated vs. expected vertical subgrade strain for simulated pavement sections ........................................................................70
Fig. 6.39 - Backcalculated vs. expected vertical stress on subgrade for simulated pavement sections ........................................................................71
Fig. 6.40 - Backcalculated vs. expected horizontal stress on subgrade for simulated pavement sections ........................................................................72
Fig. A.1 - Comparison of backcalculated and expected moduli: WESDEF, AC layer ......A45
Fig. A.2 - Comparison of backcalculated and expected moduli: EVERCALC v. 4.0, AC layer ........................................................................................................A46
Fig. A.3 - Comparison of backcalculated and expected moduli: MODCOMP3, AC layer...A47
Fig. A.4 - Comparison of backcalculated and expected moduli: EVERCALC v. 3.3, AC layer ........................................................................................................A48
Fig. A.5 - Comparison of backcalculated and expected moduli: WESDEF, base layer .....A49
Fig. A.6 - Comparison of backcalculated and expected moduli: EVERCALC v. 4.0, base layer ........................................................................................................A50
Fig. A.7 - Comparison of backcalculated and expected moduli: MODCOMP3, base layer
Fig. A.8 - Comparison of backcalculated and expected moduli: EVERCALC v. 3.3, base layer
Fig. A.9 - Comparison of backcalculated and expected moduli: WESDEF, subgrade layer
Fig. A.10 - Comparison of backcalculated and expected moduli: EVERCALC v. 4.0, subgrade layer
Fig. A.11 - Comparison of backcalculated and expected moduli: MODCOMP3, subgrade layer
Fig. A.12 - Comparison of backcalculated and expected moduli: EVERCALC v. 3.3, subgrade layer
Fig. B.1 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 4, AC layer
Fig. B.2 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 4, base layer
Fig. B.3 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 4, subgrade layer
Fig. B.4 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 17, AC layer
Fig. B.5 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 17, base layer
Fig. B.6 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 17, subgrade layer
Fig. B.7 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 22, AC layer
Fig. B.8 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 22, base layer
Fig. B.9 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 22, subgrade layer
Fig. B.10 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 25, AC layer ......................................................... B10

Fig. B.11 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 25, base layer ......................................................... B11

Fig. B.12 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 25, subgrade layer ......................................................... B12

Fig. B.13 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 27, AC layer ......................................................... B13

Fig. B.14 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 27, base layer ......................................................... B14

Fig. B.15 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, TS 27, subgrade layer ......................................................... B15

Fig. B.16 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, simulated deflection data, AC layer ........................................ B16

Fig. B.17 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, simulated deflection data, base layer ........................................ B17

Fig. B.18 - Comparison of backcalculated moduli: MODCOMP3 vs. WESDEF, simulated deflection data, subgrade layer ........................................ B18
CHAPTER 1
INTRODUCTION

In many current pavement management strategies, bearing capacity is determined using a falling-weight deflectometer (FWD). The deflection data can be used to obtain information regarding the relative strengths of the various layers within the pavement structure by doing a backcalculation analysis. In a backcalculation analysis, one has data consisting of measured loads, deflections, and information regarding the structural thicknesses. These data are used in a calculation or search procedure for the layer moduli that provide the best agreement between the measured and calculated deflections.

Estimating critical pavement responses to traffic loads is a crucial part of a mechanistic design procedure. Confidence in the accuracy of pavement response calculation models is also important for a reliable design model for new pavements. One of the features of the Minnesota Road Research Project (Mn/ROAD), a full-scale test facility constructed by the Minnesota Department of Transportation (Mn/DOT), are the in-situ pavement response sensors. Measurements from these sensors will be used to verify and calibrate pavement response models. The calibrated models will in turn be used as the basis for the mechanistic-empirical design procedure that will be developed, in part, from Mn/ROAD data.

The scope of this report deals with the evaluation of backcalculation analysis software leading to the selection of a program for routine use on both Mn/ROAD research and general Mn/DOT projects. It is hoped that the recommendations made in this report will be implemented statewide in light of the oncoming mechanistic design procedure.
CHAPTER 2

BACKGROUND

Deflection Analysis

There are a multitude of different pavement analysis procedures and programs available for use today. Some of these are more sophisticated than others and range from simple models that compute effective pavement and subgrade moduli \[1\] to more sophisticated models that estimate viscoelastic model parameters based on dynamic forward-calculation solutions \[2\].

Since mechanistic-empirical pavement design procedures are based on in-situ response of pavement sections, Mn/DOT felt it was necessary to evaluate different programs from the standpoint of both pavement surface and subsurface responses, e.g., strain at the bottom of the surface layers, pressure at the mid-depth of the intermediate (granular base) layer, etc.

As part of the backcalculation software selection process for the Strategic Highway Research Program (SHRP) an intensive study was undertaken to evaluate several different programs using both field and computer generated data \[3\]. Pavement engineering and research experts were called upon to perform analyses with the candidate programs. The main shortcoming of this particular study is that the program comparisons and evaluations were based only on the individual layer moduli and not subsurface responses.

The basic procedure for multi-layer pavement backcalculation is outlined below. Many backcalculation programs are based on an iterative procedure in which the layer moduli are adjusted until the measured deflections match the calculated deflections within a specified
tolerance. The iteration process stops if one of the following occurs:

1. The mean root-mean-square of the relative difference between measured and backcalculated readings is less than a given value;
2. The combined change of modulus for all layers from one iteration to the next is less than a given value;
3. The maximum number of user-specified iterations has been reached.

The first criterion is obvious, if the match is near perfect, the search is stopped. The difference between the two basins is referred to as the deflection error. It is expressed as the root-mean-square (RMS) deviation.

The second criterion requires some explanation. The program will base the adjusted moduli on the effect a change of the modulus has on the deflection error. This could be expressed as a slope, and a slope is determined for each unknown layer. A steep slope will lead to a quick solution, but a shallow slope may take longer or even lead to non-convergence. Further, the resolution of the sensors may not be adequate for reaching the stipulated RMS-criterion. In addition, the shortcomings of the linear elastic model, faulty assumption of layer thicknesses, or both, may deter a satisfactory match of the basins. Thus, when the change of modulus is small for each layer, the program is unable to arrive at a better match anyway and the iteration procedure stops. Such basins should always be checked critically, but may be accepted if the deviation from the measured basin is not too large.

The last criterion is as obvious as the first and is needed for practical reasons. The criteria used for all calculations in the present study was an RMS tolerance of one percent, a change of
modulus of one percent, and a maximum of 25 iterations.

**Pavement Response Analysis**

One of the factors considered in flexible pavement design and performance prediction is the tensile strain at the bottom of the asphalt concrete layers. Research has shown that good comparisons between strains measured in-situ and strains estimated from backcalculated layer moduli can be obtained from FWD tests [4, 5].

There are many factors that influence the accuracy of measured and backcalculated strains as well as modulus values. They include:

- Assumption of linear elastic, homogeneous materials, static conditions; asphalt concrete is inherently viscoelastic, damping is present in real system;

- Uniform load distribution; plate is in reality semi-rigid;

- Static conditions; the loading condition is dynamic in nature;

- Uniform layer thickness; knowledge of the total asphalt concrete layer thickness is crucial;

- Assumption of strain at a point; gage senses average strain over its length;

- Strain gage inclusion effect; gage may locally stiffen material in which it is present;

- Uncertainty in location of FWD plate relative to sensor; load plate offset relative to gage may have dramatic effect;
The effect of assumed vs. actual AC thickness is dramatic. In general, if the AC thickness can not be determined accurately (at least to within 25 mm) then the backcalculation and response calculations should be reviewed critically and moderated by the accuracy of the inputs. Both the strain-averaging and location effect work to lower the measured strain relative to backcalculated ones. The discrepancy depends on the AC thickness and modulus. In general, to obtain an accurate comparison between the measured and calculated values all these effects should be accounted for.

**Description of Programs**

A detailed study of different programs is outlined in the SHRP selection report [3]. That study led to the eventual selection of the MODULUS program for routine use on SHRP and LTPP data. Four different programs for flexible pavements were selected in the initial part of that study for further evaluation: MODULUS, WESDEF, MODCOMP3, and ISSEM4. The primary reason that the MODULUS program was not chosen for evaluation in our study is the inflexibility of the program: it requires deflections from specific sensor positions and, in addition, many features of the program are customized for Texas conditions.

From the SHRP study it was found that the WESDEF program had the highest level of user sensitivity. It was noted, however, that this could have been because the default depth-to-rigid-layer of 6 meters was not overridden by the users in cases where a semi-infinite subgrade was being modeled [3].

For this study, the key items that were examined in the candidate programs are:
1. Accuracy of backcalculated moduli and forward calculated response results;

2. Use of the same forward calculation program for both back and forward calculations;

3. Calculated moduli, stresses, and strains contained in one output file;

4. Flexibility in selection of deflection sensor positions;

5. Adaptability for users with different computer resources; obtain source code if possible;
   - ability to run in Windows, DOS, and/or UNIX environments;

6. Ability to interface with Mn/ROAD database;

7. Computational efficiency; ability to process data files in batch mode;

8. Program documentation with examples and case studies.

The seventh item above is due to the large number of deflection basins that have been collected at Mn/ROAD. An efficient method of analyzing these data is needed. The preferred candidate program would have the ability to operate in a UNIX environment to facilitate transfer of results to the Mn/ROAD database but also be capable of running in a DOS environment for the benefit of routine users.

The following programs were selected for this study: EVERCALC v. 3.3 [6], MODCOMP3 v. 3.6 [7], WESDEF [8], and EVERCALC v. 4.1 [9]. All four programs use linear elastic forward calculation subroutines. MODCOMP3 has the capability of approximating non-linear elastic layers but this feature was not used in the investigation. Both EVERCALC v. 3.3 and MODCOMP3 use linear elastic solution subroutines that are based on the CHEVRON program,
however, the code in MODCOMP3 has been revised due to concerns about possible calculation inaccuracies in the original CHEVRON code. Both WESDEF and EVERCALC v. 4.1 use the WESLEA forward calculation program which was developed for the US Army Corp of Engineers Waterways Experiment Station [8].

With the exception of EVERCALC v. 4.1 all of the programs are DOS-based applications. EVERCALC v. 4.1 is the only one of the group that operates in a Windows environment. The Washington State Department of Transportation (WSDOT) has published a pavement engineering manual [9]. Part of this manual contains documentation on the EVERCALC v. 4.1 program with examples and case studies, which gives this program an advantage over the others. The main disadvantage of this particular version of EVERCALC is that input and output files use binary code instead of ASCII text making data exchange with the Mn/ROAD database and other applications difficult. All programs, except for EVERCALC v. 3.3, are capable of running in batch mode. In other words, a large number of input data files (prepared beforehand) can be run without someone being present to enter new files. An advantage with the WESDEF program is access to the source code. This makes the program flexible in that an interface customized for Mn/DOT use could be created to interact with both the Mn/ROAD and historical Mn/DOT FWD databases. The code can also be easily compiled on a UNIX machine to interface with the Mn/ROAD computer system. However, since the existing WESDEF code does not have an interface, a program suitable for use by routine users would most likely come only at the cost of considerable programming time.
CHAPTER 3

OBJECTIVES

The objectives of this study are to:

1. Compare the performance of several different backcalculation programs in terms of accuracy and useability;

2. Compare measured strain values against calculated values obtained from deflection backcalculations;

3. Identify situations in which backcalculation procedures break down.

The recommendations from this study will be used to specify a program to be used for pavement evaluation and research on Mn/ROAD FWD data.
CHAPTER 4

RESEARCH APPROACH

The objectives of this study were accomplished by evaluating the selected programs using two approaches. In the first approach the programs were used to analyze data from field deflection testing that was conducted on five Mn/ROAD flexible pavement test sections. Strain response data from in-situ sensors were obtained during each FWD drop so that the measured strains could be compared against values obtained from the backcalculation results. In the second approach an experiment was conducted in which the programs were run on theoretical deflection data; the moduli predicted from each program were compared to the expected values and the percent error was calculated.

The field data in this study were collected during a six-week period in the spring of 1994 that began in mid-March and extended through late April. Intensive data collection and testing was conducted with the assistance of the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (USA CRREL) who supplied engineers, technicians, and a heavy-weight deflectometer (HWD) testing machine. Table 4.1 and Fig. 4.1 give the details of the Mn/ROAD flexible pavement test sections that were tested using the CRREL HWD during spring 1994. Information obtained during this period, which was chosen to coincide with the end-of-winter thawing period, included:

- Non-destructive deflection testing using the Mn/DOT FWD and USA CRREL HWD (obtained approximately twice per day for routine tests and once per day for sensors);
Subsurface in-situ moisture contents obtained from the TDR probes (obtained once per day at most sites and one site recorded several times per day);

Frost and thaw penetration depths from the soil resistivity probes (obtained daily);

Selected dynamic sensor responses using the HWD and the Mn/ROAD mobile data acquisition trailer.

A detailed description of the environmental and load response sensors that are installed at Mn/ROAD can be found elsewhere [10].

The primary pavement response investigated during these tests were the transversally and longitudinally oriented strains at the bottom of the bound asphalt concrete (AC) layers. Typically, in mechanistic design, the long-term performance of a given pavement section is related to the strain which has been shown to be a controlling factor in the fatigue life of AC mixtures. These sensors were installed during construction and were placed directly on the prepared granular base or subgrade for conventional and full-depth sections, respectively. Details on the installation procedure are given in [10]. To facilitate database storage and retrieval at the Mn/ROAD project each individual sensor has a unique identification number. This number consists of three parts: (1) test section number, (2) model, and (3) sequence number. For the two types of strain gages discussed in this report the model designations are LE (Longitudinal Embedment gage) and TE (Transverse Embedment gage). A typical flexible test section strain gage installation consists of three gages straddled across the wheelpath. The gages are spaced transversally at 305 mm apart and are numbered such that the sequence of the gage in the wheelpath is 002.
In addition to the field data the programs were also evaluated using theoretically generated data. A series of many different hypothetical cases with prescribed layer thicknesses and moduli were analyzed to obtain surface deflection data. These surface deflections were then used as input for each program studied. A range of structural configurations and parameters were modeled as given in Table 4.2 and Fig. 4.2. With all possible combinations of these parameters there are 648 individual cases. The forward calculations were done using the WES5 subroutine [8] in a program called ELC (Elastic Layer Calculations); ELC is a “front-end” program to the WES5 subroutine and was developed specifically for this study. This is the subroutine that is used in the WESLEA forward calculation program and the WESDEF and EVERCALC v. 4.1 backcalculation programs.
CHAPTER 5

SELECTION STUDY

Field Deflection Data

This section discusses the details regarding backcalculation analysis of the field data. The basic process includes the following steps:

1. Select layer thicknesses;

2. Create input files for various programs; calculate initial modulus values (seed moduli) in accordance with [11];

3. Run backcalculation programs;

4. Tabulate output for analysis;

5. In the case of WESDEF, use resulting moduli to create input files for WESS; run forward analysis to get predicted responses;

6. Analyze sensor response time-histories to determine peak response;

7. Compare peak measured responses to predicted values; compare moduli between various programs.

Three programs were used for the evaluation of the field data: EVERCALC v. 3.3, MODCOMP3, and WESDEF. At the time the evaluations of the data were performed the EVERCALC v. 4.1 program was not available. In all cases a three-layered, static, linear elastic
system was modeled. The initial modulus values (seed moduli) assigned to each layer were calculated using the regression equations developed at the University of Washington [11].

The total thickness of the AC surface layers were assumed to be equal to the thickness determined from the GPR survey [12] and the thickness at the FWD test station was assumed equal to the nearest GPR test station. These values are given in the parentheses in Table 1. A regression analysis of the thicknesses determined from the cores and GPR data revealed the following:

\[
\text{GPR THICKNESS} = 1.01 \times (\text{CORE THICKNESS})
\]

where the GPR and core thicknesses are in mm (see Fig. 5.1). The \( R^2 \) and SEE values for the regression were 0.99 and 6.0 mm, respectively. The core thicknesses ranged from about 75 to 300 mm.

The thickness of the granular base layer, if present, was assumed to be equal to the design value (see Table 4.1). In the cases of the two full-depth pavements the sections were modeled as three layer systems to represent modulus changes with depth. Experience has shown that, when modeling a full-depth section, calculations with an intermediate subgrade layer having a thickness equal to approximately three times the total thickness of the asphalt layers gives reasonable results. Intermediate subgrade layers with thicknesses equal to 915 mm and 305 inches for TS 4 and 25, respectively, were used.

All three programs that were used in this part of the study model a layered system on a semi-infinite halfspace. WESDEF, however, assumes that the halfspace is rigid. A non-rigid halfspace
can presumably be modeled in WESDEF by inserting a thick, elastic layer on top of the rigid halfspace. The sensitivity of the WESDEF program output to the thickness of the subgrade layer was investigated by doing two sets of calculations. The calculations were first done for a system with a 6-meter thick subgrade; they were then repeated for a 30-meter thick subgrade.

In all tests the HWD plate was positioned over the center of the wheelpath strain gage; only the wheelpath strain gages were tested. Dynamic sensor responses were obtained using the OPTIM MEGADACs. The mobile data acquisition trailer was used for the off-line low-volume sections (TS 25 and 27) while a laptop computer was used to control the on-line MEGADACs in the mainline roadside cabinets.

The sensor traces were analyzed to determine the maximum response. An algorithm and program specially developed for the Mn/ROAD data was used for this purpose [13]. These values were then compared to strains computed using the backcalculated moduli. Both versions of EVERCALC provide subsurface responses (including strain) directly in the backcalculation output file whereas WESDEF does not. Strains for the WESDEF results were computed by using the moduli as input to the ELC program.

After several attempts at using MODCOMP3 it was observed that the program frequently became unstable with exceedingly large or small moduli and high RMS percent values. It was thought that this may be due to the layer-to-sensor assignments (a required input to the program). Several different approaches were taken with the layer-to-sensor assignments but no improvements were observed. As will be discussed shortly, both WESDEF and EVERCALC v. 3.3 performed well on the field data and the results from these two programs (both moduli and
responses) were in good agreement. Due to the facts that (1) the moduli from MODCOMP3 and WESDEF did not compare well and (2) there is a strong correlation between the AC strain and layer modulus (see Fig. 5.2), it is likely that there would be a poor agreement between measured and calculated strains using moduli predicted by the MODCOMP3 program. Because of this it was decided that the MODCOMP3 program should be disqualified. Results from the MODCOMP3 program are presented in Appendix B.

**Simulated Deflection Data**

As discussed previously, the ELC program was used to analyze the hypothetical sections which have the structural parameters listed in Table 4.2. A description of the nomenclature used for designating the various response quantities is given in Fig. 4.2. After obtaining the predicted surface and subsurface responses from ELC the backcalculation process outlined above was followed. The results of the calculations were analyzed by comparing the expected (known) and backcalculated moduli and subsurface responses.
CHAPTER 6

DISCUSSION

Field Testing

A comparison of calculated (using EVERCALC v. 3.3) and measured strains for the TE002 sensor in TS 4 are shown in Fig. 6.1. The same data from WESDEF calculations are shown in Fig. 6.2. An example of the effects of thickness assumption on the backcalculated strain are shown in Fig. 6.3. As can be seen the assumed thickness value (GPR or design) has a dramatic effect. Fig. 6.3 also shows the relative agreement between the strains obtained from both programs.

Comparisons of calculated and measured strains for each of the remaining test sections are shown in Fig. 6.4 through 6.9. It is evident that the worst agreement comes from the calculations done for TS 27. The design thickness of TS 27 is 75 mm while the GPR survey estimates the thickness near the strain sensors to be about 89 mm. Typically, very poor backcalculation results are obtained on sections with AC thicknesses less than 100 mm.

Fig. 6.10 through 6.14 show comparisons of moduli, strains, and RMS percent error between the EVERCALC v. 3.3 and WESDEF programs for TS 4. Similar graphs for TS 17, 22, 25, and 27 are shown in Fig. 6.15 through 6.19, Fig. 6.20 through 6.24, Fig. 6.25 through 6.29, and Fig. 6.30 through 6.34, respectively.

The agreement between measured and calculated strains is favorable for all but TS 27, although there is considerable scatter for TS 25. Generally, high $R^2$ values were obtained although the
slopes of the regression lines were generally greater than unity: the range of slopes was 0.88 (22LE002) to 1.14 (04TE002). The best agreement came from TS 22:

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>22TE002</th>
<th>22LE002</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLOPE</td>
<td>1.03</td>
<td>0.88</td>
</tr>
<tr>
<td>R²</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>S.E.</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

With the exception of TS 27, the strains and moduli obtained from EVERCALC v. 3.3 and WESDEF compare fairly well. The predicted strains for TS 27 are considerably higher than the measured ones. It was noted that most of the RMS error was contributed by the innermost three sensors. This may reflect the inability of the model to represent a thin section (where the departure from assumptions and reality become prevalent, e.g., uniform load) but also the important fact that, with only three sensors within 300 mm of the load plate center, there is little deflection information regarding the bending and deformation of the AC layer.

The thickness of the subgrade had a definite effect on output from the WESDEF program. In all cases, the use of the thick (30 m) subgrade resulted in a more favorable agreement between the moduli and strains from the two programs. There was still considerable scatter in the comparisons for TS 27 owing to problems with the thin surface layer.

The changes in RMS and strain estimation error over time were investigated. In general, better RMS fits were obtained as the thaw period progressed and the change in RMS percent error stabilized near mid-April. This coincides with the approximate timing of the disappearance of subsoil frost (based on RP data). More rapid improvements in the RMS error were seen for the
thinner sections (25 and 27) but both these also displayed an increase in backcalculation RMS towards the end of April. The reason for this could possibly be due to the effects of warmer air temperatures on the AC mixture stiffness resulting in non-uniform plate loading conditions. No discernible trend between RMS and error could be found for the mainline sections. This may be attributed to the fact that the majority of the discrepancy is contributed by the base and subgrade layers as they thaw. For the two low-volume road sections an increase in the discrepancy between measured and calculated strain was found as the thaw period progressed. Again, the reason for this is not known but may be due to the non-uniform plate loading conditions.

**Simulation Study**

The results of the backcalculations done on the simulated data are summarized in Table 6.1. Table 6.1 gives the statistics on the percent prediction errors for each program studied. Several things are noted from Table 6.1. All programs appear to be able to backcalculate, at least on average, the known moduli fairly well. There was significant variation, however. It was noted that the WESDEF program had consistently low mean prediction errors as well as low ranges (spread between maximum and minimum percent error). Correlations between the prediction errors and structural parameters (e.g., thickness, modulus, etc.) were investigated but none could be found. The differences in results from the various programs are likely due to differences in the specific backcalculation and forward calculation schemes used by each program.

In Fig. 6.35, the calculated and expected AC strain (EH1) from the simulated basins are shown. A description of the nomenclature used for designating the various response quantities is given in Fig. 1. It is evident from this that all programs are able to accurately predict this particular
response. Graphs showing comparisons of the remaining subsurface responses are given in Fig. 6.36 through 6.40. From these results, it appears as though the two EVERCALC programs and WESDEF performed comparably and that the agreement between expected and backcalculated results is very good.

**Program Selection**

Based on the results of this study it is believed that the EVERCALC v. 4.1 backcalculation program should be adopted as the backcalculation program of choice for Mn/ROAD work. Even though the performance of the EVERCALC v. 3.3 program was comparable to the others it will not be considered because it is not capable of processing batch files and the developers no longer support the program. The current version of WESDEF does not have an adequate user interface. Extra programming would be required to make it useable. In addition, there is virtually no documentation or users manual available on the software. The documentation on EVERCALC v. 4.1, however, is extensive. The program is used extensively by WSDOT personnel and is an integral part of their pavement management program.
Based upon the results presented in this report it is reasonable to conclude the following:

- For the field testing data the agreement between the WESDEF and EVERCALC v. 3.3 was the best among the programs investigated.

- The output of the MODCOMP3 program frequently became unstable during the analysis of the field data. Large RMS percent errors, unreasonable results, and long computation times were observed.

- When using the WESDEF program to model a semi-infinite subgrade the minimum recommended subgrade thickness is 30 m.

- For the simulated deflection study the agreement between expected and backcalculated stress and strain was good for all of the programs, especially for the horizontal strain in the surface (AC) layer. The agreement between stresses and strains in the underlying layers was also good.

- The use of EVERCALC v. 4.1 as a “standard” backcalculation program should be implemented (at least for Mn/ROAD and research work).
General comments regarding pavement layer modulus backcalculation and the various programs evaluated in this study are as follows:

- Backcalculation analysis using static, linear elastic theory on deflection data obtained during the spring thaw period is highly problematic. This is due to the contrast in stiffness between shallow frozen/unfrozen zones and thus deviations from the real (field) situation and assumptions implicit in the theory.

- It is not recommended that backcalculation analyses of deflection data from sections having surface layer thicknesses less that 100 mm be done. This is consistent with observations and recommendations found in the literature. An alternative approach would be to use AC modulus-temperature data from thicker test sections with similar mix characteristics to fix the thin layer modulus at a known value. The moduli of the underlying layers could then be backcalculated. Another approach might involve the use of some other parameter as the primary response transfer function input, e.g., curvature or deflection obtained directly from FWD data.

- Assumed surface layer thickness can have a dramatic effect on the backcalculation results. The effects of uncertainty of surface layer thickness on estimated strains should be investigated more formally. This could be done by performing a sensitivity analysis to determine the range of effect of assumed pavement thickness on the magnitude of backcalculated strain, for a variety of structures.
REFERENCES


Table 4.1 - Mn/ROAD test sections selected for the deflection study.

<table>
<thead>
<tr>
<th>SECTION</th>
<th>FACILITY</th>
<th>SENSORS</th>
<th>STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>ML</td>
<td>TE</td>
<td>230 (246) mm AC/ R12</td>
</tr>
<tr>
<td>17</td>
<td>ML</td>
<td>TE</td>
<td>205 (210) mm AC/ 710 mm Cl3/ R12</td>
</tr>
<tr>
<td>22</td>
<td>ML</td>
<td>LE/TE</td>
<td>205 (197) mm AC/ 460 mm Cl6/ R12</td>
</tr>
<tr>
<td>25</td>
<td>LV</td>
<td>TE</td>
<td>125 (130) mm AC/ R70</td>
</tr>
<tr>
<td>27</td>
<td>LV</td>
<td>LE/TE</td>
<td>75 (93) mm AC/ 280 mm Cl6/ R12</td>
</tr>
</tbody>
</table>

Note: ML = Mainline I-94  
LV = Low volume road  
TE = Transversal strain gage, bottom of AC  
LE = Longitudinal strain gage, bottom of AC  
All thicknesses are design values except as-built AC in parentheses (from GPR survey)

Table 4.2 - Structural data used for hypothetical sections in simulation study.

<table>
<thead>
<tr>
<th>LAYER</th>
<th>THICKNESS, mm</th>
<th>MODULUS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>75, 100, 125, 150,175, 200, 225, and 280</td>
<td>690, 3 450, and 6 895</td>
</tr>
<tr>
<td>Base</td>
<td>305, 610, and 915</td>
<td>105, 205, and 345</td>
</tr>
<tr>
<td>Subgrade</td>
<td>Semi-infinite</td>
<td>35, 105, and 175</td>
</tr>
</tbody>
</table>
Table 6.1 - Summary of modulus percent prediction errors from backcalculation program performance study.

<table>
<thead>
<tr>
<th></th>
<th>AC ERROR, percent</th>
<th>BASE ERROR, percent</th>
<th>SUBGRADE ERROR, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EVE3</td>
<td>WES</td>
<td>EVE4</td>
</tr>
<tr>
<td>Mean</td>
<td>9.9</td>
<td>-1.8</td>
<td>5.6</td>
</tr>
<tr>
<td>Median</td>
<td>5.4</td>
<td>-1.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>16.3</td>
<td>2.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Coeff. Var.</td>
<td>164.3</td>
<td>-138.3</td>
<td>115.0</td>
</tr>
<tr>
<td>Range</td>
<td>144.9</td>
<td>29.3</td>
<td>62.9</td>
</tr>
<tr>
<td>Minimum</td>
<td>-27.6</td>
<td>-12.8</td>
<td>-21.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>117.3</td>
<td>16.5</td>
<td>41.8</td>
</tr>
</tbody>
</table>

Note 1: Modulus Prediction Error = 100*(Calculated Modulus - Expected Modulus)/Expected Modulus, percent; Expected Modulus = Known modulus value used to obtain theoretical deflection data; Calculated Modulus = Modulus value obtained from results of various backcalculation programs; Coeff. Var. = Standard deviation divided by the mean value, percent.

Note 2: EVE3 = EVERCALC v. 3.3  
WES = WESDEF  
EVE4 = EVERCALC v. 4.1  
MOD3 = MODCOMP3 v. 3.6
Fig. 4.1 - Mn/ROAD test sections selected for the deflection study.
Fig. 4.2 - Locations of calculation points for simulated deflection basins and subsurface responses.
Fig. 5.1 - Comparison of AC pavement thickness determined by coring and Ground-penetrating Radar (GPR).

GPR THICKNESS = 1.009 * CORE THICKNESS

$R^2 = 0.99$

SEE = 6 mm
Fig. 5.2 - Example of experimental relationship between AC strain and modulus.
Fig. 6.1 - Comparison of backcalculated and measured transverse AC strains from TS 4: EVERCALC v. 3.3.
Fig. 6.2 - Comparison of backcalculated and measured transverse AC strains from TS 4: WESDEF.
EH1: HORIZONTAL STRAIN AT BOTTOM OF SURFACE LAYER

EVE3 STRAIN = 1.02*WES STRAIN + 3.55
R² = 0.99

EVE3 = EVERCALC v. 3.3
WES = WESDEF
EVE4 = EVERCALC v. 4.1
MOD3 = MODCOMP3

Fig. 6.3 - Comparison of backcalculated AC strains showing effects of thickness assumption and program.
Fig. 6.4 - Comparison of backcalculated and measured transverse AC strains from TS 17: EVERCALC v. 3.3.
Fig. 6.5 - Comparison of backcalculated and measured longitudinal AC strains from TS 22: EVERCALC v. 3.3.
Fig. 6.6 - Comparison of backcalculated and measured transverse AC strains from TS 22: EVERCALC v. 3.3.
Fig. 6.7 - Comparison of backcalculated and measured transverse AC strains from TS 25; EVERCALC v. 3.3.
EH1: HORIZONTAL STRAIN AT BOTTOM OF SURFACE LAYER

CALC. STRAIN = 1.75 * MEAS. STRAIN - 11.13

$R^2 = 0.96$

Fig. 6.8 - Comparison of backcalculated and measured transverse AC strains from TS 27: EVERCALC v. 3.3.
EH1: HORIZONTAL STRAIN AT BOTTOM OF SURFACE LAYER
CALC. STRAIN = 1.54 * MEAS. STRAIN - 17.16
$R^2 = 0.91$

Fig. 6.9 - Comparison of backcalculated and measured longitudinal AC strains from TS 27: EVERCALC v. 3.3.
Fig. 6.11 - Comparison of intermediate subgrade layer moduli for TS 4: WESDEF vs. EVERCALC v 3.3.
Fig. 6.12 - Comparison of subgrade layer moduli for TS 4: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.13 - Comparison of RMS error for TS 4: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.14 - Comparison of AC strain for TS 4: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.15 - Comparison of AC moduli for TS 17: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.16 - Comparison of base layer moduli for TS 17: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.17 - Comparison of subgrade layer moduli for TS 17: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.19 - Comparison of AC strain for TS 17: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.20 - Comparison of AC moduli for TS 22: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.21 - Comparison of base layer moduli for TS 22: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.22 - Comparison of subgrade layer moduli for TS 22: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.23 - Comparison of RMS error for TS 22: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.24 - Comparison of AC strain for TS 22: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.25 - Comparison of AC moduli for TS 25: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.26 - Comparison of intermediate subgrade layer moduli for TS 25: WESDEF vs. EVERCALC v. 3.3.
1994 CRREL HWD
TS 25
SUBGRADE LAYER (E3)

Fig. 6.27 - Comparison of subgrade layer moduli for TS 25: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.28 - Comparison of RMS error for TS 25: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.29 - Comparison of AC strain for TS 25: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.30 - Comparison of AC moduli for TS 27: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.31 - Comparison of base layer moduli for TS 27: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.32 - Comparison of subgrade layer moduli for TS 27: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.33 - Comparison of RMS error for TS 27: WESDEF vs. EVERCALC v. 3.3.
Fig. 6.34 - Comparison of AC strain for TS 27: WESDEF vs. EVERCALC v. 3.3.
EH1: HORIZONTAL STRAIN AT BOTTOM OF SURFACE LAYER

EVE3 = EVERCALC v. 3.3
WES = WESDEF
EVE4 = EVERCALC v. 4.1
MOD3 = MODCOMP3

Fig. 6.35 - Backcalculated vs. expected AC strains for simulated pavement sections.
SV2: VERTICAL STRESS AT MID-DEPTH OF INTERMEDIATE LAYER

EVE3 = EVERCALC v. 3.3
WES = WESDEF
EVE4 = EVERCALC v. 4.1
MOD3 = MODCOMP3

Fig. 6.36 - Backcalculated vs. expected vertical stress in base for simulated pavement sections.
Fig. 6.37 - Backcalculated vs. expected horizontal stress in base for simulated pavement sections.
EV3: VERTICAL STRAIN ON TOP OF SUBGRADE

EVE3 = EVERCALC v. 3.3
WES = WESDEF
EVE4 = EVERCALC v. 4.1
MOD3 = MODCOMP3

Fig. 6.38 - Backcalculated vs. expected vertical subgrade strain for simulated pavement sections.
Fig. 6.39 - Backcalculated vs. expected vertical stress on subgrade for simulated pavement sections.
Fig. 6.40 - Backcalculated vs. expected horizontal stress on subgrade for simulated pavement sections.