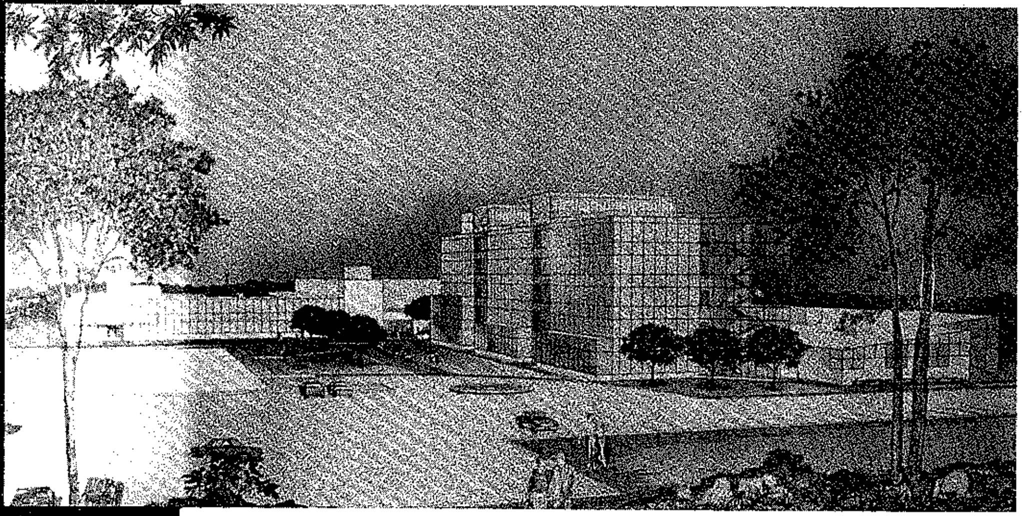
FINAL REPORT

The
University
of
Toledo

VERIFICATION OF THE ODOT OVERLAY DESIGN PROCEDURE

for

Department of Transportation, State of Ohio
and
U.S. Department of Transportation
Federal Highway Administration



College of Engineering

Civil Engineering

June 1996

1. Report No.
FHWA/OH-96/005

2. Government Accession No.

3. Recipient's Catalog No.
3 1980 00008 9827

4. Title and Subtitle
VERIFICATION OF THE ODOT OVERLAY DESIGN PROCEDURE

5. Report Date
September, 1995

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
Y. J. Chou

10. Work Unit No. (TRAIS)

9. Performing Organization Name and Address
The University of Toledo
Department of Civil Engineering
Toledo, OH 43606-3390

11. Contract or Grant No.
State Job No. 14522(0)

13. Type of Report and Period Covered
Final Report

12. Sponsoring Agency Name and Address
Ohio Department of Transportation
25 S. Front St.
Columbus, OH 43215

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The current ODOT overlay design procedure sometimes indicates additional pavement thickness is needed right after the overlay construction. Evaluation of the current procedure reveals that using spreadability to back calculate existing pavement modulus for both flexible, rigid, and composite pavements could lead to substantial errors. Spreadability value may decrease instead of increase after asphalt overlay construction. Therefore, the calculated effective thickness of the pavement is not accurate, especially for composite pavements. A modified procedure for designing AC overlay on rigid or composite pavements has been developed, where effective modulus of the pavement and modulus of subgrade reaction are back calculated from Dynaflect deflection measurements based on slab on grade theory. The old composite pavement is then compared with a new composite pavement with identical thicknesses to determine the proportional relationship between the old and new pavements. The effective PCC thickness of the existing pavement is determined based on equal-rigidity concept and an empirical ratio between new AC and PCC thicknesses. The required overlay thickness is then calculated for each deflection data point based on the AASHTO design equations. The design AC overlay thickness is calculated based on the mean and standard deviation of required AC thickness at each point and the specified reliability level. A separate procedure for designing AC overlay on flexible pavements is also included. The verification study shows that the results of these new procedures are better than or as good as that of the existing ODOT procedure.

17. Key Words
Asphalt, Concrete, Composite, Pavement, Overlay, Effective thickness, Back calculation

18. Distribution Statement
No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages

22. Price

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

FINAL REPORT

Verification of the ODOT Overlay Design Procedure

ODOT Project No. 14522(0)

Principal Investigator: Y. J. Chou

The University of Toledo

June, 1996

Prepared in Cooperation with

The Ohio Department of Transportation
and
The U.S. Department of Transportation
Federal Highway Administration

DISCLAIMER

ACKNOWLEDGMENTS

The author would like to thank the Ohio Department of Transportation and the Federal Highway Administration for supporting the study. The assistance of a number of ODOT engineers is most appreciated, especially Mr. Roger Green, Mr. Aric Morse, and Mr. William F. Edwards.

Mr. Dwayne McKinney of ODOT collected the Dynaflect deflection data for this study.

Mr. Xinming Tang, formerly a graduate research assistant at the Department of Civil Engineering, University of Toledo, made significant contribution to the data analysis and software development.

EXECUTIVE SUMMARY

Discrepancy of design overlay thicknesses based on Dynaflect deflection data taken before and after the overlay construction were found in the current ODOT overlay design procedure. The current procedure sometimes indicates substantial additional pavement thickness is needed right after the overlay construction. This discrepancy is more severe on rigid and composite pavements than on flexible pavements.

Step-by-step evaluation of the current ODOT overlay design procedure has identified several sources of errors. In particular, the practice of using spreadability to back calculate existing pavement moduli for both flexible, rigid, and composite pavements could lead to substantial errors. The current procedure assumes the spreadability would increase when pavements are strengthened by overlays. Instead, spreadability values actually decrease after asphalt overlay construction on five out of the eight pavement sections tested. As a consequence, the calculated effective thicknesses of the existing pavements are not accurate.

A new procedure for designing overlay on rigid and composite pavements has been developed. The proposed new procedure employs a simple, direct back calculation scheme, similar to the one used in the 1993 AASHTO Guide for Pavement Design, to calculate pavement elastic modulus and modulus of subgrade reaction for an existing two-layer system. The curves and equations in the 1993 AASHTO Guide were developed for deflection data collected using the Falling Weight Deflectometer device and cannot be directly used for the deflection data from Dynaflect. Similar curves and equations based on the same theory of Losberg (1960) are derived for this study so that Dynaflect data can be used. The back calculation method yields unique and stable back calculation results.

The proposed design procedure differs from the 1993 AASHTO Guide by eliminating the need to subjectively estimate existing AC layer modulus. The 1993 AASHTO Guide requires such subjective estimation because of difficulties in back calculating modulus of AC layer in a composite pavement. In the proposed procedure, however, effective modulus of the whole composite pavement is back calculated from Dynaflect deflections. From the verification results, this back calculation procedure seems to perform quite well. Moduli of pavement and subgrade seem to compensate each other, therefore, may not have significant effect on final thickness design.

An important innovation in the proposed procedure is a method for determining effective PCC thickness of existing pavement. Unlike the current method, the old composite pavement is compared with a new composite pavement with identical thicknesses to determine the proportional relationship between the old and new composite pavements. Based on the equal-rigidity concept, a exponential of 0.333 rather than 0.44 is used in the calculation of this proportion. With the help of an empirical relation between new AC and PCC thicknesses, the effective PCC thickness of the old composite pavement can be determined.

Another new feature of the proposed procedure is the application of statistical analysis in determining design overlay thicknesses. The overlay thickness is calculated for each deflection data point and the design overlay thickness is determined based on the mean, standard deviation of overlay thickness at each location and the specified reliability level. This statistical approach is employed to deal with the high variability of pavement deflections.

The verification study shows that the proposed new procedure for rigid/composite pavements works very well with hypothetical pavement cases. For actual pavement sections, the results from the new procedure are better than those obtained from the current ODOT procedure.

For overlay design on flexible pavements, a separate procedure, which is a modified version of the procedure recommended in the 1993 AASHTO Design Guide to allow use of Dynaflect deflection readings, is adopted. Design overlay thickness is determined based on statistical analysis of overlay required at every sample location. The results of this new procedures are shown to be better than or as good as that of the existing ODOT procedures.

TABLE OF CONTENTS

CHAPTER Page

1. Introduction 1
    1.1 Research Objective 2
    1.2 Outline of the Report 3
2. Evaluation of the Current Design Procedure 4
    2.1 Rigid and Composite pavements 4
    2.2 Flexible Pavements 11
    2.3 Verification with Dynaflect Data 12
3. A New Overlay Design Procedure for Composite/Rigid Pavements 18
    3.1 General 18
    3.2 Procedure Layout 19
4. Verification of the Proposed Design Procedure 26
    4.1 An Independent Approach 26
    4.2 Application on Actual Pavements 29
5. Modified Procedure for Flexible Pavements 32
    5.1 Procedure Layout 33
    5.2 Results of the Modified Procedure 44
6. Summary, Conclusions and Recommendations 47

References 50

Appendix A Back calculation Method of Composite/Rigid Pavements 51

Appendix B Verification of the Proposed Overlay Design Procedure for Composite/Rigid Pavements 61

Appendix C User's Guide for UTOVER....................76
Appendix D Output from Procedure for Flexible Pavements....................80
Appendix E FORTRAN Source Code of the UTOVER Program....................93

LIST OF TABLES

Table 1 Pavement Sections Structures and Design Traffic Data..........14

Table 2 Weather and Temperature During Testing..........15

Table 3 Summary of Dynaflect Deflection Data..........16

Table 4 Current ODOT Procedure Results..........17

Table 5 Results of New Procedure on Hypothetical Pavements..........28

Table 6 Results of New Procedure on Actual Pavements..........31

Table 7 Determination of F(z) Values..........39

Table 8 Results of Flexible Pavement Procedure Based on Actual Data..........45

Table 9 Results of Flexible Pavement Procedure Based on Increased Traffic....46

Table A1 Measured Data from Figure A1..........54

Table A2 Fitted Curves Constants..........55

Table A3 $Area - l$ Relationship..........56

Table B1 Back calculation Scheme Test Results..........71

Table B2 Thickness Design Method Test Results..........72

Table B3 Overall Procedure Test Results..........73

LIST OF FIGURES

Figure 1 New PCC Elastic Modulus vs. Effective Thickness Plot 9

Figure 2 New PCC Elastic Modulus vs. Design Thickness Plot..........................10

Figure 3 Composite Pavement Section Diagram 22

Figure 4 Determination of Effective Slab Thickness 24

Figure 5 Predicted Pavement Temperature...35

Figure 6 Temperature Adjustment Factor..37

Figure 7 Configuration of Dynaflect Loading and Deflection Sensors 39

Figure 8 F(z) versus Depth z under the First Dynaflect Sensor..........................41

Figure A1 Dynaflect Load and Deflection Sensor Configuration..........................57

Figure A2 Definition of Deflection Basin *AREA*..58

Figure A3 Nondimensional Deflection Basins for Slab on Dense Liquid Foundation...59

Figure A4 Relationship of *AREA* to *l* 60

Figure B1 KENSLABS Model for Case 1, 2 and 4 74

Figure B2 KENSLABS Model for Case 3 75

SYMBOLS AND NOTATIONS

The following symbols are used in this report:

a = Radius of assumed circular loading area load for Dynaflect

= 2.257 (in.)

A_j = Temperature adjustment factor for w_1

$AREA$ = Deflection basin area, as defined by equation A4

$AREA^*$= Nondimensional deflection basin area, as defined by equation A5

D = Flexural stiffness of slab, defined by equation A3

D_{eff} = Effective PCC thickness of existing composite or rigid pavement.

D_{new} = Effective PCC thickness of new composite pavement, defined by equation 8. (in.)

D_{req} = Required PCC thickness determined using AASHTO method. (in.)

d = Non-dimensional deflection obtained from Losberg's solution(1960)

d_i = Non-dimensional deflection at the ith geophone, defined by equation A2 (mils)

d_0 = Calculated deflection on the surface of pavement at the first geophone location. (mils)

d_p = Calculated deflection of the whole pavement above subgrade at the first geophone location. (mils)

d_s = Calculated deflection of subgrade at the first geophone location. (mils)

E_{ac} = Elastic modulus of new AC material. (psi)

E_{pcc} = Elastic modulus of new PCC material. (psi)

E_p = Back calculated effective modulus of the whole pavement above subgrade. (psi)

E_{pc} = Back calculated modulus using converted pavement thickness in the current ODOT procedure (psi)

E_{pn} = Equivalent elastic modulus of new composite pavement. (psi)

$F(z)$ = A function of depth in half space, defined in equation B2

H_{over} = Required AC overlay thickness. (in.)

$\overline{H}_{over}$ = The mean value of required AC overlay thickness. (in.)

h = $(h_{ac} + h_{pcc})$ in composite or rigid pavement. (in.)

= The whole thickness of pavement above subgrade in flexible pavement.(in.)

h_{ac} = Thickness of AC layer in existing composite pavement. (in.)

h_{pcc} = Thickness of PCC slab in existing composite or rigid pavement. (in.)

h_c = Converted pavement thickness in the current ODOT procedure (in.)

h_e = Equivalent thickness of pavement in subgrade material. (in.)

k = Back calculated dynamic modulus of subgrade reaction. (pci)

k_s = Static modulus of subgrade reaction $= 0.5\ k$ (pci)

l = Radius of relative stiffness, defined by equation A1. (inch)

M_R = Back calculated resilient modulus of subgrade. (psi)

P = Dynaflect test load = 1000 (lb)

q = Dynaflect test load pressure = 31.25 (psi)

r_i = The offset of the ith geophone from the loading center, $i = 1, 2, ..., 5$. (inch)

SN_{eff} = Effective structural number of existing flexible pavement

SN_{req} = Required structural number

SN_{over} = Required overlay structural number

s = Ratio of offset from loading center to relative stiffness radius

s_0 = Standard deviation of traffic used in AASHTO design equation

= 0.1 based on 1993 AASHTO Guide

T_a = 5-day mean air temperature before test. (°F)

T_i = Predicted pavement temperatures, defined in equation 15. (°F)

T_{mean} = Predicted mean pavement temperature. (°F)

T_p = Pavement surface temperature. (°F)

w = Calculated vertical deflection at a certain depth in a half space

w_{1a} = Adjusted w_1. (mils)

w_i = Measured surface deflection at the *ith* geophone, $i = 1, 2, ..., 5$. (mils)

v = Effective Poisson's ratio of existing composite pavement, or poison's ratio of existing rigid pavement

v_{ac} = Poisson's ratio of new AC material

v_{pcc} = Poisson's ratio of new PCC material

σ_{over} = Standard deviation of required AC overlay thickness. (in.)

CHAPTER 1

INTRODUCTION

Many existing pavements were not designed to carry the numerous repetitions of heavy axle loads common in today's traffic. As a result, many of these pavements have reached, or are rapidly approaching their design lives and in need of significant rehabilitation to increase their structural capacities. Structural overlay is the most common way of strengthening an existing pavement. It is important to design the overlay with enough thickness so the pavement would be able to carry the expected future traffic without premature failures. On the other hand, excessive thickness may require unnecessary and expensive retrofitting of bridges and drainage facilities and would take away valuable construction dollars from other competing projects.

The pavement overlay design procedure currently used by the Ohio Department of Transportation is based on the structural deficiency approach. In this approach, the required overlay thickness is based on the difference between a newly designed pavement structure over the existing subgrade and the structure of the existing pavement. The difference in structure capacity represents the theoretical structural deficiency that must be met by the overlay.

For flexible pavement, its structural capacity is expressed in terms of its Structural Number (SN); whereas for rigid and composite pavements, the structural capacity are expressed as the concrete slab thickness. Deflection measurements are often used to estimate the in-situ subgrade resilient modulus in order to determine the required structural capacity of the new pavement to carry future traffic. The "effective" structural capacity of the existing pavement may also be estimated from the measured deflections.

After the overlay has been built, pavement deflections can again be measured on the new pavement surface. These deflections may be used to back calculate subgrade and existing pavement layer moduli and determine further overlay thickness. The result should indicate that the "effective" thickness of pavement after overlay equals the pavement thickness needed for future traffic and that no further overlay is needed. However, several data sets collected by ODOT show that the "effective" thicknesses back calculated from measured surface deflections after overlay are less than the thickness required for future traffic, indicating yet more overlay is needed. This phenomenon is particularly evident in rigid and composite pavements. It is important to determine whether such discrepancies are caused by spatial variations of pavement material properties, which are random and may be accounted for statistically, or are caused by systematic errors introduced by one or more steps in the design procedure.

The 1993 AASHTO Guide to Pavement Design recommends a overlay design procedure for flexible and for rigid/composite pavements. This procedure is also based on the structural deficiency approach. However, the AASHTO procedure requires the user to estimate subjectively the effective structural capacity reduction factor based on observed distresses. The designed overlay thickness then depends on the subjective estimation. ODOT prefers that the effective thickness of the existing pavement be determined based on measured deflections. However, accurate determination of the effective thickness is not easy due to differences in performance and behavior among flexible, rigid, and composite pavements and due to lack of exact relationship between material characteristics, pavement deflections, and performance.

1.1 Research Objective

The purpose of this research study is to verify and if necessary, modify the overlay design procedure currently being used by ODOT. The verification is done by measuring Dynaflect deflections on newly overlaid pavements and calculating the required design thickness. When the calculated and actual thicknesses show discrepancies, it is evident that some steps in the current procedure, most likely the steps that determine effective thickness of an existing pavement, need to be improved to provide a more accurate effective thickness, and therefore, overlay thickness, determination.

The current procedure uses a single model, the elastic layer theory, to determine effective thickness for all three types of pavements. This increases the amount of errors and leads to inaccurate design overlay thickness. Effective thickness of rigid, flexible, and composite pavements need to be determined based on each one's specific load-deflection characteristics.

1.2 Outline of the Report

Chapter 2 comprises a detailed evaluation of the current overlay design procedure, including a verification analysis based upon Dynaflect deflection data taken from six pavements before and after the construction of an asphalt overlay one each pavement.

Based on the analysis of Chapter 2, which indicates discrepancies of design thicknesses, especially for rigid/composite pavements, exist in the current procedure, a new procedure for rigid/composite pavements is developed and is presented in Chapter 3. This new procedure is also based on the structural deficiency approach. However, it uses a back calculation method based on slab-on-grade equations which is more realistic for rigid/composite pavements than the layered elastic theory employed in the current procedure. An innovative method of calculating effective thickness of existing rigid/composite pavement is also developed. Chapter 4 describes results of verification of this new procedure based on theoretical model as well as actual data.

Chapter 5 presents the modified overlay design procedure for flexible pavements. This procedure is similar to that recommended by the 1993 AASHTO Guide for Pavement Design, but instead of deflections measured by the Falling Weight Deflectometer (FWD), deflections taken by the Dynaflect device may be used. Also, every deflection data point is used to calculate the overlay thickness required at that location. The design overlay thickness considers the variations of thickness required for the pavement section under design.

Conclusions derived from the findings of this project are offered in Chapter 6, including recommendations for further studies. Detailed analysis and the developed design software are included in a set of five appendices.

CHAPTER 2

EVALUATION OF THE CURRENT DESIGN PROCEDURE

The overlay design procedure currently used by the Ohio Department of Transportation (ODOT) was developed based on the work of Majidzadeh, et al in 1970s and early 1980s. This procedure includes back calculating existing pavement layer elastic modulus from Dynaflect deflection data, determining effective thickness of the existing pavement layer, and using AASHTO design equation to determine required asphalt concrete (AC) overlay thickness. Effective thickness of the existing pavement layer is determined solely based on the back calculated layer modulus. This approach avoids subjective evaluation of the existing pavement, but the effective thickness thus determined could be very sensitive to the back calculated layer moduli. Any errors in the back calculation scheme are confounded within the subsequent overlay design calculation. Discrepancies of required AC overlay thickness before and after the overlay construction may exist. There may be certain systematic errors within the existing overlay design procedure.

The following paragraphs summarize the current ODOT overlay design procedure. Adequate joint repair and reflective crack control actions are assumed to be taken prior to overlay.

2.1 RIGID AND COMPOSITE PAVEMENTS

The current ODOT pavement overlay design procedure for composite and rigid pavement includes the following steps:

a) Obtain deflection data using the Dynaflect device. Dynaflect applies a vibratory load on the pavement surface and uses geophone sensors to measure surface deflections at five different locations away from the load.

b) Convert existing composite pavement thickness to Portland cement concrete (PCC) pavement thickness by an AC-to-PCC factor of 2.5. Then, back calculate the modulus of subgrade reaction and the elastic modulus (E) of the converted PCC pavement. Back calculation is performed by assuming the pavement structure as a two-layer linear elastic model. Deflection measured at the outermost sensor, W5, is used to estimate the combined in-situ strength of the supporting base and subgrade. The bound pavement layer's ability to spread the load is described by a single parameter called Spreadability (SPR), defined as the summation of all five deflection sensor readings divided by five times the maximum deflection. This parameter determines the pavement layer's elastic modulus given the pavement layer's thickness and the previously determined subgrade modulus.

c) Determine equivalent PCC thickness of the existing pavement based on back calculated elastic modulus of the converted pavement. The equivalent thickness of the existing pavement is determined based on the calculated pavement layer modulus and the modulus of the new PCC material.

d) The equivalent thickness as determined in step c) is used to determine the total equivalent single axle load (ESAL) repetitions the existing pavement can carry based on the AASHTO rigid pavement design equation. This traffic volume is then used in the AASHTO flexible pavement design equation to determine the corresponding Structural Number (SN) of a flexible pavement, noted as SN_{eff}. This is taken as the effective SN of the existing pavement.

e) The required SN can be determined based on the required traffic and subgrade modulus using the AASHTO flexible pavement equation, noted as SN_{req}.

f) The AC overlay thickness can then be determined as:

$$H_{over} = \frac{SN_{req} - SN_{eff}}{a_1} \qquad (1)$$

where $a_1 = 0.35$, the assumed structural coefficient of AC overlay material.

The following comments pertaining to the above procedure highlight some likely sources for inaccuracy:

1) The composite pavement thickness is converted to an equivalent PCC thickness by dividing the AC layer thickness by a factor of 2.5 and adding it to the PCC slab thickness. The back calculation is then performed based on the converted thickness. The AC-to-PCC factor of 2.5 is an empirical value which can introduce error into the mechanistic back calculation. The above conversion alters the pavement thickness for back calculation so that it is no longer identical to the actual pavement on which deflection data were measured. Back calculation results are very much dependent upon accurate thickness input. When thickness of the pavement structure has been arbitrarily altered, back calculation procedure may not give satisfactory results.

2) Back calculation is achieved by estimating subgrade modulus directly from the last Dynaflect sensor deflection (W_5). Pavement layer modulus is then determined from multiplying the subgrade modulus to a ratio of pavement and subgrade moduli which is determined from Spreadability. The moduli ratio is very sensitive to the values of Spreadability. Any inaccuracy in estimating the subgrade modulus and the moduli ratio is multiplied and eventually leads to inaccurate pavement effective modulus estimation. Matching the whole deflection basin in back calculating pavement and subgrade moduli may yield more stable and reasonable results.

3) Since asphalt layer and concrete slab has very different structural response, using the same deflection parameter (Spreadability) to estimate the equivalent pavement modulus could yield misleading results. That is, Spreadability on asphalt layer and on concrete slab may not be comparable. When Spreadability is used indiscriminately for back calculating pavement modulus, misleading results may occur especially when comparing before and after AC overlay construction on rigid/composite pavements.

4) In determining the equivalent thickness of existing pavement, the following equation is used:

$$D_{eff} = \frac{h_c}{(E_{pcc} / E_{pc})^{0.44}} \qquad (2)$$

where h_c = converted pavement thickness

D_{eff} = effective thickness of existing pavement
E_{pcc} = elastic modulus of new PCC
E_{pc} = back calculated pavement elastic modulus using converted pavement thickness h_c

In accordance with Majidzadeh (1977), the exponential of 0.44 used in above equation was determined from dimensional analysis using layer elastic solution of a two layer system.

For two different pavement sections on the same subgrade with h_A, E_A and h_B, E_B as the corresponding pavement thickness and elastic modulus respectively in order to have equal tensile strain at the bottom of pavement layer, the following relation was found:

$$\frac{h_A}{h_B} = \left(\frac{E_B}{E_A}\right)^{0.552} \tag{3}$$

Similarly, based on equal subgrade vertical strain criterion, the following relation holds:

$$\frac{h_A}{h_B} = \left(\frac{E_B}{E_A}\right)^{0.444} \tag{4}$$

The two major failure modes for flexible pavements, caused by tensile and vertical strains respectively, correspond to two different exponential values. In general, the tensile strain seems to be the more dominant cause for flexible pavement failure. In the current design procedure, however, the exponential value corresponding to vertical strain, i.e., 0.44, is used.

For rigid pavements and composite pavements, the major cause for failure is the tensile strain underneath the bound layer. However, the above equation was derived for flexible pavements while behavior of rigid pavements is quite different from that of flexible pavements. In the current procedure, the same exponential of 0.44, is used for flexible, rigid and composite pavements, this is questionable considering the source of this value.

Based on the following theoretical derivations using the equal-rigidity concept, the exponential of 0.333 is recommended for rigid and rigid-dominated composite pavements. This value is also recommended by the 1986 AASHTO Guide for Design of Pavement Structures for rigid pavements.

For the two aforementioned pavement sections to have the same rigidity,

$$E_A I_A = E_B I_B \tag{5}$$

or

$$E_A \frac{h_A^3}{12} = E_B \frac{h_B^3}{12} \tag{6}$$

therefore,

$$\frac{h_A}{h_B} = \left(\frac{E_B}{E_A} \right)^{0.333} \tag{7}$$

5) The elastic modulus of new PCC in the existing procedure is assumed to be $3.4\text{x}10^6$ psi, which is much lower than the $5.0\text{x}10^6$ psi as used in the 1986 AASHTO Design Guide. The use of lower new PCC elastic modulus, while holding all other parameters constant, results in higher effective PCC thickness of existing pavement from equation (2) and lower required thickness from the AASHTO design equation. Eventually it yields thinner design overlay thickness. This is demonstrated in Figure 1 and 2. It can be concluded that the selection of lower new PCC elastic modulus as used by the present ODOT procedure is not a conservative approach.

6) A constant 2.5 is used as the AC-to-PCC factor in transferring AC layer thickness to the equivalent PCC thickness in evaluating composite pavement and also used in overlay design. As shown by AASHTO and many other agencies, this value may not be a constant for all situations.

7) In the present procedure, the mean or mean plus standard deviation of collected deflection data are used in the back calculation. There is a mechanistic relationship between the W_5 and spreadability for a specific

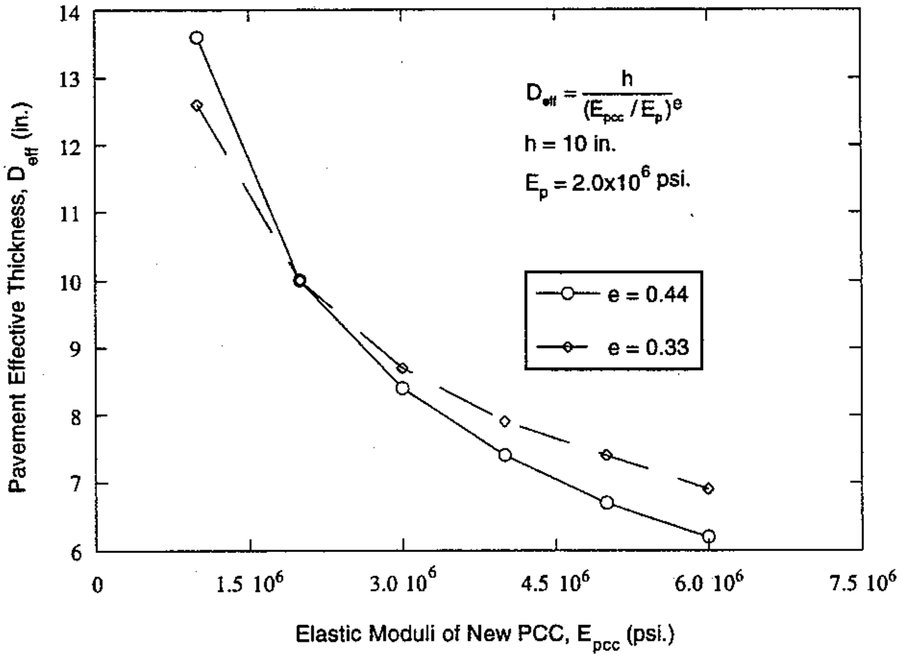


Figure 1 New PCC Elastic Modulus vs. Effective Thickness Plot

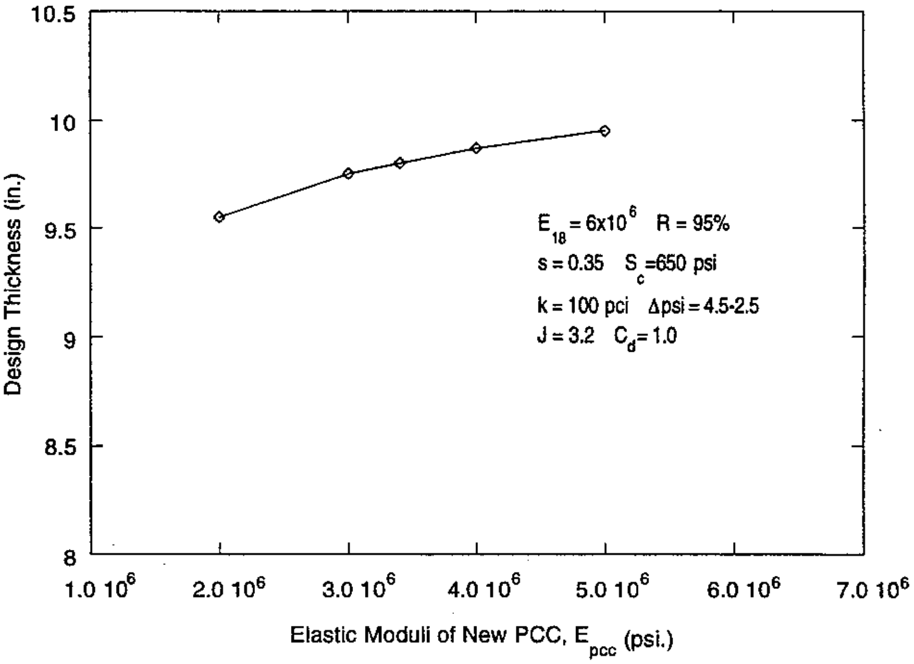


Figure 2 New PCC Elastic Moduli vs. Design Thickness Plot

deflection basin. However, it is incorrect to use this relationship for the mean or mean plus standard deviation of a set of data. Instead, the back calculation should be performed at every point and the mean or mean plus standard deviation of the back calculated moduli be used for design.

2.2 FLEXIBLE PAVEMENTS

The current overlay design procedure for flexible pavement is similar to the procedure for rigid/composite pavements except that in step b), no AC-to-PCC conversion is needed therefore the pavement thickness remains the actual total asphalt stabilized thickness and in step c) the equivalent or "effective" thickness depends on the back calculated pavement modulus and the assumed new AC modulus. The AC overlay thickness is calculated by subtracting the effective thickness from the required AC thickness for future traffic.

After evaluating the current procedure for designing asphalt concrete overlay on flexible pavements, the following statements can be made:

1) As is in the case for rigid/composite pavements, W_5 is used for estimating subgrade modulus while spreadability is used for back calculating the existing pavement modulus. This may not yield accurate enough pavement and subgrade moduli and, therefore, inaccurate effective and overlay thickness.

2) In determination of effective thickness of existing flexible pavement, the same equation (2) as used in rigid/composite pavement is used. But we know that flexible pavement behave differently from rigid or rigid-dominated composite pavement, it seems improper to use the same equation to evaluate the effective thickness of both types of pavements.

3) The design equation as recommended in the 1982 AASHTO Guide procedure is used to determine the required Structural Number (SN). This equation is rather dated and the equation in the latest edition of the AASHTO Guide should be used.

2.3 VERIFICATION WITH DEFLECTION DATA

Eight pavement sections were selected for this study. These sections include two flexible pavement sections (SR-7 and SR-11), three composite pavement sections (SR-4, I-70 and I-71) and three rigid pavement sections (SR-32, I-270-1 and I-270-2). Dynaflect deflection tests were carried out on each of these sections before and after overlay construction. The constructed overlay thicknesses were determined based on the current ODOT design procedure. Existing pavement structures of the eight selected sections, design traffic loads, and the corresponding AC overlay thicknesses are shown in Table 1. Weather and temperature conditions during Dynaflect testing are shown in Table 2. The Dynaflect deflection test results are summarized in Table 3.

As shown in Table 3, deflections taken after overlay are, as expected, always less than those taken before overlay. The current overlay design procedure, however, also assumes that the spreadability would increase after overlay indicating increased pavement structural capacity hence increased effective thickness. Unfortunately, this is not always the case as shown in the data. The Spreadability increases only on SR-11 and I-71, and slightly on I-270-2. However, on SR-4, SR-7, SR-32, I-70, and I-270-1, the spreadability actually decreases.

Evidently, the decrease in spreadability would lead to the erroneous conclusion that the equivalent modulus, hence, the effective thickness, of the pavement after overlay is less than that before overlay. The subgrade modulus, being inversely proportional to the W5 deflection reading, is always greater after overlay than before overlay because W5 always decreases after overlay.

Table 4 shows the overlay design results for the eight pavement sections using current ODOT procedure. The major problem of the current ODOT procedure is that in many instances, especially for composite pavements, after the design overlay thickness has been laid, the newly collected deflection data on the overlaid pavement indicate that an additional overlay is needed. A major objective of this research is to pinpoint and fix this problem.

The data in Table 4 indicate that the most unsatisfactory results are associate with rigid/composite pavements. As a result, much research effort has been devoted to finding a better way to represent the composite pavement structure instead of using the same layer elastic model as used for flexible pavements. A new procedure has been developed for designing asphalt concrete overlay on rigid/composite pavements. In this procedure, a two-layer system is used and all layers above subgrade are combined into one. Instead of estimating the resilient modulus of surface AC layer subjectively, as required by the 1993 AASHTO Design Guide procedure, a new, straight-forward back calculation scheme is developed based on the slab on grade theory (Losberg, 1960). Moreover, unlike the existing procedure which uses converted total thickness during back calculation, the revised procedure uses the actual thickness of the combined pavement layer for back calculation. As a result, the back calculation results of the revised procedure are more accurate than the current procedure.

A new scheme based on the equal-rigidity concept is developed in the revised procedure for determination of effective thickness of the existing composite pavement. This method eliminates the need for subjective judgment, which is required by the 1993 AASHTO Design Guide procedure, for determination of effective thickness of existing pavement.

The above improvements in back calculation and effective thickness determination make the revised overlay design procedure for composite and rigid pavements an objective procedure while maintaining the accuracy in theory and applicability for actual pavements. This is proven in the verification chapter of this report.

Another important new feature of the revised procedure is the application of statistical concept in determining overlay thickness. This makes the design overlay thickness of a section depends not only on the average but on the variability of pavement conditions to achieve a desired level of reliability.

Table 1 Pavement Sections Structure and Design Traffic Data

Section	Design E18 (millions)	Existing	Overlay
SR-4 (Montgomery County)	7.3/5.3	2.5" AC 9" JRCP subbase	4.5" AC
SR-7 (Belmont County)	1.4	2.75" AC 2.5" AC 5" bitu. aggr. base 7" agg.-lime-ash base	1.25" AC planing off*, add: 1.25" AC, type 2, AC-20 1" AC, type 2, AC-20
SR-11 (Columbiana County)	14	2.25+4" AC 6" bitu. base 8" aggr. subbase	5.5" AC (1.25+1.75+2.5)
SR-32 (Jackson County)	0.29	8" plain concrete 4" cement stab. base	1.25" AC surf., type 1, AC-20 1.75" AC inter., type 2, AC-20
I-70 (Belmont County)	36	3" AC 9" reinf. concrete 6" subbase	1" AC planing off, add: 1.25" AC, type 1, AC-20 1.75" AC, type 2, AC-20
I-71 (Richland County)	24	4" AC 10" JRCP 6" subbase	Remove 4" AC Add 5.75" AC
I-270-1 (Franklin County)	36	8" CRCP 4" bitu. aggr. base	1.25" AC, type 1, AC-20 1.75" AC, type 2, AC-20 3.25" bitu. aggr. base, AC-20
I-270-2 (Franklin County)	36	10" JRCP 6" subbase	1.25" AC, type 1, AC-20 4" AC, type 2, AC-20

* Dynaflect deflection data were taken after planing, but before overlay.

Table 2 Weather and Temperature During Testing

Section	Phase	Weather	Air Temp. (degree F)	Pavement Surface Temp. (degree F)
SR-4	Before	Cloudy	72	74
	After	Clear	39	37
SR-7	Before	Clear	34	58
	After	Cloudy	50	57
SR-11	Before	Cloudy	39	50
	After		45	43
SR-32	Before	Cloudy	29	43
	After	Clear	44	47
I-70	Before	Clear	20	41
	After	Cloudy	45	44
I-71	Before	Cloudy	60	64
	After	Cloudy	30	42
I-270-1	Before	Rain	45	42
	After	Cloudy	64	68
I-270-2	Before	Cloudy	50	46
	After	Cloudy	50	55

Table 3 **Summary of Dynaflect Deflection Data** (unit: 1 mils = 1/1000 in.)

Section/ Date	Pavement. Type	No. of Data	w_1	w_2	w_3	w_4	w_5	SPR Spreadability
SR-4	Bef. overlay	102	μ= .39	.35	.29	.25	.21	76.65
09/18/92	Composite		σ= .08	.07	.06	.05	.04	3.56
SR-4	Aft. overlay	102	μ= .34	.28	.23	.20	.15	71.34
11/18/93	Composite		σ= .08	.07	.04	.03	.03	4.02
SR-7	Bef. overlay	105	μ= .562	.469	.298	.238	.191	64.05
03/16/92	Flexible		σ= .276	.117	.081	.077	.078	6.76
SR-7	Aft. overlay	105	μ= .396	.278	.226	.186	.142	61.99
11/02/92	Flexible		σ= .094	.066	.063	.060	.054	5.59
SR-11	Bef. overlay	105	μ= .564	.421	.231	.163	.118	53.52
03/17/92	Flexible		σ= .168	.121	.067	.048	.041	4.38
SR-11	Aft. overlay	105	μ= .250	.175	.143	.105	.083	60.22
11/03/92	Flexible		σ= .080	.059	.052	.039	.032	3.95
SR-32	Bef. overlay	101	μ= .565	.512	.471	.384	.330	80.03
01/22/92	Rigid		σ= .128	.118	.114	.095	.083	3.04
SR-32	Aft. overlay	100	μ= .44	.40	.35	.30	.26	79.72
09/23/92	Composite		σ= .10	.09	.08	.07	.06	3.52
I-70	Bef. overlay	100	μ= .259	.240	.167	.147	.124	71.85
03/16/91	Composite		σ= .080	.070	.060	.057	.051	3.39
I-70	Aft. overlay	100	μ= .171	.136	.116	.105	.082	70.68
11/02/92	Composite		σ= .039	.032	.032	.032	.028	3.98
I-71	Bef. overlay	96	μ= .304	.242	.191	.165	.130	67.90
03/18/92	Composite		σ= .071	.053	.045	.044	.038	3.85
I-71	Aft. overlay	102	μ= .239	.210	.174	.147	.127	75.48
09/21/92	Composite		σ= .062	.053	.048	.039	.033	5.90
I-270-1	Bef. overlay	101	μ= .68	.55	.46	.38	.318	70.56
03/23/93	Rigid		σ= .18	.14	.12	.10	.088	5.20
I-270-1	Aft. overlay	101	μ= .33	.26	.21	.18	.11	66.30
09/21/93	Composite		σ= .04	.04	.03	.03	.02	2.27
I-270-2	Bef. overlay	101	μ= .54	.46	.39	.33	.276	73.01
03/23/93	Rigid		σ= .09	.07	.07	.07	.061	2.96
I-270-2	Aft. overlay	101	μ= .40	.35	.29	.25	.19	73.11
10/28/93	Composite		σ= .09	.09	.07	.06	.05	2.19

Table 4 Current ODOT Procedure Results

Section	E_{18} (million)	Required SN	Equiv. SN	Req. Overlay (in.)	Actual Overlay (in.)
SR4 -before1	7.3	4.21	3.94	0.78	4.5
SR4 -after1	7.3	3.86	3.24	1.76	
SR4 -before2	30	5.2	3.94	3.59	4.5
SR4 -after2	30	4.79	2.95	5.25	
SR7 -before	1.4	3.52	2.66	2.45	2.25*
SR7 -after	1.4	3.22	2.66	1.62	
SR11 -before	14	4.27	2.25	4.42	5.5
SR11 -after	14	4.25	3.96	0.83	
SR32 -before1	0.29	2.97	4.75	0.00	3.0
SR32 -after1	0.29	2.71	4.61	0.00	
SR32 -before2	30	6.0	4.75	3.57	3.0
SR32 -after2	30	5.56	4.61	2.70	
I70 -before	36	4.86	3.17	4.82	2.5**
I70 -after	36	4.61	3.40	3.46	
I71 -before	24	4.48	2.71	5.04	3.75**
I71 -after	24	4.37	3.92	1.29	
I270-1-before	36	6.11	2.98	8.93	6.25
I270-1 -after	36	4.61	2.79	5.20	
I270-2-before	36	5.75	3.18	7.32	5.25
I270-2 -after	36	5.29	3.18	6.03	

* Dynaflect test was performed after the planing off for SR7 section.

** 1 inch of removed old AC material is taken as 0.5 inch of new AC material

CHAPTER 3

A REVISED PROCEDURE FOR COMPOSITE/RIGID PAVEMENTS

3.1 GENERAL

A revised overlay design procedure for rigid and composite pavements has been developed. In this procedure, rigid pavement is considered as a special case of composite pavement with the asphalt concrete surface layer thickness, h_{ac}, equals zero. In most composite pavements, their structural behaviors are dominated by the underlying concrete slabs, unless the slabs were broken-and-seated before overlay. For most situations, it is reasonable to use the AASHTO rigid pavement design equation to determine the required pavement thickness. Currently, no unique design equation is available for composite pavements.

In this proposed procedure, the back calculation and overlay design process is carried out for each measured Dynaflect data point. The final design overlay thickness is determined based on the desired reliability level and the mean and standard deviation of required overlay thickness.

The rigid pavement design equation in the 1993 AASHTO Guide is used to determine the required pavement thickness. Among the input data required by this equation, the overall standard deviation, s_0, includes two parts of variation: the variation of traffic and the variation of pavement. In accordance with the 1993 AASHTO Guide, the traffic portion of s_0 is estimated to be about 0.1, and the pavement portion is about 0.25 for rigid pavement and 0.35 for flexible pavement. Therefore, the total standard deviation is 0.35 for rigid pavement and 0.45 for flexible pavement, respectively.

In the proposed procedure, since the design is performed for each and every measured deflection basin and the final design overlay thickness is determined using the mean and standard deviation of required overlay thickness at each point, the pavement variation is included within the procedure. The pavement variation includes all factors that influence the behavior of pavement except traffic, for example, variability of materials, environment, construction, and so on. Therefore, in using the AASHTO equation to determine the required thickness, only that portion of standard deviation related to traffic variation, i.e., 0.1, is used.

3.2 PROCEDURE LAYOUT

The revised procedure may be divided into five parts:

Part I	Back calculate effective modulus of pavement and subgrade
Part II	Determine effective thickness of existing pavement
Part III	Calculate the required new PCC pavement thickness
Part IV	Determine AC overlay thickness
Part V	Statistical inference of design AC overlay thickness

Details of these five parts are described as follows:

Part I Back calculation of E_p of pavement and k of subgrade

Based on measured Dynaflect deflection data, back calculate effective elastic modulus of the existing pavement (combine all layers above subgrade or subbase as a single layer), E_p, and modulus of subgrade reaction, k. This back calculation is performed for each and every point of deflection data collected .

A back calculation scheme is developed in accordance with the theoretical solutions of slab-on-grade developed by Losberg(1960) and Westergaard(1939). This back calculation method is similar to the one recommended in the 1993 AASHTO Design Guide. The advantages of this method includes:

1) Unlike most other back calculation programs such as CHEVDEF and MODULUS, it theoretically assures that a unique solution will be achieved. Furthermore, it is derived based on the rigid slab on grade theory and therefore is better suited for rigid or rigid-dominated composite pavements.
2) The computer time consumed for the calculation is trivial compared with CHEVDEF or MODULUS.

3) With a properly defined deflection basin parameter, *AREA*, the contribution of every deflection sensor readings, from w_1 to w_5, can be taken into account.
4) Perhaps most importantly, the back calculation results from this method seem to be at least as good as, if not better than, those of MODULUS or CHEVDEF.

Detailed derivations and calculation steps of this back calculation scheme are included in Appendix A. Outcome of this back calculation includes effective modulus of pavement layer, E_p, and dynamic modulus of subgrade reaction, k.

Part II Effective thickness of existing pavement

To determine effective thickness of an existing composite pavement, it is proposed to compare the existing pavement with a new composite pavement having the same geometry. This is more reasonable theoretically than to compare it with a new PCC pavement as in the current ODOT procedure. The two approaches give quite different results. This part can be subdivided into two steps:

1) The effective PCC thickness of the new composite pavement with h_{pcc} as the PCC slab thickness and h_{ac} as the asphalt layer thickness can be calculated as:

$$D_{new} = \frac{h_{ac}}{2} + h_{pcc} \tag{8}$$

Note that a AC-to-PCC factor of 2.0 is used to transfer new asphalt layer thickness into equivalent PCC slab thickness. This is recommended by the 1993 AASHTO Guide to convert existing composite pavement to effective PCC pavement prior to overlay design.

Effective elastic modulus of the new pavement can be determined based on the equivalent rigidity concept as illustrated below.

For a bonded two-layer system as illustrated in Figure 3 (a PCC slab overlaid by an AC layer), the rigidity of each layer can be calculated according to Huang (1993):

$$R_1 = \frac{E_{ac}\left[\frac{h_{ac}^3}{12} + h_{ac}(0.5h_{ac} + h_{pcc} - b)^2\right]}{1 - {v_{ac}}^2} \tag{9}$$

$$R_2 = \frac{E_{pcc}\left[\frac{h_{pcc}^3}{12} + h_{pcc}(b - 0.5h_{pcc})^2\right]}{1 - {v_{pcc}}^2} \tag{10}$$

$$b = \frac{\left(\frac{E_{ac}}{E_{pcc}}\right)h_{ac}(0.5h_{ac} + h_{pcc}) + 0.5{h_{pcc}}^2}{\left(\frac{E_{ac}}{E_{pcc}}\right)h_{ac} + h_{pcc}} \tag{11}$$

where R_1 = rigidity of the AC layer
R_2 = rigidity of the PCC layer
h_{ac} = thickness of AC layer
h_{pcc} = thickness of PCC slab
E_{ac} = elastic modulus of new AC material
E_{pcc} = elastic modulus of new PCC material
v_{ac} = Poisson's ratio of AC material
v_{pcc} = Poisson's ratio of PCC material

The overall rigidity of the pavement can be calculated by either

$$R_{t1} = R_1 + R_2 \tag{12}$$

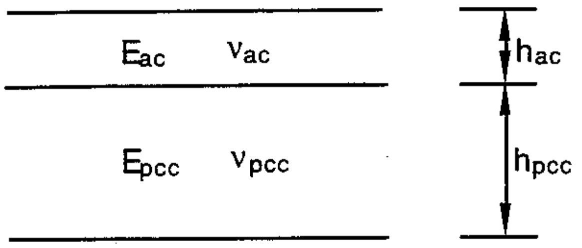
or

$$R_{t2} = \frac{E_{eff}h^3}{12(1 - v^2)} \tag{13}$$

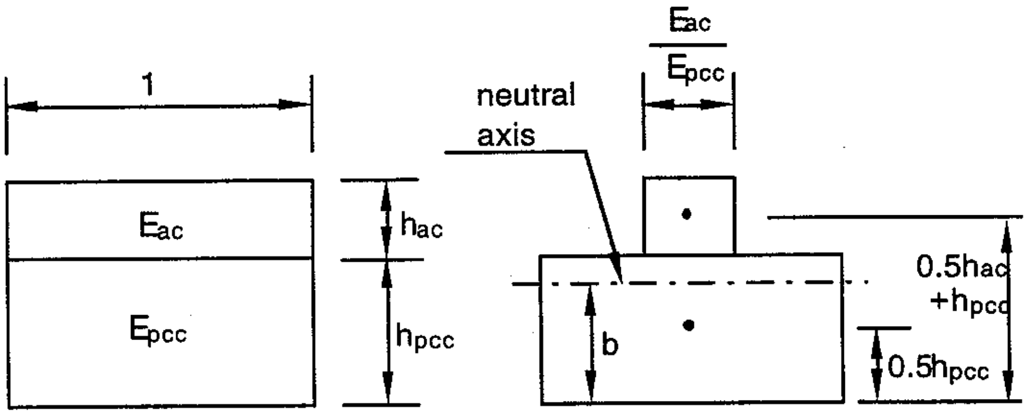
where

$$h = h_{ac} + h_{pcc}$$

$$v = \frac{v_{ac}h_{ac} + v_{pcc}h_{pcc}}{h_{ac} + h_{pcc}} \tag{14}$$



a) Original Pavement Section



b) Original versus Equivalent Section

Figure 3 Composite Pavement Section Diagram

With known layer thicknesses and elastic moduli of PCC and AC layers, the value of R_{t1} can be determined. Since

$$R_{t1} = R_{t2} \tag{15}$$

E_{eff} can be obtained by using the following equation:

$$E_{eff} = \frac{12(1-v^2)(R_1 + R_2)}{h^3} \tag{16}$$

E_{eff} is the equivalent elastic modulus of the new combined pavement layer.

2) Effective thickness of the existing pavement can be calculated by the following equation:

$$D_{eff} = \frac{D_{new}}{(E_{eff} / E_p)^{0.333}} \tag{17}$$

Derivation of the above equation is shown in Figure 4., in which the existing composite pavement is compared with a new composite pavement with the same geometric parameters, i.e., the same AC and PCC thicknesses except that the materials are all new. The thickness of existing pavement after being converted into new composite pavement material, noted as h_{eq} in step 3 of Figure 4, is calculated using a exponential of 0.333. The conversion of new composite to new PCC pavement is done using an empirical approach, i.e., the thickness of AC thickness is converted into the corresponding PCC thickness by multiplying a factor of 0.5. Finally, the effective PCC thickness of existing composite pavement is determined based on proportion relations.

Part III. Determination of required pavement thickness, D_{req}

The required pavement thickness is determined by using the 1993 AASHTO rigid pavement design equation. As recommended by AASHTO and explained in section 3.1, the standard deviation s_0 is taken as 0.1 to account for traffic variations only.

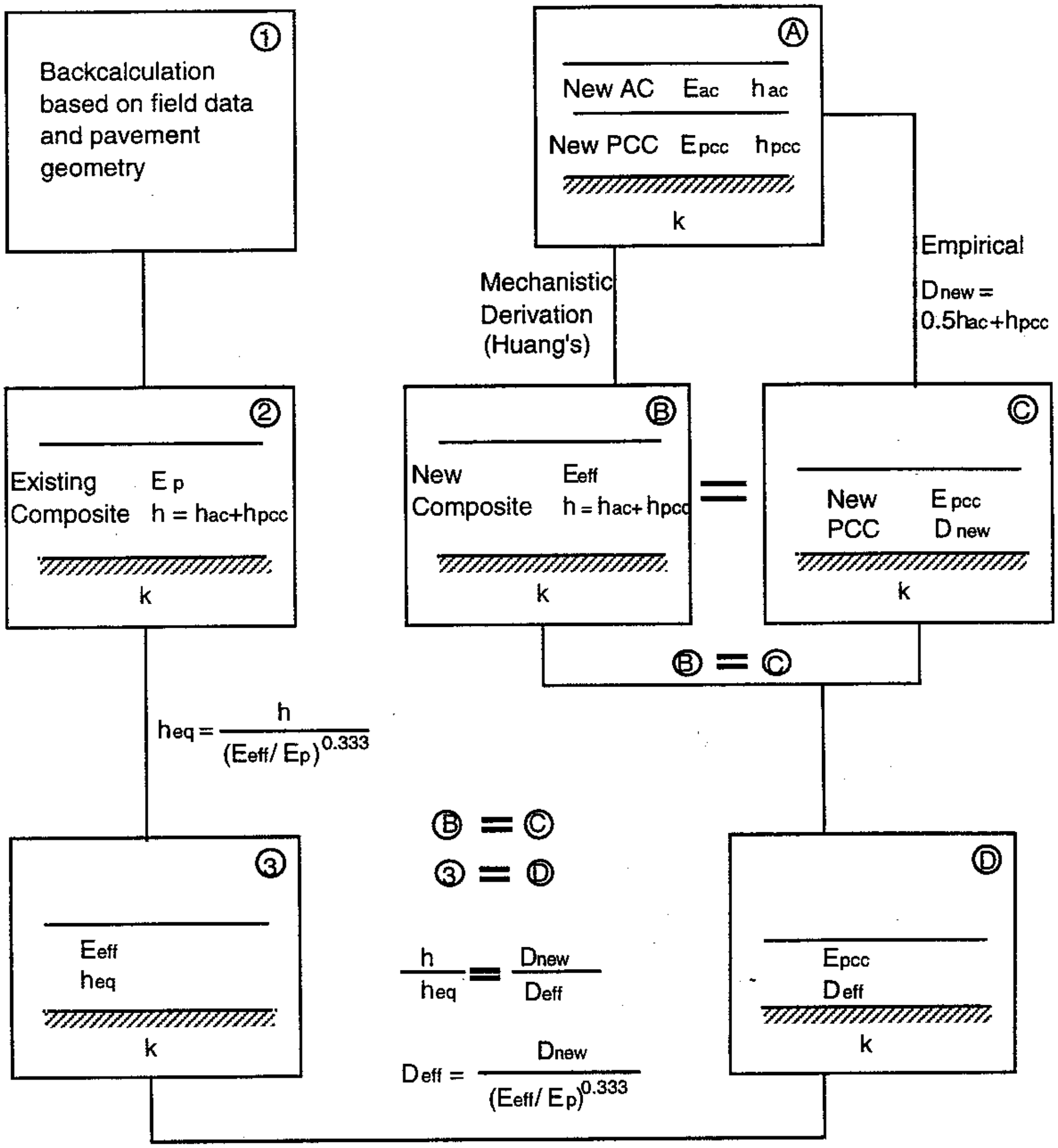


Figure 4 Determination of Effective Slab Thickness

The back calculated modulus of subgrade reaction, k, as obtained from Part I (see Appendix A for details) is a dynamic value. The AASHTO design equation requires the static modulus of subgrade reaction. According to the research results presented in the 1993 AASHTO Guide, a factor of 0.5 should be multiplied to the dynamic value to obtain the static modulus of subgrade reaction.

$$k_s = 0.5k \tag{18}$$

The reliability term, Z_R, in the 1993 AASHTO equation can be considered to represent how conservative the calculated results will be. The reliability level R, as defined in percentage, represents the probability that the designed thickness exceeds the actual required thickness. The higher the reliability, the more conservative the result will be. Value of reliability may be determined based on classification of the route as specified in AASHTO Guide.

Part IV Determination of AC overlay thickness

Required overlay thickness is calculated by:

$$\overline{H}_{over} = A(D_{req} - D_{eff}) \tag{19}$$

The AC-to-PCC factor, A, is determined as:

$$A = 2.2233 + 0.0099(D_{req} - D_{eff})^2 - 0.1534(D_{req} - D_{eff}) \tag{20}$$

Part V Statistical Calculation

The above calculation process from Part I through Part IV is carried out for each and every data point. The mean and standard deviation of the required overlay thickness can then be computed using normal statistical methods. The design overlay thickness is given as:

$$Design\ H_{over} = \overline{H}_{over} + Z_R s_{over} \tag{21}$$

where $\overline{H}_{over}$ = mean value of H_{over}
s_{over} = standard deviation of H_{over}
Z_R = reliability term, determined based on reliability level R

CHAPTER 4

VERIFICATION OF THE PROPOSED DESIGN PROCEDURE

4.1 AN INDEPENDENT APPROACH

An independent approach is employed to verify the proposed overlay design procedure for rigid and composite pavements. The overall verification scheme includes the following three parts:

1) Verifying accuracy of the back calculated pavement layer modulus and subgrade modulus of reaction;
2) Validating the thickness design method; and
3) Confirm the overall design procedure which includes both part 1) and 2).

As mentioned earlier, the proposed procedure is designed based on the configuration of a composite pavement. Rigid pavement is considered as a special case of composite pavement. However, since both the slab-on-grade theory (Losberg, 1960) and the AASHTO thickness design equation were derived for rigid pavements, they are approximations, at best, when used on composite pavements. As a result, errors may be larger for composite pavements than for rigid pavements. Three composite pavement cases and a rigid pavement case are studied for verification purpose (see Appendix B for details of these cases).

In each verification study, an hypothetical composite or rigid pavement with known geometry and material properties is defined and loaded with a hypothetical Dynaflect device. With the help of KENSLAB (Huang, 1993), a finite element program developed for rigid and composite pavement analysis, the surface deflections corresponding to the five Dynaflect geophones are calculated. With these five deflections as input, the moduli of pavement and subgrade are back calculated using the proposed procedure. The results are compared with the known original values to see how accurate the back calculation procedure is.

Similar approach is used for verifying the overlay thickness design method. With known pavement geometry and material properties, the effective PCC thickness of the existing pavement and the required total PCC thickness for an assumed traffic can be determined. After an appropriate AC overlay, its thickness determined by the thickness design method, is added to the existing pavement, the effective PCC thickness of the whole overlaid pavement is calculated and its value should be about the same as the required PCC thickness before overlay if the thickness design method works well.

In testing overall accuracy of the proposed design procedure, both errors in back calculation and in overlay thickness design method are lumped together, i.e., material properties needed to determine the effective PCC thickness of existing and overlaid pavements and the required PCC thicknesses are obtained from back calculation rather than assumed known. The new procedure is considered to be verified when the additional overlay thickness required is near zero after overlay.

Details about the verification scheme and calculation process are included in Appendix B. Table 5 summarizes the results from these case studies. Four hypothetical cases are included. Case 1 through 3 are overlays on composite pavements and case 4 is on a rigid pavement. The first (1) column in Table 5 shows the effective elastic moduli of the whole pavement above subgrade, calculated from known layer moduli, and the moduli of subgrade reaction of the existing pavement. The second (2) column gives the corresponding values back calculated from surface deflections using the proposed method. The third (3) column shows the total required PCC thickness and the effective PCC thickness after overlay using data in column one (1). The difference of the two comes from error of the thickness design method. The fourth (4) column shows the required and effective thicknesses after overlay from the overall design procedure, i.e., when data in column two (2) are used in thickness design.

The following are found from these results:

1) The back calculation method of the revised design procedure underestimates the effective moduli of pavement by about 10 percent and overestimates the moduli of subgrade reaction by about 20 percent in all the cases. These errors decrease as the dimensions of slab increase. Since the theoretical slab-on-grade solutions presented by Losberg (1960) were based on infinitely large slabs while actual pavements have limited dimensions, certain modification of Losberg's solutions may be needed to reduce the errors of back calculation.

Table 5 Verification Results Summary

Case	Effective Modulus Calculated from Known Layer Moduli (1)		Effective Modulus Back calculated from Deflections (2)		Thickness Design Only Results with Known Moduli (3)		Overall Procedure Results with Back calculated Moduli (4)	
	E_p (psi)	k (pci)	E_p (psi)	k (pci)	D_{req} (in.)	D_{eff} (in.)	D_{req} (in.)	D_{eff} (in.)
1	1089845	100	936409	124	12.92	13.09	10.78	10.36
2	855905	200	793026	239	10	10.62	10.53	10.3
3	1089845	100	993088	119.5	12.92	13.09	10.77	10.24
4	2000000	100	1845156	119.7	10	10.04	10.77	10.47

2) The errors in the overlay thickness design method range from -0.62 inches (negative value indicates effective PCC thickness after overlay is greater than the required PCC thickness) to 0.70 inches. A nearly perfect match is reached for the rigid pavement case where the error is only 0.04 inches. This overlay thickness design method is a hybrid of mechanistic and empirical approaches. Due to the scope of this study, the selection of some empirical factors, such as the structural coefficient of AC materials and the AC-to-PCC factor for new composite pavement, is mostly based on previous experience or widely accepted values without in-depth investigations. Despite such empiricism, the thickness design method of the new procedure seem to perform very well.

3) The errors of the overall design procedure are generally higher than the corresponding errors of the thickness design method, as the former also include errors of the back calculation procedure. Pavement thickness, as determined by the AASHTO design equation for rigid pavement, is not very sensitive to the value of modulus of subgrade reaction. However, effective thickness of the existing pavement is directly affected by the back calculated pavement layer modulus. Therefore, the overestimation of modulus of subgrade reaction can not fully compensate the underestimation of pavement effective modulus. The net result is the calculated thickness would be more than actually needed.

4) Despite of various possible errors in back calculation and overlay thickness design methods, the proposed overlay design procedure for composite and rigid pavements yields good match between thickness required before and after overlay.

4.2 APPLICATION ON ACTUAL PAVEMENTS

The proposed overlay design procedure for composite and rigid pavements are used for the six actual composite and rigid pavement sections shown in Table 1. A reliability of 95 percent is assumed for all sections. Design overlay thicknesses for the rigid and composite sections based on the proposed procedure are shown in Table 6. By comparing the required overlay thicknesses before and after overlay and the actual overlay thickness, results of the proposed procedure are better than the current ODOT procedure in all sections, although for some pavements (e.g., sections SR4, I70, and I270-2), the results are still not very good. The following may be contributing to the discrepancies when the procedure is used on actual pavement cases:

1) The in-situ conditions of pavements and subgrade are highly variable. The proposed procedure assumes the deflection data are obtained from relatively homogeneous section and the variations are random and normally distributed. This assumption may not hold true unless proper section delineation has been conducted.

2) Some pavement structures may conform to the slab-on-grade theory better than others. Errors in matching the measured and calculated deflection basins may be indicative of this. Inaccuracy in back calculated moduli certainly affect the calculated overlay thickness.

3) Assumptions of some empirical constants, such as the conversion factor between old and new AC layer thickness and the AC layer structural coefficient, may not be accurate enough in all cases.

Table 6 Revised Procedures Results

Section (1)	E_{18} (million) (2)	Average Required AC Overlay thickness (3)	Standard Deviation of Overlay thickness (4)	Design* AC Overlay Thickness (in.) (5)	Actual AC Overlay (in.) (6)
SR4 -before2	30	1.57	1.734	4.42	4.5
-after2	30	0.908	2.541	5.09	
SR32 -before2	30	5.182	0.377	5.803	3.0
-after2	30	2.447	0.728	3.646	
I70 -before	36	0.796	1.285	2.91	2.5**
-after	36	-3.095***	1.060	-1.351	
I71 -before	24	1.363	1.95	4.571	3.75
-after	24	-4.429	3.446	1.240	
I270-1-before	36	7.456	1.156	9.358	6.25
-after	36	3.159	0.523	4.020	
I270-2-before	36	6.230	0.575	7.175	5.25
-after	36	2.596	1.406	4.908	

* Design thickness based on an assumed 95 % reliability.

** 1 inch of removed old AC material is taken as 0.5 inch of new AC material.

*** Negative value indicates the required thickness for the design traffic volume is less than the existing thickness.

CHAPTER 5

MODIFIED PROCEDURE FOR FLEXIBLE PAVEMENTS

The updated overlay design procedure for flexible pavement basically follows the recommended procedure outlined in the 1993 AASHTO Design Guide. However, AASHTO procedure requires the use of deflection data collected by the Falling Weight Deflectometer (FWD). To make the procedure compatible with the deflection data collected by the Dynaflect device, modification of the back calculation scheme was necessary.

For flexible pavements, measured deflections typically need to be adjusted to account for difference in asphalt temperature. It was originally proposed to use a software, MASS, developed by Wolfe, et al (Wolfe, 1989) for adjusting deflection data to that corresponding to a standard temperature. However, problems arise in running the MASS program. The most troublesome is that the MASS software relies on a version of CHEVDEF to back calculate modulus of finely divided asphalt concrete layer from deflection data. Frequently, however, this back calculation routine becomes unstable and would not converge to a set of solutions. Since this routine is embedded in the MASS software which also includes other heat transfer calculations, to replace the back calculation routine requires major effort. Furthermore, many parameters not typically collected by ODOT are required to run the MASS procedure. After many unsuccessful attempts to modify the MASS program and after consultation with ODOT engineers, it was decided that a simpler method recommended by the 1986 AASHTO Guide could be used for temperature-deflection adjustment. This procedure is very similar to the one used in the current ODOT procedure.

In the revised overlay design procedure for flexible pavement, a two-layer system is used. The first layer includes the overall thickness of pavement above subgrade and the second layer represents the subgrade. Deflection w_5 is used to back calculate the subgrade resilient modulus and w_1 for the effective modulus of the first layer, the whole thickness of pavement above subgrade. The design subgrade resilient modulus is then obtained by multiplying the back calculated resilient modulus by a factor of 0.33 to account for the difference between the back calculated modulus and modulus of cored sample using laboratory testing. As shown in the research results presented in the 1993 AASHTO Guide, the back calculated subgrade resilient moduli are normally three to four times the moduli obtained from laboratory testing. The AASHTO design equation for flexible pavement is based on the laboratory testing results. Therefore, a modification factor of 0.33 or lower is employed to compensate this difference. After that, the effective modulus of the first layer is used to determine the effective structural number of the existing pavement, and the required structural number is given by 1993 AASHTO flexible pavement design equation. Finally, the required overlay thickness can be decided accordingly.

The above process is applied to every field collected data point. If we take the required overlay thicknesses for the collected deflection data as the sample from the whole pavement population, the mean and standard deviation of the sample can be used to estimate the population mean and standard deviation. Base on the calculated mean and standard deviation of the sample overlay thicknesses, we can determine the design overlay thickness using routine statistical method.

5.1 PROCEDURE LAYOUT

The revised overlay design procedure for flexible pavement is comprised of the following six parts:

Part I Temperature Adjustment of w_1

As commonly known, the mechanical properties of asphalt concrete varies with temperature. For pavement overlay design purpose, the collected deflections and back calculated properties are adjusted to a standard temperature, 68 degrees F, as recommended by AASHTO Guide. Only the temperature of surface asphalt layer change significantly with the ambient temperature. The base and subbase course are usually far away from surface and shielded by surface AC layer, and the asphalt content in these courses are less or even no asphalt content and therefore much less susceptible to temperature variation. For these reasons, it is reasonable to perform temperature adjustment based only on the thickness and temperature of the surface asphalt concrete layer. Moreover, the deflection w_5, which is the farthest measured deflection from test loads, mostly reflects the reaction of subgrade and is not susceptible to the change of mechanical properties of upper layers. Therefore, no temperature adjustment is performed for w_5.

1) Determine the Mean Temperature of Surface AC Layer

The mean temperature of the surface AC layer is calculated using the method included in the 1986 AASHTO Guide. The required input data include the pavement surface temperature, T_p, and the 5-day mean air temperature before field test, T_a. The temperature at different depths within the AC pavement can be determined from Figure 5. As recommended by 1986 AASHTO, the following scheme is used:

$$T_{mean} = \frac{T_1 + T_2 + T_3}{3} \tag{22}$$

where T_{mean} = mean temperature of AC layer
T_1 = temperature at 1 inch depth of AC layer
T_2 = temperature at mid depth of AC layer
T_3 = temperature at the bottom of AC layer

2) Temperature Adjustment Factor, A_j

The temperature adjustment factor can be determined using the curve in Figure 6. This is the curve recommended by 1993 AASHTO Guide for asphalt concrete pavement with granular or asphalt-treated base.

3) The Adjusted w_1

The deflection w_1 is adjusted by the following equation:

$$w_{1a} = A_j w_1 \tag{23}$$

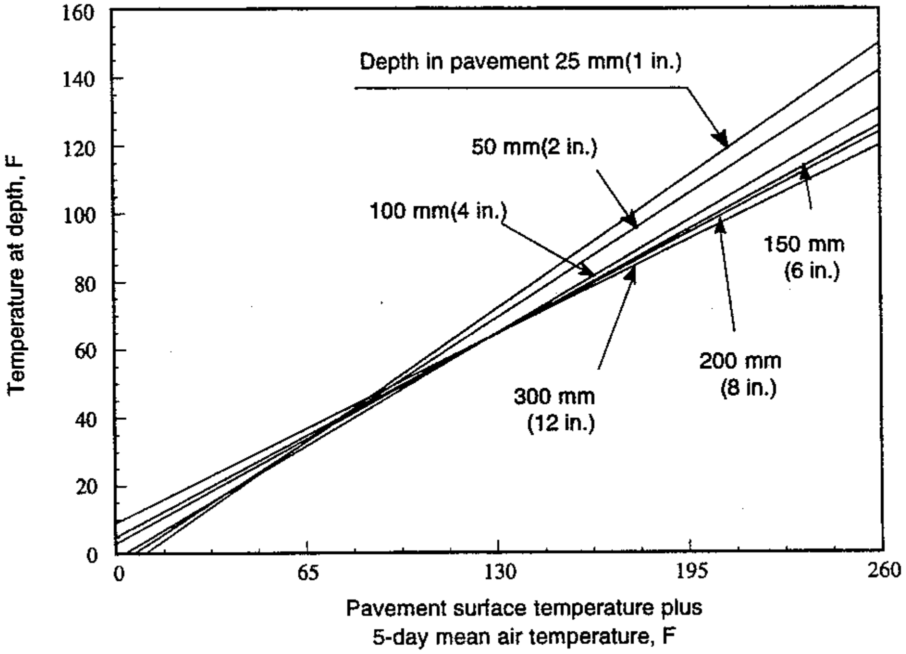


Figure 5 Predicted Pavement Temperature

(From 1986 AASHTO Guide for Design of Pavement Structures)

Part II Back calculation of E_p and M_R

A two-layer system is used to model flexible pavement in the back calculation process. In this model, the first layer comprises the whole pavement layers above subgrade while the second layer is the subgrade. The objective of back calculation is to determine effective modulus of the pavement thickness above subgrade, E_p, and the resilient modulus of subgrade, M_R.

1) Resilient modulus of subgrade, M_R

Based on Figure A1(b) and the 1993 AASHTO Guide, the subgrade resilient modulus can be calculated using the measured deflection w_5 as follows:

$$\begin{aligned} M_R &= \frac{0.24P}{w_5 r_5 / 1000} \\ &= \frac{0.24 \times 1000}{w_5 \times 49.03 / 1000} \\ &= \frac{4895}{w_5} \end{aligned} \tag{24}$$

Note that w_5 is in mils.

2) Effective modulus of pavement above subgrade, E_p

In accordance with linear elastic theory, the vertical deflection at a depth of z in a elastic half space below the first sensor in Figure A1(a) can be calculated as:

$$w = \frac{qa}{E_p} F(z) \tag{25}$$

where $w =$ deflection in inches
$a =$ 2.257 inches
$q =$ 31.25 psi
$F(z) =$ a function of z

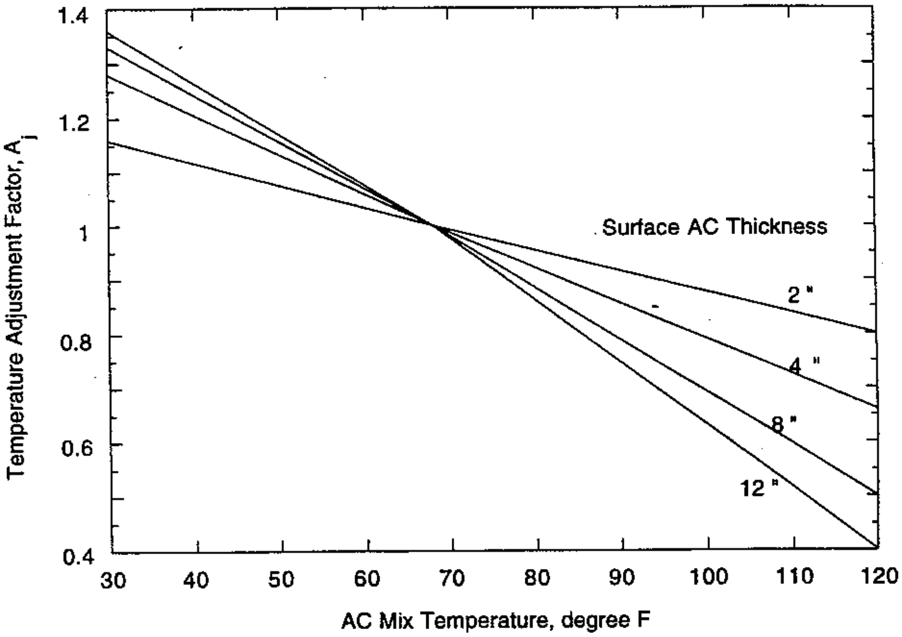


Figure 6 Temperature Adjustment Factor

(From 1993 AASHTO Guide for Design of Pavement Structures)

By using KENLAYER, a linear elastic layer computer program, to model the actual loading condition shown in Figure 7, deflections at various z coordinates can be calculated. The values of $F(z)$ are then determined and are shown in Table 7 and plotted in Figure 8. Different E values are tried in this calculation and they all resulted in very close $F(z)$ values. This is the characteristic of linear elastic theory.

The deflection at the surface, noted as d_0, is comprised of two parts: the deformation of the whole pavement thickness, noted as d_p, and the deflection of subgrade, d_s.

$$d_o = d_p + d_s \tag{26}$$

For pavement with effective modulus of E_p and thickness h, the pavement deformation is

$$\begin{aligned} d_p &= d_p(z=0) - d_p(z=h) \\ &= 1000\frac{qa}{E_P}[F(0) - F(h)] \\ &= \frac{70531}{E_P}[F(0) - F(h)] \qquad (mils) \end{aligned} \tag{27}$$

The deflection in the subgrade is calculated by transforming the two-layer system into an equivalent one-layer system of subgrade material with modulus M_R. To do so, the pavement of thickness h and modulus E_p is represented by an equivalent thickness h_e of subgrade material. The deflection at the top of the subgrade is given by:

$$\begin{aligned} d_s &= 1000\frac{qa}{M_R}F(h_e) \\ &= \frac{70531}{M_R}F(h_e) \end{aligned} \tag{28}$$

where

$$h_e = h\sqrt[3]{\frac{E_P}{M_R}} \tag{29}$$

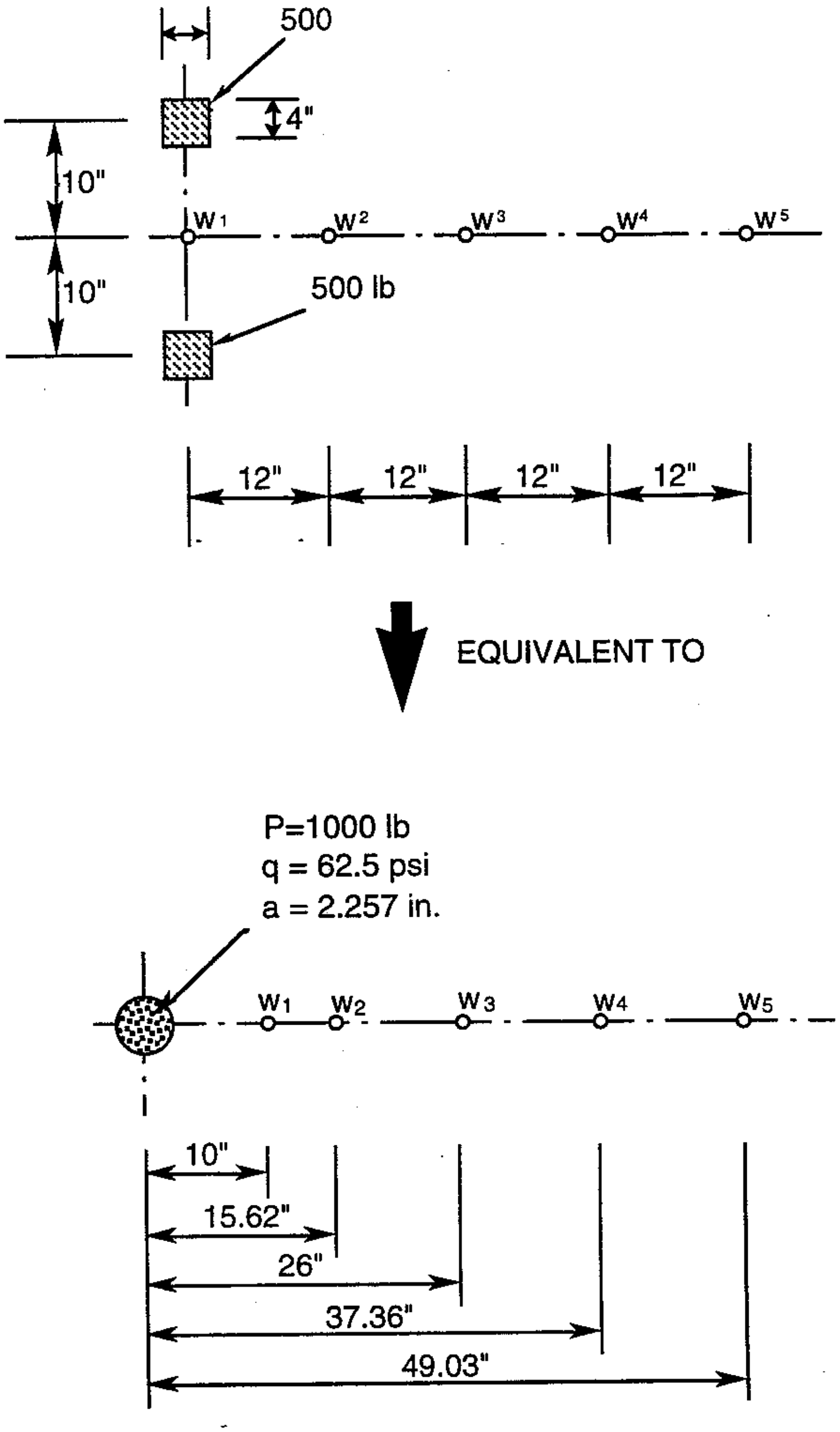


Figure 7 Configuration of Dynaflect Load and Deflection Sensors Used in Running KENLAYER

Table 7 Determination of F(z) Values

Vertical Coordinate, z (in.)	Vertical Deflection, w(z) (in.)	Function F(z)
0.0	0.00568	0.4027
2	0.00568	0.4027
4	0.00578	0.4097
6	0.00579	0.4105
8	0.00569	0.4034
10	0.00547	0.3878
12	0.00519	0.3679
14	0.00489	0.3467
16	0.00459	0.3254
18	0.00430	0.3048
20	0.00403	0.2857
24	0.00355	0.2517
28	0.00316	0.2240
30	0.00298	0.2113
35	0.00262	0.1857
40	0.00233	0.1652
60	0.00161	0.1141
80	0.00122	0.0865
100	0.00098	0.0695
1000	0.00009	0.00638

$E_P = 5000$ psi $\quad q = 31.25$ psi $\quad a = 2.257$ in.

$$F(z) = \frac{E_P w(z)}{qa} = 70.891 w(z)$$

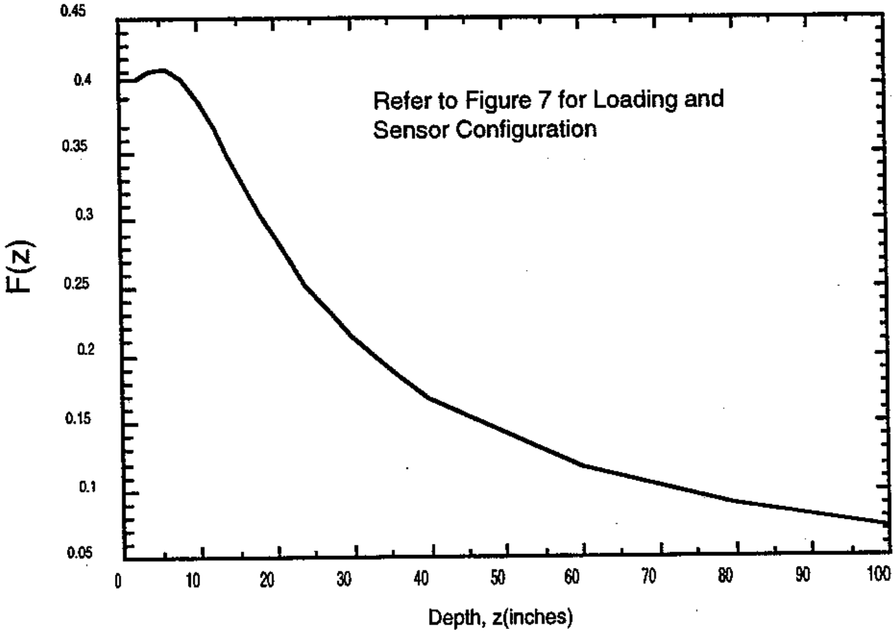


Figure 8 F(z) versus Depth z Under the First Dynaflect Sensor

Therefore,

$$\begin{aligned} d_0 &= d_p + d_s \\ &= 70531\left(\frac{F(0)-F(h)}{E_P} + \frac{F(h_e)}{M_R}\right) \end{aligned} \tag{30}$$

In equation (30), the only independent unknown variable is E_p. The other variables are either known or can be determined based on a given E_p value. By trial-and-error procedure, the effective modulus of pavement, E_p, can be determined to satisfy the following equation:

$$d_0 = w_1 \tag{31}$$

Where w_1 is the field measured deflection at the first sensor.

Part III Effective Structural Number for Existing Pavement, SN_{eff}

The effective structural number of existing pavement, SN_{eff}, is determined by the following equation as recommended by 1993 AASHTO Guide:

$$SN_{eff} = 0.0045\ h\ \sqrt[3]{E_p} \tag{32}$$

where h = total depth of pavement above subgrade
E_p = back calculated effective modulus of pavement

Part IV Required Structural Number, SN_{req}

To determine the required structural number, SN_{req}, 1993 AASHTO design equation for flexible pavement is used as if a new flexible pavement is designed. The back calculated resilient modulus for subgrade, however, must be modified before being used in the design.

In accordance with the research work conducted by AASHTO, the back calculated subgrade resilient moduli are usually much higher than the field core test results. To compensate this, a correction factor of 0.33 is recommended by

AASHTO to modify the back calculated subgrade resilient modulus to the corresponding field resilient modulus.

$$\text{Design } M_R = 0.33\, M_R \tag{33}$$

Part V Determine Overlay Thickness, D_{over}

The required overlay structural number is the difference of required structural number, SN_{req}, and effective structural number of existing pavement, SN_{eff}:

$$SN_{over} = SN_{req} - SN_{eff} \tag{34}$$

The required overlay thickness is determined as follows:

$$D_{over} = \frac{SN_{req} - SN_{eff}}{a_{o1}} \tag{35}$$

where a_{o1} is the structural coefficient for the AC overlay.

Based on 1993 AASHTO Guide, the structural coefficient for new overlay AC material should be 0.44. The revised procedure presented herein basically follows the method in the 1993 AASHTO Guide. To be consistent with the AASHTO Design Guide recommendation, an a_{ol} coefficient of 0.44 is used in the computer program. However, in current ODOT overlay design procedure, this coefficient is assumed as 0.35. A smaller a_{ol} value yields more conservative result, i.e., thicker AC overlay. The selection of structural coefficient may be modified based on findings of further research study.

Part VI Statistical Calculation

This part is the same as Part V in the composite/rigid pavement overlay design procedure. That is, required overlay thicknesses are computed at every deflection measurement. The design overlay thickness is then determined based on the mean and standard deviation of the required overlay as well as the level of desired reliability.

5.2 RESULTS OF THE NEW PROCEDURE

The revised procedure for designing overlay on flexible pavements is tested using actual data collected on two flexible pavement sections: SR7 and SR11. The results are summarized in Table 8 with detailed output listed in Appendix D. A negative overlay thickness means no structural overlay is needed, although overlay may be needed for functional improvement. As shown in Table 8, the design overlay thickness based on the modified procedure for section SR7 before overlay construction was only 0.83 inches. After an actual thickness of 2.25 inches was built, the modified procedure indicates an excess thickness of 2.16 inches. The error is 0.74 inch (2.25 minus 2.16 minus 0.83). For section SR11, the modified procedure gives an design thickness of 2.93 inches. After an 5.5-inch actual overlay, the procedure indicates there is an 3.73 inches of excess thickness. The error is 1.16 inch (5.5 minus 3.73 minus 2.93). In both cases, the results are very good considering the various assumptions and approximations made in the design procedure. A 95 percent reliability level was assumed for all design. At other reliability levels, the "errors" calculated may be slightly lower or higher than at 95% depending on the sizes of the standard deviations.

By assigning a higher traffic volume, therefore, larger ESAL numbers, the required overlay thickness can be made to be equal to that of actually constructed. Then, the deflection data collected after overlay should indicate the additional overlay thickness needed is nearly zero. This analysis is performed and the results shown in Table 9. The errors for SR7 and SR11 are 0.91 and 1.28 inch respectively.

The modified overlay design procedure for flexible pavements generates thinner design thickness than the current ODOT procedure. The verification results based on two sections-SR7 and SR11-seem to indicate reasonable match before and after overlay. Considering the fact that several steps in the design procedure, including the temperature correction and converting the Structural Number to overlay thickness, are not fully validated, the match before and after overlay is fairly good.

Table 8 Results of Modified Procedure for Overlay on Flexible Pavements Based on Actual Data

Section	E_{18} (million)	Mean AC Overlay (inch)	Standard Deviation of AC Overlay (inch)	Design Overlay (inch)	Actual Overlay (inch)	Discrepancy (inch)
SR7 (before)	1.4	-2.31	1.91	0.83	2.25	0.74
SR7 (after)	1.4	-5.06	1.76	-2.16		
SR11 (before)	14	0.55	1.45	2.93	5.5	1.16
SR11 (after)	14	-6.97	1.97	-3.73		

Table 9 Results of Modified Procedure for Overlay on Flexible Pavements Based on Hypothetical Traffic

Section	E_{18} (million)	Mean AC Overlay (inch)	Standard Deviation of AC Overlay (inch)	Design Overlay (inch)	Actual Overlay (inch)
SR7 (before)	4.5	-0.91	1.90	2.22	2.25
SR7 (after)	4.5	-3.79	1.75	-0.91	
SR11 (before)	75	2.95.	1.56	5.52	5.5
SR11 (after)	75	-4.78	2.13	-1.28	

CHAPTER 6

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

Discrepancy of design overlay thicknesses based on Dynaflect deflection data taken before and after the overlay construction were found in the current ODOT overlay design procedure. The current procedure sometimes indicates substantial additional pavement thickness is needed right after the overlay construction. This discrepancy is more severe on rigid and composite pavements than on flexible pavements.

Step-by-step evaluation of the current ODOT overlay design procedure has identified several sources of errors. In particular, the practice of using spreadability to back calculate existing pavement moduli for both flexible, rigid, and composite pavements could lead to substantial errors. The current procedure assumes the spreadability would increase when pavements are strengthened by overlays. Instead, spreadability values actually decrease after asphalt overlay construction on five out of the eight pavement sections tested. As a consequence, the calculated effective thicknesses of the existing pavements are not accurate.

A new procedure for designing overlay on rigid and composite pavements has been developed. The proposed procedure employs a simple, direct back calculation scheme, similar to the one used in the 1993 AASHTO Guide for Pavement Design, to calculate pavement elastic modulus and modulus of subgrade reaction for an existing two-layer system. The curves and equations in the 1993 AASHTO Guide were developed for deflection data collected using the Falling Weight Deflectometer (FWD) device and cannot be directly used for the deflection data from Dynaflect. Similar curves and equations based on the same theory of Losberg (1960) are derived for this study so Dynaflect data can be used. The back calculation method yields unique and stable back calculation results.

The proposed design procedure differs from the 1993 AASHTO Guide by eliminating the need to subjectively estimate existing AC layer modulus. The 1993 AASHTO Guide requires such subjective estimation because of difficulties in back calculating modulus of AC layer in a composite pavement. In the proposed procedure, however, effective modulus of the whole composite pavement is back calculated from Dynaflect deflections. From the verification results, this back calculation procedure seems to perform quite well. Moduli of pavement and subgrade seem to compensate each other, therefore, may not have significant effect on final thickness design.

An important innovation in the proposed procedure is a method for determining effective PCC thickness of existing pavement. Unlike the current method, the old composite/rigid pavement is compared with a new composite/rigid pavement with identical thicknesses to determine the proportional relationship between the old and new composite/rigid pavements. Based on the equal-rigidity concept, a exponential of 0.333 rather than 0.44 is used in the calculation of this proportion. With the help of an empirical relation between new AC and PCC thicknesses, the effective PCC thickness of the old composite/rigid pavement can be determined. The same method can also be used to determine the effective thickness of existing concrete pavement for, say, design of unbonded concrete overlay.

Another new feature of the proposed procedure is the application of statistical analysis in determining design overlay thicknesses. The overlay thickness is calculated for each deflection data point and the design overlay thickness is determined based on the mean, standard deviation of overlay thickness at each location and the specified reliability level. This statistical approach is employed to deal with the high variability of pavement deflections.

The verification study shows that the proposed new procedure for rigid/composite pavements works quite well with hypothetical pavement cases. For actual pavement sections, the results from the new procedure are better than those obtained from the current ODOT procedure.

For overlay design on flexible pavements, a separate procedure, which is a modified version of the procedure recommended in the 1993 AASHTO Design Guide, is adopted. Design overlay thickness is determined based on statistical analysis of overlay required at every sample location. The results of this new procedures are shown to be better than or as good as that of the existing ODOT procedures.

To obtain satisfactory design results, the following implementation suggestions are provided:

1) In delineating pavement sections, only pavement with the same geometry and similar subgrade conditions should be included in the same section. The design overlay thickness is determined based on the calculated mean and standard deviation of overlay thicknesses for all data points. The mean and standard deviation values should reflect the average and variability of a substantially uniform pavement.

2) Since design values are determined using statistical method, the more deflection data obtained from the design section, the higher the reliability achieved. Deflection data should be collected uniformly along the length of pavement section.

3) As mentioned earlier, accurate information about the structures of existing pavement is vital to accurate overlay design. If needed, field coring should be conducted to verify pavement structural information.

Verification results show the proposed procedures produce good results for most cases. These procedures, however, are not perfect. For further improvements, the following studies are recommended:

1) Modify the Losberg slab-on-grade solution for actual pavement conditions. Losberg's solution was developed for rigid slab with infinite dimensions. The actual pavements all have finite dimensions and have different boundary conditions. The verification work of this study shows that using the solution based on infinite dimensions results in back calculating lower pavement layer modulus and higher modulus of subgrade reaction than actual values. Proper modification of the theory may solve this problem.

2) Determine AC materials layer structural coefficient and AC-to-PCC conversion factor for new composite pavements. Currently, in the proposed procedure, these two parameters are selected based on empirical experience rather than rigorous investigation. They may contribute to errors in the

designed overlay thickness. A study is being conducted to more accurately determine AC materials layer structural coefficients.

3) The proposed new procedures do not consider reflective cracking which must be controlled by either a crack relief layer or sawing and sealing above each existing transverse joint after overlay. Effectiveness of these measures and their effects on pavement life should be understood, since they could change the required overlay thickness.

4) The back calculated effective thickness of rigid/composite pavement and modulus of subgrade reaction may be used for purposes other than designing asphalt overlay. For example, the U.S. Corps of Engineers procedure for designing unbonded concrete overlay on PCC pavements requires thickness of the existing pavement and a condition factor to quantify its structural conditions. The back calculated effective thickness, being less subjective, may be used instead. However, to fully understand the implication of such substitution, more study may be needed.

5) The back calculated subgrade modulus of reaction may also be used, at least as a first estimate, to determine subgrade soil strength for purposes such as designing rubblerized or break-and-seat pavements. However, since the structural behaviors and failure modes of these pavements are quite different from those of concrete or composite pavements, thickness design procedure developed here should not be used without further investigations.

REFERENCES

AASHTO. (1986). AASHTO Guide for Design of Pavement Structures 1986, American Association of State and Highway Transportation Officials, Washington, D.C.

AASHTO. (1993). AASHTO Guide for Design of Pavement Structures 1993, American Association of State and Highway Transportation Officials, Washington, D.C.

Barenberg, E.J. and Petros, K.A. (1991). "Final Summary Report Evaluation of Concrete Pavements Using NDT Results."

Houston, W.N. and Mamlouck, M.S. and Perera, R.W.S. (1992). "Laboratory Versus Nondestructive Testing for Pavement Design." Journal of Transportation Engineering, ASCE, 118(2), 207-222.

Huang, Y.H. (1993). Pavement Analysis and Design, Prentice-Hall Publisher.

Ioannides, A.M. (1988). "Dimensional Analysis in NDT Rigid Pavement Evaluation." Journal of Transportation Engineering, ASCE, July, 1988

Losberg, A. (1960). "Structural Reinforced Concrete Pavements", Doktorsavhandlingar Vid Chalmers Tekniska Hogskola, Goteborg, Sweden, 1960.

Majidzadeh, Kamran (1977). "Pavement Condition Evaluation Utilizing Dynaflect Deflection Measurement", Final report to the Ohio Department of Transportation.

Majidzadeh, K. and Kumar, V. (1983). "Manual of Operation and Use of Dynaflect for Pavement Evaluation", Ohio Department of Transportation.

Monismith, C.L. and Finn, F.N. (1984) "Overlay Design–A Synthesis of Methods." Symposium on Asphalt Concrete Overlays: Theory and Practice, Association of Asphalt Paving Technologies, 217-266.

Vesic, A.S. and Saxena, S.K. (1970). "Analysis of Structural Behavior of AASHO Road Test Rigid Pavements", National Cooperative Highway Research Program Report 97, Highway Research Board, National Research Council.

Westergaard, H.M. (1939). "Stresses in Concrete Runways of Airports", Proc., 19th Annual Meeting, Highway Research Board, Washington D.C., 197-202.

APPENDIX A

BACK CALCULATION METHOD OF COMPOSITE/RIGID PAVEMENT

The following method is based on the theory for slab-on-grade developed by Losberg(1960), Westergaard(1926, 1939) and Ioannides(1988). Strictly speaking, this back calculation scheme can only be applied to rigid pavements. However, since most composite pavements are rigid-dominant, i.e., the rigidity of PCC slab far exceeds the rigidity of AC layer, and the response of composite pavement is much closer to rigid than to flexible pavement, this method may therefore be used as an approximation for composite pavements.

While this back calculation method may be applied to both composite and rigid pavement, the following derivation is carried out for rigid pavement only. The method is subdivided into the following two parts.

1) Generation of the *AREA* versus relative stiffness (l) Curve

Consider a rigid slab sitting on a dense liquid foundation. Based on Westergaard(1939), the radius of relative stiffness of the slab, l, is defined as:

$$\ell = \left(\frac{E_p h^3}{12(1-\mu^2)k} \right)^{1/4} \qquad (A1)$$

Based on Losberg(1960), the non dimensional deflection at sensor i is defined to be:

$$d_i = \frac{w_i \mathcal{D}}{P\ell^2} \qquad (A2)$$

Where the flexural stiffness of the slab is:

$$\mathcal{D} = \frac{E_p h^3}{12(1-\mu^2)} \qquad (A3)$$

The arrangement of deflection sensors is shown in Figure A1(a), which is equivalent to the arrangement of Figure A1(b). We define

$$AREA = \frac{1}{w_1}(2.81w_1 + 8.0w_2 + 10.87w_3 + 11.515w_4 + 5.835w_5) \qquad (A4)$$

as shown in Figure A2 and

$$AREA^* = \frac{1}{\ell}(2.81d_1 + 8.0d_2 + 10.87d_3 + 11.515d_4 + 5.835d_5) \qquad (A5)$$

From equation A2 we have

$$\frac{d_1}{w_1} = \frac{d_2}{w_2} = \frac{d_3}{w_3} = \frac{d_4}{w_4} = \frac{d_5}{w_5} = \frac{\mathcal{D}}{P\ell^2} \qquad (A6)$$

or

$$d_i = \frac{d_1}{w_1} w_i \qquad i = 1,2,3,4,5 \qquad (A7)$$

Substitute equation A7 into equation A5 and compare with equation A4, we have

$$AREA = \frac{\ell}{w_1} AREA^* \qquad (A8)$$

The solution for the non dimensional deflections which was developed by Losberg(1960) is plotted as shown in Figure A3.

In the case when Dynaflect is used to collect deflection data, the load radius and the offsets of the five deflection sensors are:

$a = 2.257$ (inch)
$r_i = 10, 15.26, 26, 37.36, 49.03$ (inch) for i = 1, 2, 3, 4, 5

Assuming a value for l with above data for a and r_i, the non dimensional deflections d_1 through d_5 can be determined by using Figure A3. $AREA^*$ can then be calculated by equation A5 using known l and d_i and finally the term $AREA$ is determined using equation A8.

As many as desired number of data point showing the relationship between $AREA$ and l can be determined by assuming different l values and go through the above calculation process.

For the convenience of calculation, curve-fitting technique is used to incorporate the curves in Figure A3 into a computer program to calculate $AREA$ for any arbitrary assumed l value. The measured data from Figure A3 are shown in Table A1.

The fitted curves for the above data are in the form of

$$d = A + Bs + Cs^2 + Ds^3 + Es^4 + Fs^5 \qquad (A9)$$

in which A, B, C, D, E and F are constants as shown in Table A2.

The calculated data points for $AREA^* - l$ relationship are shown in Table A3. It is also plotted in Figure A4.

2) Determination of E_p and k

By definition(equation A2), we have:

$$d_1 = \frac{w_1 \mathcal{D}}{P\ell^2} = \frac{w_1}{P\ell^2} \frac{E_p h^3}{12(1-\mu^2)} \qquad (A10)$$

hence,

$$E_P = \frac{12P\ell^2(1-\mu^2)}{h^3} \frac{d_1}{w_1} \qquad (A11)$$

using the method in Part 1 of this appendix.

For the calculation of k, by equation A1 and A3, we have

$$\mathcal{D} = \ell^4 k \qquad (A12)$$

So

$$d_1 = \frac{w_1 \mathcal{D}}{P\ell^2} = \frac{w_1 \ell^4 k}{P\ell^2} \qquad (A13)$$

or

$$k = \frac{d_1}{w_1} \frac{P}{\ell^2} \qquad (A14)$$

Based on the back calculation results about l, d_1 from Part 1 of this appendix, E_p and k can be determined independently using equation A11 and A14.

Table A1 Measured Data from Figure A1

	$a/l = 0.0$	$a/l = 0.5$	$a/l = 1.0$	$a/l = 2.0$	$a/l = 3.0$
$s = r/l$	d	d	d	d	d
0	0.125	0.114	0.096	0.063	0.038
0.25	0.12	0.110	0.094	0.062	0.038
0.5	0.109	0.102	0.088	0.060	0.037
0.75	0.094	0.091	0.081	0.057	0.036
1.0	0.080	0.080	0.072	0.054	0.035
1.5	0.056	0.056	0.052	0.044	0.032
2.0	0.035	0.035	0.035	0.032	0.028
2.5	0.020	0.020	0.020	0.022	0.022
3.0	0.010	0.010	0.010	0.013	0.016
3.5	0.005	0.005	0.005	0.007	0.010
4.0	0.000	0.000	0.000	0.004	0.006
4.5	-0.001	-0.001	-0.001	0.001	0.003
5.0	-0.002	-0.002	-0.002	0.000	0.002

Table A2 Fitted Curves Constants

	$a/l = 0.0$	$a/l = 0.5$	$a/l = 1.0$	$a/l = 2.0$	$a/l = 3.0$
A	0.12592	0.11399	$9.5961\text{x}10^{-2}$	$6.2771\text{x}10^{-2}$	$3.8249\text{x}10^{-2}$
B	$-1.9334\text{x}10^{-2}$	$-5.8421\text{x}10^{-3}$	$1.2830\text{x}10^{-4}$	$4.1902\text{x}10^{-4}$	$-3.2254\text{x}10^{-2}$
C	$-4.4026\text{x}10^{-2}$	$-4.6153\text{x}10^{-2}$	$-3.7181\text{x}10^{-2}$	$-1.1447\text{x}10^{-2}$	$2.4954\text{x}10^{-3}$
D	$2.2903\text{x}10^{-2}$	$2.1074\text{x}10^{-2}$	$1.5007\text{x}10^{-2}$	$1.3215\text{x}10^{-3}$	$-3.0040\text{x}10^{-3}$
E	$-4.3265\text{x}10^{-3}$	$-3.6447\text{x}10^{-3}$	$-2.3239\text{x}10^{-3}$	$3.7434\text{x}10^{-4}$	$7.1804\text{x}10^{-4}$
F	$2.9147\text{x}10^{-4}$	$2.2743\text{x}10^{-4}$	$1.3040\text{x}10^{-4}$	$-5.6973\text{x}10^{-5}$	$-4.9843\text{x}10^{-5}$

Table A3 *AREA* -- *l* Relationship

l (in.)	*AREA*(in.)	l(in.)	*AREA*(in.)
10	10.628	60	34.598
15	16.989	65	35.061
20	21.865	70	35.447
25	25.438	75	35.773
30	28.032	80	36.052
35	29.941	85	36.291
40	31.376	90	36.499
45	32.479	95	36.681
50	33.345	100	36.841
55	34.036		

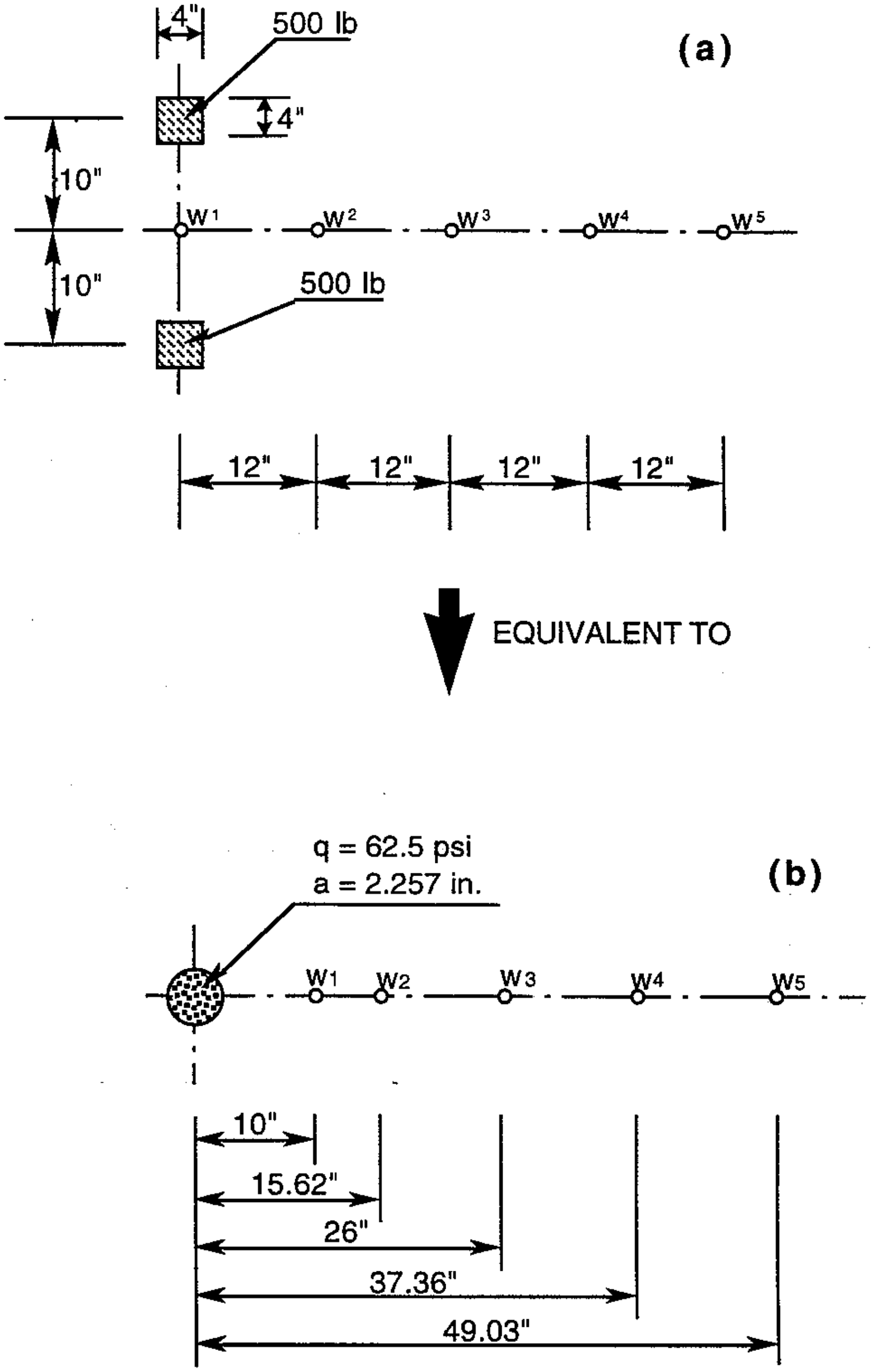


Figure A1 Dynaflect Test Diagram

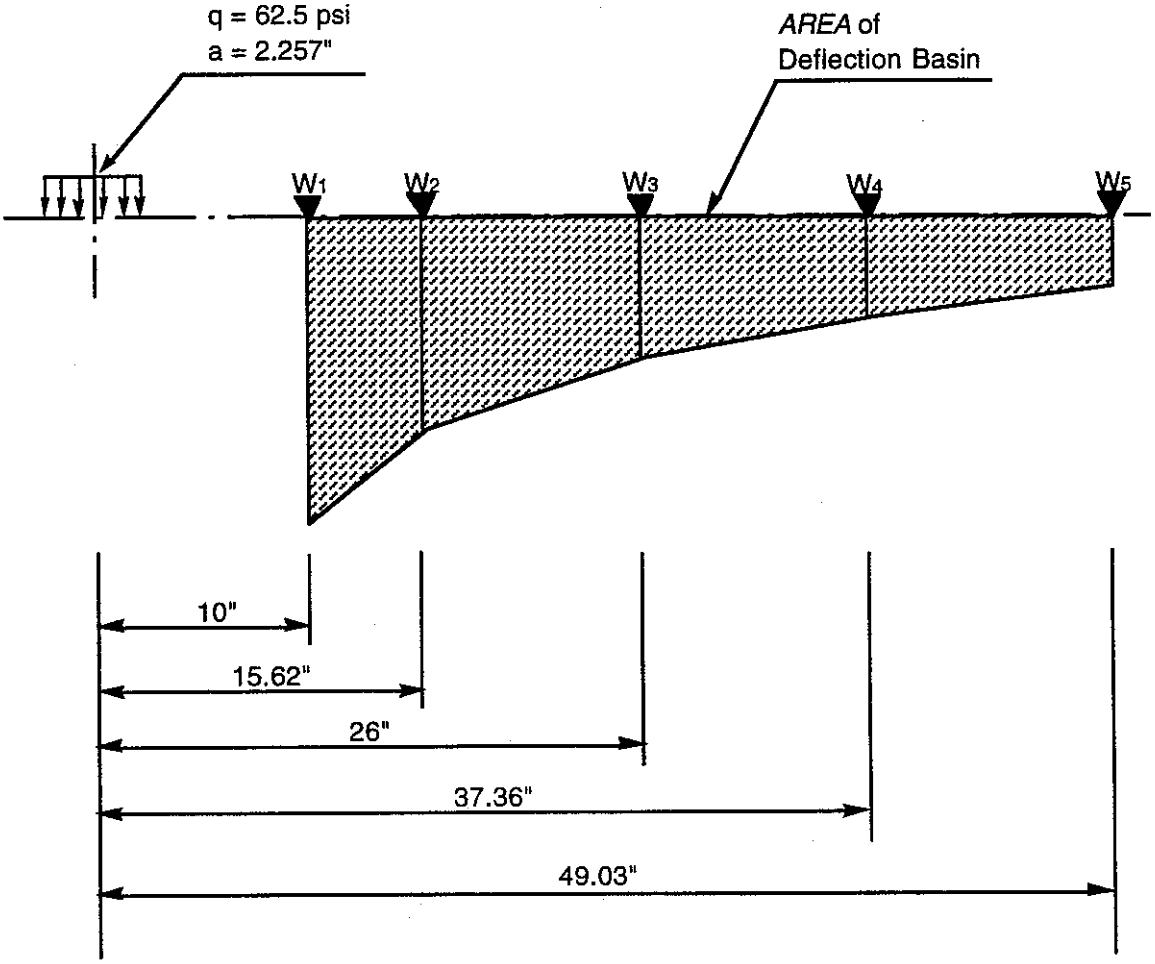


Figure A2 Definition of Deflection Basin *AREA*

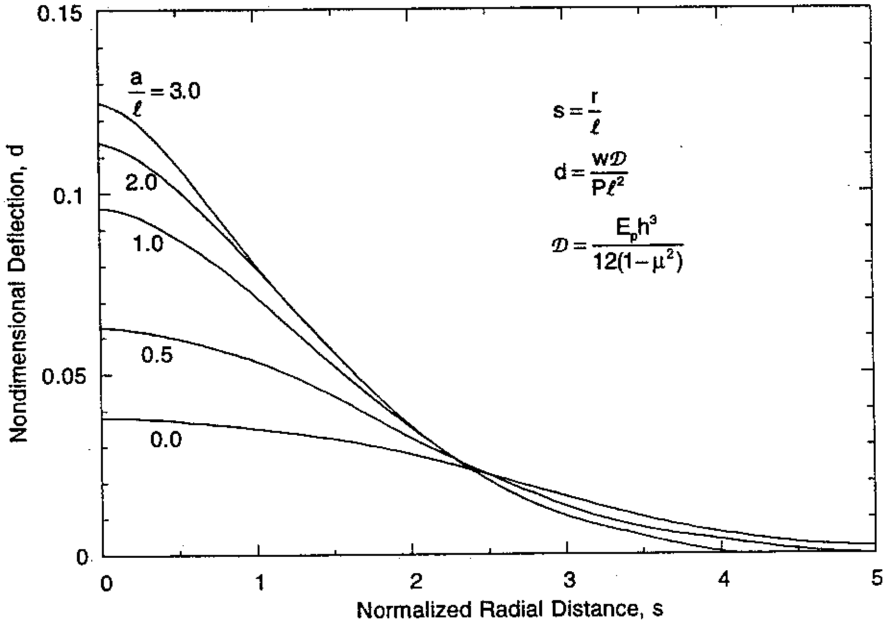


Figure A3 Nondimensional Deflection Basins for Slab on Dense Liquid Foundation
(Follows Losberg 1960)

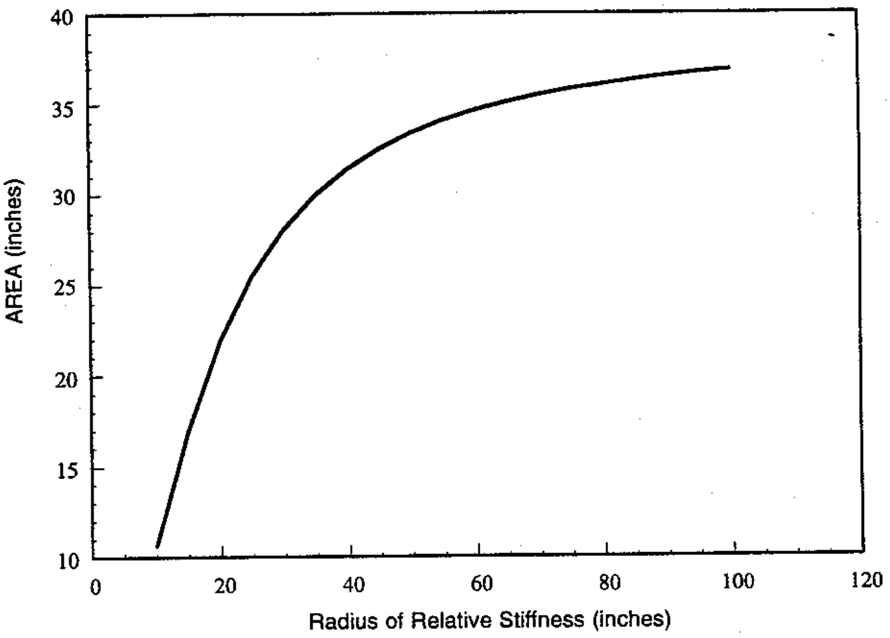


Figure A4 Relationship of AREA to ℓ

APPENDIX B

VERIFICATION OF THE NEW OVERLAY DESIGN PROCEDURE FOR COMPOSITE/RIGID PAVEMENTS

To verify the revised overlay design procedure for composite/rigid pavements, an independent approach is employed as follows:

1) Define an old composite pavement with known pavement thicknesses, elastic moduli and subgrade reaction modulus.

2) Calculate the pavement surface deflections corresponding to the five geophone locations in Dynaflect test under the same load as of Dynaflect test. These five deflections can be considered as the predicted field deflections using Dynaflect device. This step is carried out using KENSLABS, a finite element program for rigid/composite pavement analysis.

3) With the known parameters of the old pavement, we can calculate the effective elastic modulus of the whole pavement using equation (3) through (9), noted as E_{P1}.

4) With the deflections from step 2), as well as the geometry of the old pavement, the effective elastic modulus of the whole pavement and the modulus of subgrade reaction can be determined using the back calculation scheme of the revised composite/rigid pavement overlay design procedure, noted as E_{P2} and k_2.

5) We can compare the values of E_{P1} and E_{P2}, the known k_1 value and back calculated k_2 to determine how accurately the revised procedure performs in back calculation.

6) The second part of verification is to test the accuracy in overlay thickness design of the revised procedure. With known parameters of the old pavement, we can design an overlay on it. After the overlay is laid on the old pavement, the effective elastic modulus of the whole pavement can be calculated and the overlay thickness can be determined. Ideally, the overlay thickness required for the overlaid pavement should be very close to zero, i.e., no more overlay is needed. This part of test can tell us how well the revised procedure works on the overlay thickness design.

7) Finally, we want to validate the whole revised procedure. Following step 4), the overlay thickness for the old pavement can be determined, noted as H_{over1}. After this thickness of overlay is laid on the old pavement, step 2) and 3) are repeated to determine the effective elastic modulus of the pavement after overlay. Then the required overlay thickness on the overlaid pavement can be determined, noted as H_{over2}. Again, this H_{over2} value should be close to zero.

8) The above validation process from step 1) to 7) is also performed on a rigid pavement case to test the performance of the revised procedure for rigid pavement. Hopefully, the results for rigid pavement cases would be better than those of composite pavement cases.

CASE 1 Composite pavement 1

Geometry(Refer to Figure 3 for typical composite pavement section)

1 AC layer $h_{ac}=4''$ $E_{ac}=2\times10^5$ psi $\nu=0.35$

2 PCC slab $h_{pcc}=8"$ $E_{pcc}=3\times10^6$ psi $\nu=0.15$

The effective elastic modulus of the whole pavement determined using equation 3 through 9 is:

E_{P1} = 1,089,845 psi

Subgrade reaction modulus, k_1 = 100 pci
Traffic, E_{18} = 30 million
Reliability, R = 95 %

Part 1 Test of back calculation scheme

With the finite element model shown in Figure B1, in which AC layer and PCC slab are modeled as two bonded layers, the calculated deflection basin is:

$w_1, w_2, ..., w_5$ = 0.8708, 0.8181, 0.6996, 0.5636, 0.4351 mils

Based on the above deflection basin, the back calculated elastic modulus of pavement and subgrade reaction modulus using the method in the revised procedure are:

E_{P2} = 936,409 psi
k_2 = 124.04 pci

Theoretically, E_{P2} should be equal to E_{P1} and k_2 be equal to k_1. We can see that the revised procedure underestimates the effective elastic modulus of the whole pavement by about 14 percent but overestimates the modulus of subgrade reaction by about 24 percent in this case.

Part 2 Test of overlay thickness design method

In this part of study, presumed moduli about pavement and subgrade are used to test the accuracy of overlay thickness design method of the revised overlay design procedure.

BEFORE OVERLAY

The effective modulus of old pavement is:

E_{P1} = 1,089,845 psi

From equation (2), the effective thickness of the new composite pavement with the same geometry is:

$D_{new} = 8 + 0.5\times4 = 10$ in.

Effective modulus of the new composite pavement is determined using new material properties (E_{ac} = 45,000 psi, E_{pcc} = 5000,000 psi) as:

E_{eff} = 1,928,175 psi

The effective thickness of old composite pavement is calculated using equation (10):

D_{eff} = 8.27 in.

The required thickness is calculated using AASHTO equation with known traffic and subgrade reaction modulus:

$$D_{req} = 12.92 \text{ in.}$$

The AC-to-PCC factor, A, as determined by equation (13), is

$$A = 1.724$$

The design asphalt concrete overlay thickness is

$$\begin{aligned} H_{overl} &= 1.724 \text{ x } (12.92 - 8.27) \\ &= 8.02 \text{ in.} \end{aligned}$$

Use 8.0 inches as the asphalt overlay thickness.

AFTER OVERLAY

Geometry of pavement:

AC layer	8"	$4.5\text{x}10^5$ psi (new material)
AC layer	4"	$2.0\text{x}10^5$ psi
PCC slab	8"	$3.0\text{x}10^6$ psi

Calculation results are:

E_{P2} = 941,730 psi (effective modulus of pavement)
E_{eff} = 1,151,016 psi
H_{pcc} = 14 in.
D_{eff} = 13.09 in

We can see that the effective thickness of the pavement after overlay, 13.09, is very close to the required thickness, 12.92. From this case study, it seems that the overlay thickness design method of the revised procedure works very well.

To show that the correctness of overlay thickness method holds for any amount of traffic, the following additional tests are performed.

a) Assuming that D_{req} = 10" (corresponding to different traffic from above)

BEFORE OVERLAY

E_{P1} = 1,089,845 psi (effective modulus of old pavement)
E_{eff} = 1,928,175 psi (effective modulus of new pavement)
D_{new} = 10 in.
D_{eff} = 8.27 in
A = 1.988
H_{over} = 3.44"

AFTER OVERLAY

Geometry	AC	3.44"	450,000 psi	0.35

AC	4"	200,000 psi	0.35
PCC	8"	3,000,000 psi	0.15

E_{P2} = 963,905 psi (effective modulus of old pavement)
E_{eff} = 1,359,691 psi (effective modulus of new pavement)
D_{new} = 11.72 in.
D_{eff} = 10.45 in
H_{over} = 0

b) Assuming that $D_{req} = 15"$

BEFORE OVERLAY

E_{P1} = 1,089,845 psi (effective modulus of old pavement)
E_{eff} = 1,928,175 psi (effective modulus of new pavement)
D_{new} = 15 in.
D_{eff} = 8.27 in
A = 1.639
H_{over} = 11.03" (use 11 inches)

AFTER OVERLAY

Geometry	AC	11"	450,000 psi	0.35
	AC	4"	200,000 psi	0.35
	PCC	8"	3,000,000 psi	0.15

E_{P2} = 942,520 psi (effective modulus of old pavement)
E_{eff} = 1,108,664 psi (effective modulus of new pavement)
D_{new} = 15.50 in.
D_{eff} = 14.68 in.
A = 2.175
H_{over} = 0.7 in.

The above calculation results show that, based on the overlay thickness design method, the effective PCC thickness after overlay is very close to the required PCC thickness in different traffic conditions. This is what needed for a theoretically correct and stable design method.

Part 3 Test of the whole procedure

The good match in part 2, however, does not guarantee that our procedure will work well since the effective moduli used in part 2 are preset values, i.e., with the assumption that the back calculation scheme can provide 100 percent accurate modulus of pavement and subgrade. Unfortunately, this is not the case from the results in part 1. In part 1, however, the lower estimation of pavement modulus is accompanied by a higher estimation of the modulus of subgrade reaction. As a result, the inaccuracy in layer moduli estimation may compensate each other.

In this part of test, we will see how the overlay thickness results look like when using the back calculated moduli of pavement and subgrade rather than preset values.

Following the results of part 1, we have

E_{P2} = 936,409 psi
k_2 = 124.04 pci

The design results using above input values are:

D_{eff} = 7.86 in.
D_{req} = 10.75 in.
H_{over} = 5.38 in.

The pavement geometry after overlay is

AC layer	5.38"	450,000 psi (new material)
Composite	12"	1,089,845 psi (old pavement)

The calculated deflection basin is

$w_1, w_2, ..., w_5$ = 0.6229, 0.5950, 0.5300, 0.4520, 0.3738 mils

The back calculation and overlay thickness design results are

E_{P2} = 672,495 psi
k_2 = 113.81 pci
D_{eff} = 10.36 in.
D_{req} = 10.78 in.
H_{over} = 0.90 in.

Additional 0.9 inches of AC overlay is needed on the overlaid pavement. Considering the thicknesses of the whole pavement and design AC overlay, this is a good match.

In the following two case studies, the modeling parameters of a composite pavement such as slab size, pavement thickness and moduli, as well as subgrade moduli, are varied to see the corresponding effect. Moreover, one rigid pavement case study is carried out to investigate the procedure's suitability for rigid pavement.

CASE 2 Composite pavement 2

Geometry

1	AC layer	h_{ac}=3"	$E_{ac}=3\times10^5$ psi	ν=0.35
2	PCC slab	h_{pcc}=8"	$E_{pcc}=1.5\times10^6$ psi	ν=0.15

Theoretical Effective modulus, E_{P1} = 855,905 psi
Subgrade reaction modulus, k_1 = 200 pci
Traffic, E_{18} = 30 million
Reliability, R = 95 %

Part 1 Test of back calculation scheme

With the finite element model shown in Figure B1, the calculated deflection basin is:

$w_1, w_2, ..., w_5$ = 0.6663, 0.6088, 0.4851, 0.3531, 0.2397 mils

The back calculated elastic modulus of pavement and subgrade reaction modulus are:

E_{P2} = 793,026 psi
k_2 = 239.04 pci

We can see that, again, the revised procedure gives lower estimation of the effective elastic modulus of the whole pavement but higher estimation of the modulus of subgrade reaction.

Part 2 Test of overlay thickness design method

BEFORE OVERLAY

Following the sequence part 2 in case 1, we have

E_{P1} = 855,905 psi
D_{new} = 10.5 in.
E_{eff} = 2,436,712 psi
D_{eff} = 7.41 in.
D_{req} = 10 in.(assumed value)
A = 1.8924
H_{over1} = 4.9 in.

Use 4.9 inches overlay.

AFTER OVERLAY

Geometry of pavement:

AC layer	4.9"	$4.5\text{x}10^5$ psi (new material)
AC layer	3"	$3\text{x}10^5$ psi
PCC slab	9"	$1.5\text{x}10^6$ psi

Calculation results are:

E_{P1} = 769,796 psi (effective modulus of old pavement)
E_{eff} = 1,398,310 psi
D_{new} = 12.95 in.
D_{eff} = 10.62 in
D_{req} = 10 in.

We can see that the effective thickness of the pavement after overlay, 10.62, is very close to the required thickness, 10 inches. This shows good match of overlay thickness design method.

Part 3 Test of the whole procedure

Following the results of part 1, we have for BEFORE OVERLAY:

E_{P2} = 793,026 psi

k_2 = 239.04 pci

The design results using above input values are:

D_{eff} = 7.23 in.
D_{req} = 10.53 in.(determined using E_{18} = 30 million)
H_{over} = 6.02 in.

The pavement geometry after overlay is

AC layer	6.02"	450,000 psi (new material)
Composite	12"	855,905 psi (old pavement)

The calculated deflection basin is

$w_1, w_2, ..., w_5$ = 0.4336, 0.4075, 0.3486, 0.2810, 0.2172 mils

The back calculation and overlay thickness design results are

E_{P2} = 582,478 psi
k_2 = 234.9 pci
D_{eff} = 10.3 in.
D_{req} = 10.53 in.
H_{over} = 0.50 in.

The numerical results in this case study look even better than those of case 1.

After the above case studies, it seems that the revised procedure works well with composite pavement in overlay thickness design. Though the back calculated elastic moduli of pavement and subgrade are not very close to the assumed values, they do compensate each other, i.e., a lower estimation of pavement modulus is accompanied by a higher subgrade modulus. Therefore, the whole procedure works quite well with composite pavement.

Since the pavement surface deflections are obtained by using KENSLABS, a finite element program. The modeling size of the pavement surely has influence on the results. The back calculation method in the revised procedure is derived from the Losberg's theory, which is for infinite pavement slab dimensions. Therefore, it is believed that increasing the modeling dimensions of pavement in KENSLABS may yield closer back calculated moduli. The following case demonstrates this.

CASE 3 Composite pavement for larger KENSLABS model

This case is identical to case 1 in all parameters except the dimension of slab size modeled in finite element analysis for deflection basin. The slab size in this case is 1900x1800 inches, which is much larger than that in case 1, where the slab size is 480x288 inches.

Geometry

1	AC layer	h_1=4"	$E_1=2\times10^5$ psi	ν=0.35
2	PCC slab	h_2=8"	$E_2=3\times10^6$ psi	ν=0.15

Theoretical Effective modulus, E_{P1} = 1,084,225 psi
Subgrade reaction modulus, k_1 = 100 pci
Traffic, E_{18} = 30 million

Reliability, R = 95 %

Part 1 Test of back calculation scheme

With the finite element model shown in Figure B2, the calculated deflection basin is:

$w_1, w_2, ..., w_5 = 0.8638, 0.8112, 0.6929, 0.5572, 0.4291$ mils

The back calculated elastic modulus of pavement and subgrade reaction modulus are:

E_{P2} = 993,088 psi
k_2 = 119.5 pci

The back calculated results are closer to the presumed values than those in case 1. This confirms that the larger the slab dimensions in KENSLABS modeling the better the match is with the infinite dimension solutions presented by Losberg 1960.

Part 2 Test of overlay thickness design method

This part is identical to the part 2 in case 1 study.

Part 3 Test of the whole procedure

E_{P2} = 993,088 psi
k_2 = 119.5 pci
D_{eff} = 8.02 in.
D_{req} = 10.77 in.
H_{over} = 5.16 in.

The pavement geometry after overlay is

AC layer	5.16"	450,000 psi (new material)
Composite	12"	1,084225 psi (old pavement)

The calculated deflection basin is

$w_1, w_2, ..., w_5 = 0.6202, 0.5915, 0.5249, 0.4451, 0.3655$ mils

The back calculation and overlay thickness design results are

E_{P2} = 672,079 psi
k_2 = 118.9 pci
D_{eff} = 10.24 in.
D_{req} = 10.77 in.
H_{over} = 1.13 in.

Again, only 1.13 inches more overlay is needed. Considering that any numerical process may yield errors and the AASHTO design equation is a empirical solution, this result shows good match of revised procedure. Compare this result with that in case 1, however, even though the back calculated moduli of pavement and subgrade in this case compare better with the presumed values, the final required overlay thickness after the design overlay has been laid(1.13 inches) is a little higher than that of case 1(0.90 inches).

After the above three case studies for composite pavements, we can conclude that the revised procedure works quite well and will yield theoretically correct and consistent overlay design results for composite pavements. Since rigid pavement is only a special case of composite pavement with zero AC layer thickness, the correctness of the procedure for composite pavement should also hold for rigid pavements. This is shown by the following case study for a rigid pavement.

CASE 4 A rigid pavement case study

Geometry

1	PCC slab	h=8"	$E=2\times10^6$ psi	$\nu=0.15$

Subgrade reaction modulus, k_1 = 100 pci
Traffic, E_{18} = 30 million
Reliability, R = 95 %

Part 1 Test of back calculation scheme

With the finite element model shown in Figure B1, the calculated deflection basin is:

$$w_1, w_2, \ldots, w_5 = 1.156,\ 1.067,\ 0.8718,\ 0.6586,\ 0.4692 \text{ mils}$$

The back calculated elastic modulus of pavement and subgrade reaction modulus are:

E_{P2} = 1,845,156 psi
k_2 = 119.7 pci

Similar results as those of composite pavements are obtained.

Part 2 Test of overlay thickness design method

BEFORE OVERLAY

E_{P1} = 2,000,000 psi
E_{eff} = 5,000,000 psi
D_{new} = 8 in.
D_{eff} = 5.9 in.
D_{req} = 10 in. (Assumed)
A = 1.761
H_{over} = 7.22 in.

AFTER OVERLAY

Geometry of pavement:

AC layer	7.22"	4.5×10^5 psi (new material)
PCC slab	8"	2×10^6 psi

E_{P2} = 891,173 psi
E_{eff} = 1,379,364 psi
D_{new} = 11.61 in.

D_{eff} = 10.04 in.
D_{req} = 10 in.
H_{over} = 0.09 in.

The effective PCC thickness of the overlaid pavement, 10.04 inches, is almost the same as the required thickness, 10 inches. The perfect match shows that the overlay thickness design method works well for rigid pavements.

Part 3 Test of the whole procedure

E_{P2} = 1,845,156 psi
k_2 = 119.7 pci
D_{eff} = 5.74 in.
D_{req} = 10.77 in.
H_{over} = 8.56 in.

The pavement geometry after overlay is

AC layer	8.56"	450,000 psi (new material)
Composite	12"	2,000,000 psi (old pavement)

The calculated deflection basin is

$w_1, w_2, \ldots, w_5 =$ 0.6044, 0.5770, 0.5134, 0.4369, 0.3603 mils

The back calculation and overlay thickness design results are

E_{P2} = 792,517 psi
k_2 = 118.7 pci
D_{eff} = 10.47 in.
D_{req} = 10.77 in.
H_{over} = 0.65 in.

As expected, a good match is reached for the rigid pavement case study.

The results of the above four case studies are summarized as in Table B1.

Table B1 Back calculation Scheme Test Results

Case	Presumed		Back calculated	
	E_p(psi)	k(pci)	E_p(psi)	k(pci)
1	1,089,845	100	936,409	124
2	885,905	200	793,026	239
3	1,089,845	100	993,088	119.5
4	2,000,000	100	1,845,156	119.7

Table B2 Thickness Design Method Test Results (Using Assumed E_p and k)

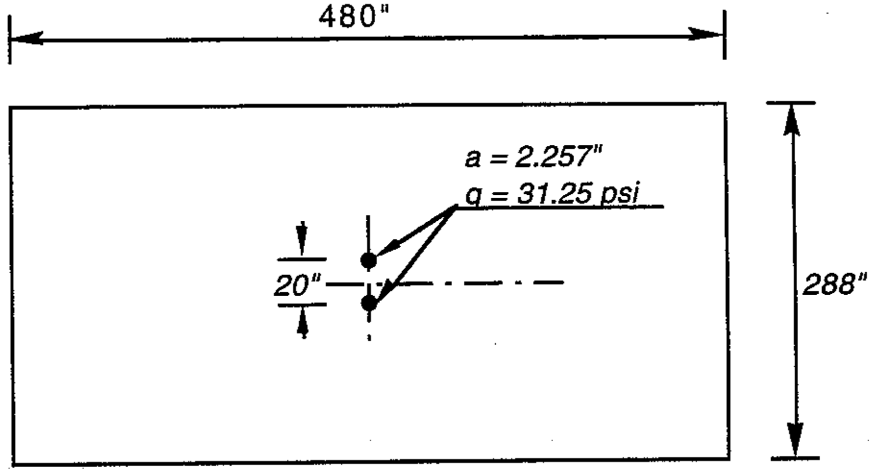
Case	Before Overlay					After Overlay				
	E_p (psi)	k (pci)	D_{req} (in.)	D_{eff} (in.)	H_{over} (in.)	E_p (psi)	k (pci)	D_{req} (in.)	D_{eff} (in.)	H_{over}* (in.)
1	1089845	100	12.92	8.27	8.02	941730	100	12.92	13.09	0.0
1	1089845	100	10	8.27	3.44	963905	100	10	10.45	0.0
1	1089845	100	15	8.27	11.03	942520	100	15	14.68	0.7
2	855905	200	10	7.41	4.9	769796	200	10	10.62	0.0
4	2000000	100	10	5.9	7.22	891173	100	10	10.04	0.0

* Asphalt concrete overlay thickness.

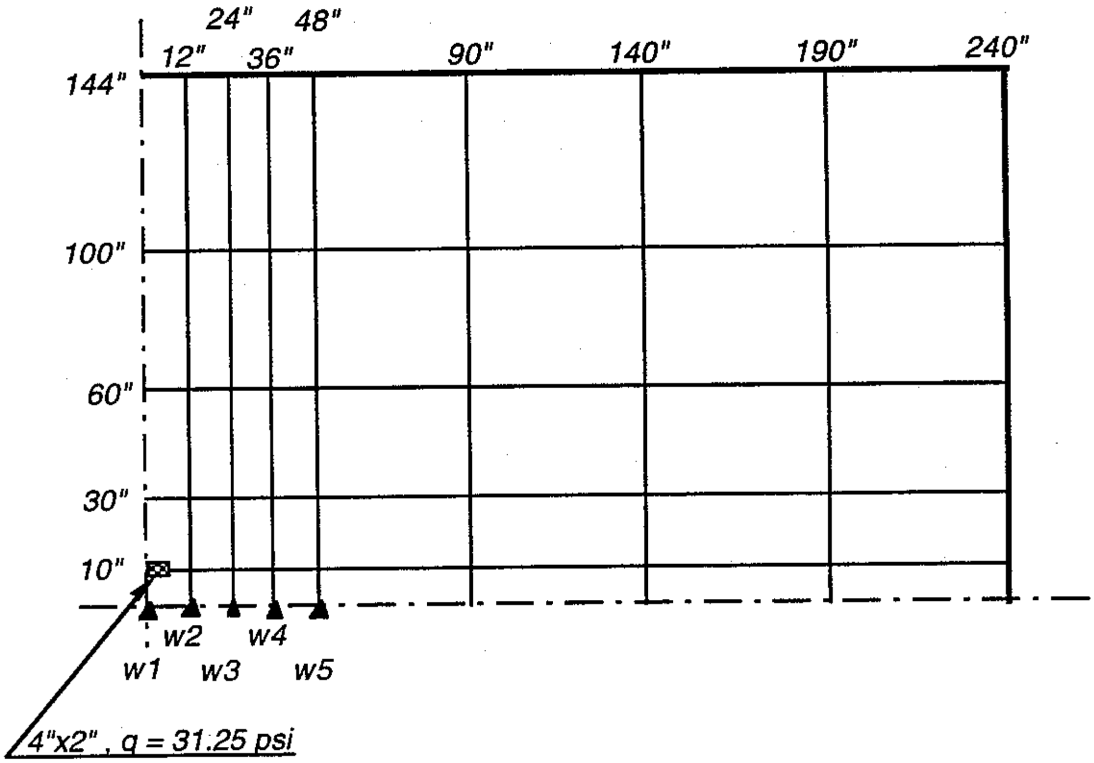
Table B3 Overall Procedure Test Results (Using Back calculated E_p and k)

Case	Before Overlay					After Overlay				
	E_p (psi)	k (pci)	D_{req} (in.)	D_{eff} (in.)	H_{over} (in.)	E_p (psi)	k (pci)	D_{req} (in.)	D_{eff} (in.)	H_{over}* (in.)
1	936409	124	10.75	7.86	5.38	672495	114	10.78	10.36	0.91
2	793026	239	10.53	7.23	6.02	582478	235	10.53	10.3	0.50
3	993088	120	10.77	8.02	5.16	672079	119	10.77	10.24	1.14
4	1845156	120	10.77	5.74	8.56	792517	119	10.77	10.47	0.65

* Asphalt concrete overlay thickness.

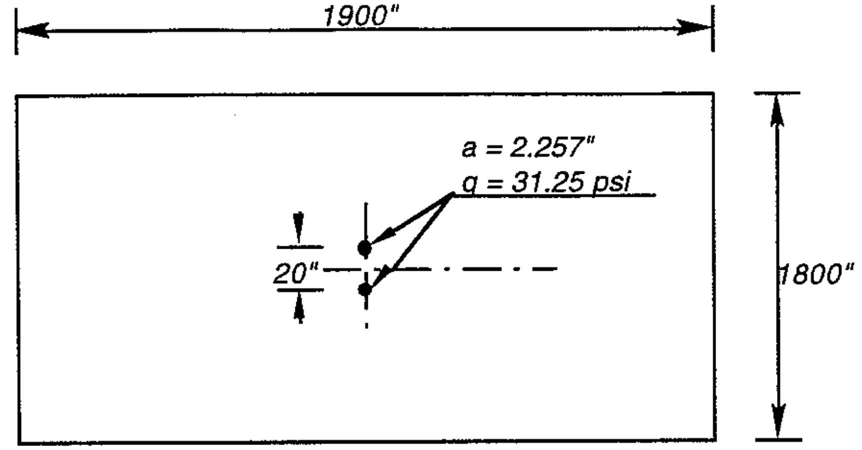


a) Total Slab Size and Load

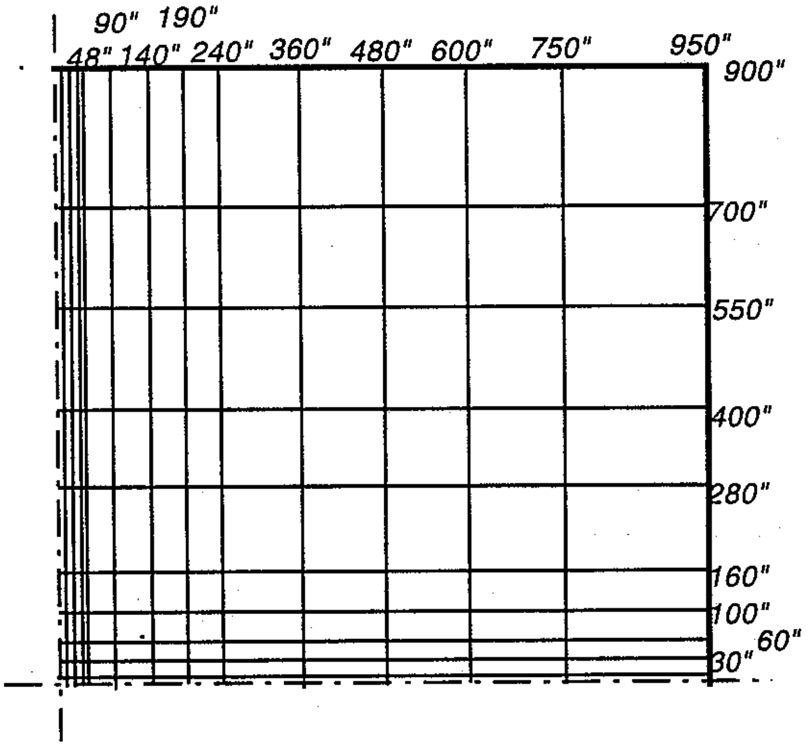


b) One-fourth Slab KENSLABS Model

Figure B1 KENSLABS Model for Case 1, 2 and 4



a) Total Slab Size and Load



b) One-fourth Slab KENSLABS Model
(For the omitted details, refer to Figure B1)

Figure B2 KENSLABS Model for Case 3

APPENDIX C

User's Guide for UTOVER

A computer program, UTOVER, has been developed to incorporate the overlay design procedures outlined in this report. This program is written in FORTRAN and is capable of performing overlay design for rigid, composite and flexible pavements. The following instructions apply to rigid and composite pavements only.

The input required to perform an overlay design for rigid and composite pavements includes the following:

1. Dynaflect deflection data. The format of the data file is shown in Figure C1.
2. Pavement structural information, including:
    - PCC slab thickness
    - AC layer thickness(for composite pavement)
    - Elastic modulus of new PCC material(default = 5,000,000 psi)
    - Poisson's ratio of PCC material(default = 0.15)
    - New PCC modulus of rupture(default = 700 psi)
    - Elastic modulus of new AC material(for composite pavement, (default = 450,000 psi)
    - Poisson ratio of AC material(default = 0.35)
3. Traffic information, including
    - Design E-18 repetition number
    - Standard deviation of traffic(default = 0.1)
4. Other data, including:
    - Reliability level
    - Initial PSI for new pavement(default = 4.5)
    - Terminal PSI(default = 2.5)
    - Load transfer coefficient(default = 3.2)
    - Drainage coefficient(default = 1.0)

The analysis results are stored in an output file named by the user.

An example session using actual deflection data collected from pavement section I71 is shown in the following pages. The text or data entered by user are in bold Helvetica font. The output file of this example problem, I71BEF.OUT, is shown in Figure C2.

Another program named UTPLOT is also written to assist the user plotting the various Dynaflect deflection parameters and required overlay thickness versus pavement milepost. The program is written to automatically extract information from the Dynaflect raw data file. The program is interactive and menu driven and is provided as a design tool for ODOT engineers.

```
B:> UTOVER

******************************************************
*                                                    *
*                WELCOME TO UTOVER                   *
*  A COMPUTER PROGRAM FOR PAVEMENT OVERLAY DESIGN    *
*                                                    *
******************************************************

  ENTER THE EXISTING PAVEMENT TYPE OR EXIT:
       1.   RIGID
       2.   FLEXIBLE
       3.   COMPOSITE
       4.   EXIT
3

  ENTER THE TITLE OF THE ANALYSIS:
I71BEFORE

  ENTER DESIGN E-18(MILLIONS):
24

  ENTER THE RELIABILITY IN %:
  THE RECOMMENDED VALUES ARE:
                                Urban           Rural
Interstate and Other Freeways   85-99.9         80-99.9
Principal Arterials             80-99           75-95
Collectors                      80-95           75-95
Local                           50-80           50-80

95

  ENTER THE STANDARD DEVIATION OF TRAFFIC:
  ENTER 0 TO USE 0.1
0

  ENTER THE FILE NAME CONTAINING DYNAFLECT DATA:
  (MAX. 15 CHARACTERS, PLEASE)
I71BEF.MSD

  ENTER THE OUTPUT FILE NAME:
  (MAX. 15 CHARACTERS, PLEASE)
I71BEF.OUT

  ENTER THICKNESS OF EXISTING AC LAYER:
4

  ENTER POISSON RATIO OF EXISTING AC LAYER:
  ENTER 0 TO USE 0.35
0

  ENTER NEW AC RESILIENT MODULUS:
  ENTER 0 TO USE 450,000
```

```
0

   ENTER THICKNESS OF EXISTING PCC SLAB:
10

   ENTER POISSON RATIO OF EXISTING PCC SLAB:
   ENTER 0 TO USE 0.15
0

   ENTER NEW CONCRETE ELASTIC MODULUS:
   ENTER 0 TO USE 5,000,000
0

   ENTER INITIAL PSI FOR NEW PAVEMENT:
   ENTER 0 TO USE 4.5
0

   ENTER TERMINAL PSI:
   ENTER 0 TO USE 2.5
0

   ENTER NEW CONCRETE MODULUS OF RUPTURE:
   ENTER 0 TO USE 700
0

   ENTER LOAD TRANSFER COEFFICIENT, J:
   ENTER 0 TO USE 3.2
0

   ENTER DRAINAGE COEFFICIENT, Cd:
   ENTER 0 TO USE 1.0
0

1.  TITLE =  I71BEFORE
2.  DESIGN E-18 =                                 24000000
3.  RELIABILITY =                                 95.00%
4.  STANDARD DEVIATION OF TRAFFIC =               0.1
5.  DYNAFLECT DATA FILE =                         I71BEF.MSD
6.  OUTPUT FILE NAME =                            I71BEF.OUT
7.  AC LAYER THICKNESS OF EXISTING PAVEMENT =     4.000
8.  POISSON RATIO OF AC MATERIAL =                0.350
9.  RESILIENT MODULUS OF NEW AC MATERIAL =        450000
10. PCC SLAB THICKNESS OF EXISTING PAVEMENT =     10.000
11. POISSON RATIO OF PCC MATERIAL    =            0.150
12. ELASTIC MODULUS OF NEW PCC MATERIAL =         5000000
13. PAVEMENT INITIAL PSI =                        4.5
14. TERMINAL PSI =                                2.5
15. NEW CONCRETE MODULUS OF RUPTURE =             700.00
16. LOAD TRANSFER COEF. =                         3.200
17. DRAINAGE COEF. =                              1.000

    WHICH FACTOR DO YOU WANT TO CHANGE ?
    ENTER O FOR NONE.
0
```

```
EXECUTION IN PROCESS. PLEASE WAIT ...

EXECUTION COMPLETED.

   ENTER THE DESIRED ACTIVITY:

   1.    ANOTHER OVERLAY DESIGN.
   2.    EXIT
2

*******************************************************
*                                                     *
*             THANK YOU FOR USING THIS PROGRAM !      *
*                                                     *
*******************************************************
Execution terminated : 0

B:>
```

APPENDIX D

OUTPUT DATA OF OVERLAY PROCEDURE FOR FLEXIBLE PAVEMENTS

```
TITLE: SR-7 BEFORE

 EXISTING PAVEMENT TYPE:     FLEXIBLE
 OVERLAY PAVEMENT TYPE:       AC OVERLAY

GEOMETRY OF EXISTING PAVEMENT:
        TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE =  16.00
        SURFACE AC LAYER THICKNESS           =  4.00

TEMPERATURE ADJUSTMENT:
        PAVEMENT SURFACE TEMPERATURE  =  58.0
        5-DAY MEAN AIR TEMPERATURE    =  34.0
        PAVEMENT MEAN TEMPERATURE     =  47.5
        W1 ADJUSTMENT FACTOR, AJ      = 1.151


OVERLAY DESIGN:

        DESIGN TRAFFIC,          E18 =   1400000.
        RELIABILITY:             R =    95.0%
                                 ZR =   -1.645
        TRAFFIC STANDARD DEVIATION, S0 =     0.10
        INITIAL PSI               =     4.20
        TERMINAL PSI                 =     2.50

 ------------------------------------------------------------------------

 No   W1     W5       MR       Ep      SNeff  SNreq    Dover
    (mils) (mils)    (psi)    (psi)                    (in.)

 ------------------------------------------------------------------------

  1 0.770 0.090    54389.    14125.    1.740  2.234    1.12
  2 0.450 0.030   163167.    15916.    1.811  1.432   -0.86
  3 0.390 0.060    81583.    39971.    2.461  1.905   -1.26
  4 0.490 0.100    48950.    53418.    2.711  2.327   -0.87
  5 0.410 0.100    48950.    93610.    3.268  2.327   -2.14
  6 0.280 0.070    69929.   145125.    3.782  2.025   -3.99
  7 0.320 0.100    48950.   210826.    4.283  2.327   -4.45
  8 0.320 0.090    54389.   165599.    3.952  2.234   -3.90
  9 0.460 0.130    37654.   116378.    3.514  2.575   -2.13
 10 0.430 0.130    37654.   145234.    3.783  2.575   -2.74
 11 0.440 0.090    54389.    59770.    2.814  2.234   -1.32
 12 0.320 0.070    69929.    94565.    3.279  2.025   -2.85
 13 0.390 0.080    61187.    67832.    2.935  2.133   -1.82
 14 0.490 0.090    54389.    43336.    2.528  2.234   -0.67
 15 0.450 0.100    48950.    69503.    2.959  2.327   -1.44
 16 0.400 0.120    40792.   153262.    3.852  2.497   -3.08
 17 0.450 0.150    32633.   172311.    4.005  2.721   -2.92
 18 0.360 0.180    27194.   551539.    5.902  2.920   -6.78
```

19	0.480	0.170	28794.	183646.	4.091	2.856	-2.81
20	0.470	0.160	30594.	172660.	4.008	2.790	-2.77
21	0.850	0.160	30594.	26187.	2.137	2.790	1.48
22	0.510	0.180	27194.	171641.	4.000	2.920	-2.45
23	0.600	0.190	25763.	115846.	3.509	2.981	-1.20
24	0.610	0.190	25763.	109775.	3.446	2.981	-1.06
25	0.520	0.180	27194.	161725.	3.921	2.920	-2.28
26	0.500	0.140	34964.	104985.	3.395	2.650	-1.69
27	0.420	0.140	34964.	184619.	4.098	2.650	-3.29
28	0.600	0.150	32633.	67723.	2.934	2.721	-0.48
29	0.630	0.170	28794.	76879.	3.060	2.856	-0.46
30	0.540	0.160	30594.	110147.	3.450	2.790	-1.50
31	0.510	0.170	28794.	152043.	3.841	2.856	-2.24
32	0.470	0.130	37654.	108790.	3.436	2.575	-1.96
33	0.480	0.130	37654.	101729.	3.360	2.575	-1.78
34	0.460	0.160	30594.	184676.	4.099	2.790	-2.97
35	0.480	0.140	34964.	119176.	3.542	2.650	-2.03
36	0.550	0.150	32633.	90154.	3.227	2.721	-1.15
37	0.720	0.140	34964.	32950.	2.307	2.650	0.78
38	0.520	0.140	34964.	92671.	3.257	2.650	-1.38
39	0.570	0.140	34964.	68358.	2.943	2.650	-0.67
40	0.590	0.160	30594.	83001.	3.140	2.790	-0.79
41	0.410	0.110	44500.	116624.	3.516	2.414	-2.50
42	0.580	0.140	34964.	64696.	2.889	2.650	-0.54
43	0.540	0.150	32633.	95561.	3.290	2.721	-1.29
44	0.580	0.140	34964.	64696.	2.889	2.650	-0.54
45	0.660	0.160	30594.	57389.	2.776	2.790	0.03
46	0.980	0.210	23310.	29574.	2.226	3.098	1.98
47	0.700	0.280	17482.	165771.	3.954	3.459	-1.13
48	0.790	0.360	13597.	194850.	4.172	3.802	-0.84
49	0.870	0.440	11125.	235803.	4.446	4.092	-0.81
50	0.590	0.380	12882.	576470.	5.990	3.878	-4.80
51	0.590	0.340	14397.	475482.	5.617	3.722	-4.31
52	0.970	0.360	13597.	101438.	3.357	3.802	1.01
53	0.640	0.320	15297.	310241.	4.872	3.637	-2.81
54	0.640	0.310	15790.	281939.	4.719	3.594	-2.56
55	0.540	0.280	17482.	406709.	5.332	3.459	-4.26
56	0.800	0.340	14397.	165370.	3.950	3.722	-0.52
57	0.510	0.210	23310.	240844.	4.478	3.098	-3.14
58	2.990	0.210	23310.	2463.	0.972	3.098	4.83
59	0.380	0.160	30594.	340516.	5.026	2.790	-5.08
60	0.360	0.140	34964.	303872.	4.839	2.650	-4.97
61	0.440	0.180	27194.	275708.	4.684	2.920	-4.01
62	0.540	0.160	30594.	110147.	3.450	2.790	-1.50
63	0.540	0.150	32633.	95561.	3.290	2.721	-1.29
64	0.400	0.160	30594.	290099.	4.764	2.790	-4.49
65	0.410	0.140	34964.	199239.	4.204	2.650	-3.53
66	0.490	0.160	30594.	151620.	3.838	2.790	-2.38
67	0.450	0.130	37654.	124509.	3.594	2.575	-2.31

68	0.500	0.140	34964.	104985.	3.395	2.650	-1.69
69	0.640	0.200	24475.	105414.	3.400	3.040	-0.82
70	0.380	0.150	32633.	297154.	4.803	2.721	-4.73
71	0.430	0.160	30594.	230229.	4.411	2.790	-3.68
72	0.390	0.180	27194.	404706.	5.323	2.920	-5.46
73	0.400	0.180	27194.	375146.	5.191	2.920	-5.16
74	0.370	0.190	25763.	578336.	5.996	2.981	-6.85
75	0.400	0.190	25763.	423743.	5.406	2.981	-5.51
76	0.410	0.200	24475.	449836.	5.514	3.040	-5.62
77	0.480	0.200	24475.	262799.	4.610	3.040	-3.57
78	0.600	0.250	19580.	210242.	4.280	3.312	-2.20
79	0.520	0.200	24475.	205356.	4.246	3.040	-2.74
80	0.500	0.190	25763.	207879.	4.263	2.981	-2.92
81	0.570	0.210	23310.	169616.	3.984	3.098	-2.01
82	0.520	0.200	24475.	205356.	4.246	3.040	-2.74
83	0.600	0.220	22250.	159282.	3.901	3.154	-1.70
84	0.520	0.240	20396.	303529.	4.837	3.261	-3.58
85	0.530	0.230	21283.	261878.	4.605	3.208	-3.17
86	0.510	0.240	20396.	322246.	4.934	3.261	-3.80
87	0.470	0.250	19580.	498874.	5.708	3.312	-5.44
88	0.490	0.260	18827.	475602.	5.618	3.362	-5.13
89	0.520	0.260	18827.	381835.	5.221	3.362	-4.23
90	0.660	0.270	18130.	183806.	4.092	3.411	-1.55
91	0.500	0.260	18827.	442563.	5.484	3.362	-4.82
92	0.540	0.270	18130.	367696.	5.156	3.411	-3.97
93	0.640	0.320	15297.	310241.	4.872	3.637	-2.81
94	0.500	0.270	18130.	486485.	5.660	3.411	-5.11
95	0.650	0.330	14833.	319035.	4.918	3.680	-2.81
96	0.810	0.360	13597.	180511.	4.067	3.802	-0.60
97	0.860	0.310	15790.	106530.	3.412	3.594	0.41
98	0.680	0.270	18130.	168088.	3.972	3.411	-1.28
99	0.630	0.220	22250.	135953.	3.701	3.154	-1.24
100	0.550	0.220	22250.	210980.	4.285	3.154	-2.57
101	0.550	0.220	22250.	210980.	4.285	3.154	-2.57
102	0.590	0.230	21283.	186381.	4.111	3.208	-2.05
103	0.780	0.200	24475.	55278.	2.742	3.040	0.68
104	0.650	0.180	27194.	78864.	3.086	2.920	-0.38
105	0.580	0.230	21283.	196549.	4.185	3.208	-2.22

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS = 105
MEAN OF OVERLAY = -2.307
STANDARD DEVIATION OF OVERLAY = 1.909
ZR = 1.645
DESIGN OVERLAY = 0.83

```
TITLE: SR7 AFTER

 EXISTING PAVEMENT TYPE:      FLEXIBLE
 OVERLAY PAVEMENT TYPE:        AC OVERLAY

GEOMETRY OF EXISTING PAVEMENT:
        TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE = 18.25
        SURFACE AC LAYER THICKNESS             =  6.25

TEMPERATURE ADJUSTMENT:
        PAVEMENT SURFACE TEMPERATURE  = 57.0
        5-DAY MEAN AIR TEMPERATURE   = 50.0
        PAVEMENT MEAN TEMPERATURE     = 55.5
        W1 ADJUSTMENT FACTOR, AJ     = 1.102

OVERLAY DESIGN:

        DESIGN TRAFFIC,          E18 =  1400000.
        RELIABILITY:             R =   95.0%
                                        ZR =  -1.645
        TRAFFIC STANDARD DEVIATION, S0 =    0.10
        INITIAL PSI              =    4.20
        TERMINAL PSI               =    2.50

-------------------------------------------------------------------

 No   W1     W5       MR       Ep        SNeff  SNreq    Dover
     (mils) (mils)   (psi)    (psi)                       (in.)

-------------------------------------------------------------------

  1 0.510 0.100    48950.    53109.    3.086  2.327    -1.72
  2 0.290 0.050    97900.    77256.    3.496  1.771    -3.92
  3 0.300 0.050    97900.    71265.    3.404  1.771    -3.71
  4 0.350 0.080    61187.    99790.    3.808  2.133    -3.81
  5 0.320 0.080    61187.   127250.    4.129  2.133    -4.54
  6 0.200 0.050    97900.   203605.    4.829  1.771    -6.95
  7 0.240 0.070    69929.   225680.    4.998  2.025    -6.76
  8 0.270 0.070    69929.   160335.    4.460  2.025    -5.53
  9 0.380 0.090    54389.    97741.    3.782  2.234    -3.52
 10 0.320 0.080    61187.   127250.    4.129  2.133    -4.54
 11 0.310 0.070    69929.   110312.    3.937  2.025    -4.35
 12 0.260 0.050    97900.   101071.    3.824  1.771    -4.67
 13 0.310 0.070    69929.   110312.    3.937  2.025    -4.35
 14 0.310 0.060    81583.    85622.    3.618  1.905    -3.89
 15 0.310 0.070    69929.   110312.    3.937  2.025    -4.35
 16 0.290 0.080    61187.   168391.    4.533  2.133    -5.45
 17 0.340 0.100    48950.   161725.    4.473  2.327    -4.88
 18 0.280 0.130    37654.   497952.    6.507  2.575    -8.93
 19 0.430 0.140    34964.   153491.    4.395  2.650    -3.97
```

20	0.410	0.140	34964.	177730.	4.616	2.650	-4.47
21	0.540	0.130	37654.	70733.	3.395	2.575	-1.86
22	0.430	0.150	32633.	176963.	4.609	2.721	-4.29
23	0.470	0.150	32633.	135598.	4.218	2.721	-3.40
24	0.500	0.140	34964.	100459.	3.816	2.650	-2.65
25	0.430	0.140	34964.	153491.	4.395	2.650	-3.97
26	0.360	0.110	44500.	163470.	4.489	2.414	-4.71
27	0.310	0.110	44500.	253850.	5.198	2.414	-6.33
28	0.450	0.130	37654.	118289.	4.030	2.575	-3.31
29	0.410	0.130	37654.	153640.	4.397	2.575	-4.14
30	0.370	0.130	37654.	208606.	4.869	2.575	-5.21
31	0.320	0.120	40792.	272492.	5.322	2.497	-6.42
32	0.330	0.100	48950.	175630.	4.597	2.327	-5.16
33	0.390	0.100	48950.	108905.	3.920	2.327	-3.62
34	0.300	0.100	48950.	230968.	5.037	2.327	-6.16
35	0.420	0.110	44500.	105151.	3.875	2.414	-3.32
36	0.380	0.120	40792.	164563.	4.499	2.497	-4.55
37	0.410	0.100	48950.	95258.	3.749	2.327	-3.23
38	0.310	0.090	54389.	173266.	4.577	2.234	-5.32
39	0.390	0.120	40792.	152879.	4.390	2.497	-4.30
40	0.610	0.130	37654.	50706.	3.039	2.575	-1.05
41	0.420	0.090	54389.	74349.	3.452	2.234	-2.77
42	0.380	0.100	48950.	117316.	4.019	2.327	-3.84
43	0.430	0.110	44500.	98399.	3.790	2.414	-3.13
44	0.370	0.120	40792.	177186.	4.611	2.497	-4.80
45	0.410	0.130	37654.	153640.	4.397	2.575	-4.14
46	0.390	0.140	34964.	206328.	4.851	2.650	-5.00
47	0.560	0.210	23310.	155711.	4.416	3.098	-3.00
48	0.590	0.260	18827.	203679.	4.830	3.362	-3.34
49	0.830	0.310	15790.	104310.	3.864	3.594	-0.61
50	0.450	0.280	17482.	555179.	6.747	3.459	-7.47
51	0.450	0.260	18827.	497060.	6.503	3.362	-7.14
52	0.510	0.290	16879.	426988.	6.181	3.505	-6.08
53	0.430	0.210	23310.	369521.	5.891	3.098	-6.35
54	0.580	0.260	18827.	217853.	4.940	3.362	-3.59
55	0.550	0.240	20396.	212989.	4.902	3.261	-3.73
56	0.530	0.240	20396.	245421.	5.140	3.261	-4.27
57	0.390	0.160	30594.	267978.	5.292	2.790	-5.69
58	0.440	0.160	30594.	187394.	4.698	2.790	-4.34
59	0.340	0.140	34964.	309600.	5.553	2.650	-6.60
60	0.290	0.120	40792.	366466.	5.874	2.497	-7.68
61	0.400	0.140	34964.	191497.	4.732	2.650	-4.73
62	0.510	0.150	32633.	107818.	3.907	2.721	-2.70
63	0.360	0.120	40792.	192475.	4.740	2.497	-5.10
64	0.390	0.130	37654.	177667.	4.615	2.575	-4.64
65	0.430	0.140	34964.	153491.	4.395	2.650	-3.97
66	0.350	0.120	40792.	209945.	4.879	2.497	-5.41
67	0.320	0.110	44500.	230853.	5.036	2.414	-5.96
68	0.360	0.110	44500.	163470.	4.489	2.414	-4.71

69	0.570	0.120	40792.	53161.	3.087	2.497	-1.34
70	0.300	0.100	48950.	230968.	5.037	2.327	-6.16
71	0.350	0.120	40792.	209945.	4.879	2.497	-5.41
72	0.280	0.110	44500.	341569.	5.738	2.414	-7.55
73	0.270	0.130	37654.	568047.	6.798	2.575	-9.60
74	0.320	0.140	34964.	367724.	5.881	2.650	-7.34
75	0.310	0.150	32633.	500945.	6.520	2.721	-8.63
76	0.390	0.160	30594.	267978.	5.292	2.790	-5.69
77	0.340	0.150	32633.	354638.	5.811	2.721	-7.02
78	0.360	0.140	34964.	259944.	5.239	2.650	-5.88
79	0.370	0.150	32633.	275857.	5.344	2.721	-5.96
80	0.330	0.140	34964.	337558.	5.716	2.650	-6.97
81	0.350	0.140	34964.	283765.	5.394	2.650	-6.24
82	0.420	0.150	32633.	189723.	4.717	2.721	-4.54
83	0.400	0.150	32633.	217990.	4.941	2.721	-5.04
84	0.380	0.170	28794.	330565.	5.676	2.856	-6.41
85	0.380	0.160	30594.	289069.	5.428	2.790	-5.99
86	0.410	0.180	27194.	289830.	5.433	2.920	-5.71
87	0.370	0.170	28794.	366185.	5.873	2.856	-6.86
88	0.370	0.200	24475.	536536.	6.670	3.040	-8.25
89	0.380	0.190	25763.	442346.	6.255	2.981	-7.44
90	0.400	0.180	27194.	319407.	5.611	2.920	-6.12
91	0.360	0.180	27194.	466916.	6.368	2.920	-7.84
92	0.340	0.180	27194.	560162.	6.767	2.920	-8.74
93	0.360	0.180	27194.	466916.	6.368	2.920	-7.84
94	0.350	0.180	27194.	511806.	6.566	2.920	-8.29
95	0.390	0.190	25763.	404981.	6.073	2.981	-7.03
96	0.500	0.230	21283.	271857.	5.318	3.208	-4.79
97	0.610	0.230	21283.	144324.	4.306	3.208	-2.49
98	0.430	0.180	27194.	252671.	5.190	2.920	-5.16
99	0.420	0.160	30594.	213389.	4.906	2.790	-4.81
100	0.460	0.210	23310.	289321.	5.429	3.098	-5.30
101	0.530	0.180	27194.	135964.	4.221	2.920	-2.96
102	0.440	0.150	32633.	165061.	4.503	2.721	-4.05
103	0.430	0.140	34964.	153491.	4.395	2.650	-3.97
104	0.400	0.150	32633.	217990.	4.941	2.721	-5.04
105	0.420	0.140	34964.	164981.	4.502	2.650	-4.21

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS = 105
MEAN OF OVERLAY = -5.055
STANDARD DEVIATION OF OVERLAY = 1.761
ZR = 1.645
DESIGN OVERLAY = -2.16

```
TITLE: SR11 BEFORE

 EXISTING PAVEMENT TYPE:                FLEXIBLE
 OVERLAY PAVEMENT TYPE:                 AC OVERLAY

GEOMETRY OF EXISTING PAVEMENT:
         TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE = 20.25
         SURFACE AC LAYER THICKNESS            =  6.25

TEMPERATURE ADJUSTMENT:
         PAVEMENT SURFACE TEMPERATURE  = 50.0
        5-DAY MEAN AIR TEMPERATURE    = 39.0
        PAVEMENT MEAN TEMPERATURE     = 45.8
        W1 ADJUSTMENT FACTOR, AJ      = 1.180

OVERLAY DESIGN:

        DESIGN TRAFFIC,        E18 =  14000000.
        RELIABILITY:             R =   95.0%
                                ZR =   -1.645
        TRAFFIC STANDARD DEVIATION, S0 =     0.10
        INITIAL PSI              =     4.20
        TERMINAL PSI             =     2.50

-----------------------------------------------------------------------

 No   W1     W5       MR       Ep      SNeff  SNreq    Dover
    (mils) (mils)    (psi)    (psi)                     (in.)

-----------------------------------------------------------------------

 1 1.100 0.260    18827.    26673.    2.722  4.818     4.76
 2 1.330 0.220    22250.    14325.    2.212  4.550     5.31
 3 1.460 0.220    22250.    11905.    2.080  4.550     5.61
 4 0.610 0.120    40792.    37883.    3.059  3.654     1.35
 5 0.560 0.110    44500.    41196.    3.146  3.535     0.88
 6 0.610 0.120    40792.    37883.    3.059  3.654     1.35
 7 0.640 0.110    44500.    30976.    2.861  3.535     1.53
 8 0.650 0.130    37654.    36252.    3.015  3.765     1.70
 9 0.600 0.130    37654.    43565.    3.205  3.765     1.27
10 0.610 0.140    34964.    46248.    3.270  3.870     1.36
11 0.610 0.140    34964.    46248.    3.270  3.870     1.36
12 0.590 0.120    40792.    40807.    3.136  3.654     1.18
13 0.680 0.120    40792.    30009.    2.831  3.654     1.87
14 0.710 0.120    40792.    27440.    2.748  3.654     2.06
15 0.600 0.140    34964.    48068.    3.312  3.870     1.27
16 0.560 0.150    32633.    62619.    3.617  3.969     0.80
17 0.550 0.140    34964.    58923.    3.545  3.870     0.74
18 0.630 0.120    40792.    35325.    2.989  3.654     1.51
19 0.650 0.150    32633.    43719.    3.209  3.969     1.73
20 0.530 0.170    28794.    87024.    4.037  4.154     0.27
```

21	0.460	0.150	32633.	102788.	4.267	3.969	-0.68
22	0.630	0.130	37654.	38930.	3.087	3.765	1.54
23	0.590	0.150	32633.	54820.	3.460	3.969	1.16
24	0.840	0.110	44500.	18285.	2.400	3.535	2.58
25	0.510	0.130	37654.	63678.	3.638	3.765	0.29
26	0.670	0.120	40792.	30965.	2.861	3.654	1.80
27	0.740	0.150	32633.	32395.	2.904	3.969	2.42
28	0.550	0.140	34964.	58923.	3.545	3.870	0.74
29	0.620	0.110	44500.	33111.	2.925	3.535	1.39
30	0.790	0.090	54389.	17478.	2.364	3.275	2.07
31	0.730	0.090	54389.	20053.	2.475	3.275	1.82
32	0.610	0.070	69929.	22748.	2.581	2.974	0.89
33	0.630	0.100	48950.	29019.	2.799	3.410	1.39
34	0.500	0.090	54389.	41722.	3.159	3.275	0.26
35	0.550	0.070	69929.	27291.	2.743	2.974	0.53
36	0.450	0.100	48950.	60061.	3.567	3.410	-0.36
37	0.350	0.090	54389.	94056.	4.143	3.275	-1.97
38	0.420	0.090	54389.	61337.	3.592	3.275	-0.72
39	0.400	0.100	48950.	79024.	3.909	3.410	-1.13
40	0.430	0.080	61187.	50368.	3.364	3.131	-0.53
41	0.400	0.090	54389.	68690.	3.731	3.275	-1.03
42	0.480	0.090	54389.	45527.	3.253	3.275	0.05
43	0.380	0.080	61187.	66247.	3.686	3.131	-1.26
44	0.520	0.090	54389.	38409.	3.073	3.275	0.46
45	0.410	0.040	122375.	30416.	2.843	2.397	-1.02
46	0.370	0.060	81583.	50477.	3.367	2.802	-1.28
47	0.450	0.060	81583.	34650.	2.970	2.802	-0.38
48	0.340	0.060	81583.	60016.	3.566	2.802	-1.74
49	0.540	0.070	69929.	28213.	2.773	2.974	0.46
50	0.350	0.070	69929.	67328.	3.706	2.974	-1.66
51	0.510	0.050	97900.	24528.	2.647	2.613	-0.08
52	0.490	0.070	69929.	33774.	2.945	2.974	0.07
53	0.450	0.070	69929.	39828.	3.111	2.974	-0.31
54	0.300	0.090	54389.	138774.	4.716	3.275	-3.27
55	0.690	0.130	37654.	31846.	2.887	3.765	1.99
56	0.530	0.120	40792.	52279.	3.406	3.654	0.56
57	0.550	0.100	48950.	38363.	3.072	3.410	0.77
58	0.420	0.100	48950.	70539.	3.764	3.410	-0.80
59	0.470	0.120	40792.	69274.	3.741	3.654	-0.20
60	0.510	0.130	37654.	63678.	3.638	3.765	0.29
61	0.560	0.120	40792.	46002.	3.264	3.654	0.89
62	0.460	0.140	34964.	92425.	4.118	3.870	-0.56
63	0.710	0.180	27194.	45362.	3.249	4.240	2.25
64	0.510	0.150	32633.	79276.	3.913	3.969	0.13
65	0.480	0.160	30594.	102084.	4.257	4.064	-0.44
66	0.460	0.140	34964.	92425.	4.118	3.870	-0.56
67	0.500	0.130	37654.	66974.	3.699	3.765	0.15
68	0.440	0.120	40792.	81937.	3.956	3.654	-0.69
69	0.420	0.090	54389.	61337.	3.592	3.275	-0.72
70	0.730	0.180	27194.	42518.	3.179	4.240	2.41

71	0.560	0.050	97900.	21169.	2.520	2.613	0.21
72	0.620	0.070	69929.	22124.	2.557	2.974	0.95
73	0.510	0.070	69929.	31331.	2.872	2.974	0.23
74	0.470	0.050	97900.	28024.	2.767	2.613	-0.35
75	0.620	0.020	244750.	13661.	2.178	1.826	-0.80
76	0.620	0.080	61187.	24476.	2.645	3.131	1.10
77	0.630	0.070	69929.	21529.	2.534	2.974	1.00
78	0.680	0.080	61187.	20780.	2.504	3.131	1.42
79	0.520	0.110	44500.	48715.	3.327	3.535	0.47
80	0.450	0.090	54389.	52365.	3.408	3.275	-0.30
81	0.340	0.100	48950.	118913.	4.479	3.410	-2.43
82	0.360	0.140	34964.	176654.	5.111	3.870	-2.82
83	0.430	0.150	32633.	123582.	4.537	3.969	-1.29
84	0.550	0.200	24475.	103761.	4.280	4.402	0.28
85	0.630	0.190	25763.	66596.	3.692	4.323	1.43
86	0.600	0.180	27194.	69388.	3.743	4.240	1.13
87	0.540	0.130	37654.	55678.	3.478	3.765	0.65
88	0.410	0.130	37654.	110530.	4.371	3.765	-1.38
89	0.510	0.140	34964.	71403.	3.779	3.870	0.21
90	0.520	0.160	30594.	83179.	3.976	4.064	0.20
91	0.550	0.170	28794.	79202.	3.912	4.154	0.55
92	0.530	0.130	37654.	58156.	3.529	3.765	0.54
93	0.510	0.090	54389.	40011.	3.116	3.275	0.36
94	0.350	0.090	54389.	94056.	4.143	3.275	-1.97
95	0.380	0.090	54389.	77422.	3.882	3.275	-1.38
96	0.620	0.120	40792.	36567.	3.024	3.654	1.43
97	0.540	0.150	32633.	68673.	3.730	3.969	0.54
98	0.610	0.140	34964.	46248.	3.270	3.870	1.36
99	0.550	0.160	30594.	72312.	3.795	4.064	0.61
100	0.690	0.150	32633.	38049.	3.064	3.969	2.06
101	0.640	0.150	32633.	45333.	3.248	3.969	1.64
102	0.630	0.150	32633.	47027.	3.288	3.969	1.55
103	0.590	0.150	32633.	54820.	3.460	3.969	1.16
104	0.610	0.140	34964.	46248.	3.270	3.870	1.36
105	0.680	0.140	34964.	35966.	3.007	3.870	1.96

STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS = 105
MEAN OF OVERLAY = 0.548
STANDARD DEVIATION OF OVERLAY = 1.445
ZR = 1.645
DESIGN OVERLAY = 2.93

```
TITLE:  SR11 AFTER

 EXISTING PAVEMENT TYPE:      FLEXIBLE
 OVERLAY PAVEMENT TYPE:        AC OVERLAY

GEOMETRY OF EXISTING PAVEMENT:
         TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE  =  25.75
         SURFACE AC LAYER THICKNESS              =  11.75

TEMPERATURE ADJUSTMENT:
         PAVEMENT SURFACE TEMPERATURE   =  43.0
         5-DAY MEAN AIR TEMPERATURE     =  45.0
         PAVEMENT MEAN TEMPERATURE      =  45.9
         W1 ADJUSTMENT FACTOR, AJ       = 1.208

 OVERLAY DESIGN:

         DESIGN TRAFFIC,           E18 =  14000000.
         RELIABILITY:              R =    95.0%
                                   ZR =   -1.645
         TRAFFIC STANDARD DEVIATION, S0 =     0.10
         INITIAL PSI               =     4.20
         TERMINAL PSI              =     2.50

 ------------------------------------------------------------------------

 No   W1     W5       MR       Ep       SNeff  SNreq    Dover
     (mils) (mils)   (psi)    (psi)                      (in.)

 ------------------------------------------------------------------------

  1 0.480 0.170    28794.    82143.    5.035  4.154    -2.00
  2 0.530 0.150    32633.    58339.    4.492  3.969    -1.19
  3 0.480 0.180    27194.    87962.    5.151  4.240    -2.07
  4 0.460 0.180    27194.    96454.    5.312  4.240    -2.44
  5 0.550 0.170    28794.    61652.    4.576  4.154    -0.96
  6 0.440 0.170    28794.    99372.    5.365  4.154    -2.75
  7 0.510 0.170    28794.    71855.    4.816  4.154    -1.50
  8 0.340 0.120    40792.   115479.    5.641  3.654    -4.52
  9 0.290 0.110    44500.   147563.    6.121  3.535    -5.88
 10 0.300 0.120    40792.   151649.    6.177  3.654    -5.73
 11 0.300 0.110    44500.   137029.    5.972  3.535    -5.54
 12 0.310 0.100    48950.   114329.    5.622  3.410    -5.03
 13 0.280 0.110    44500.   159184.    6.277  3.535    -6.23
 14 0.270 0.120    40792.   200927.    6.784  3.654    -7.11
 15 0.290 0.120    40792.   165782.    6.363  3.654    -6.16
 16 0.260 0.120    40792.   222184.    7.015  3.654    -7.64
 17 0.300 0.110    44500.   137029.    5.972  3.535    -5.54
 18 0.310 0.110    44500.   127484.    5.830  3.535    -5.21
 19 0.350 0.130    37654.   119273.    5.702  3.765    -4.40
```

20	0.340	0.130	37654.	127044.	5.823	3.765	-4.68
21	0.300	0.120	40792.	151649.	6.177	3.654	-5.73
22	0.330	0.110	44500.	111051.	5.568	3.535	-4.62
23	0.360	0.110	44500.	93066.	5.249	3.535	-3.89
24	0.280	0.090	54389.	126111.	5.809	3.275	-5.76
25	0.260	0.100	48950.	167281.	6.382	3.410	-6.76
26	0.270	0.100	48950.	154086.	6.210	3.410	-6.36
27	0.240	0.100	48950.	202683.	6.804	3.410	-7.71
28	0.280	0.090	54389.	126111.	5.809	3.275	-5.76
29	0.250	0.090	54389.	160855.	6.299	3.275	-6.87
30	0.330	0.080	61187.	80890.	5.009	3.131	-4.27
31	0.290	0.080	61187.	103795.	5.444	3.131	-5.26
32	0.260	0.060	81583.	98468.	5.349	2.802	-5.79
33	0.230	0.080	61187.	167716.	6.388	3.131	-7.40
34	0.250	0.060	81583.	105826.	5.479	2.802	-6.08
35	0.260	0.070	69929.	112870.	5.598	2.974	-5.96
36	0.220	0.060	81583.	135198.	5.945	2.802	-7.14
37	0.200	0.070	69929.	194335.	6.709	2.974	-8.49
38	0.200	0.060	81583.	164334.	6.344	2.802	-8.05
39	0.200	0.060	81583.	164334.	6.344	2.802	-8.05
40	0.200	0.070	69929.	194335.	6.709	2.974	-8.49
41	0.200	0.070	69929.	194335.	6.709	2.974	-8.49
42	0.220	0.070	69929.	158835.	6.273	2.974	-7.50
43	0.240	0.060	81583.	114306.	5.621	2.802	-6.41
44	0.210	0.050	97900.	125121.	5.793	2.613	-7.23
45	0.190	0.040	122375.	124938.	5.791	2.397	-7.71
46	0.160	0.050	97900.	214356.	6.932	2.613	-9.82
47	0.220	0.050	97900.	114907.	5.631	2.613	-6.86
48	0.180	0.040	122375.	137853.	5.984	2.397	-8.15
49	0.190	0.050	97900.	151128.	6.170	2.613	-8.08
50	0.160	0.050	97900.	214356.	6.932	2.613	-9.82
51	0.210	0.040	122375.	104384.	5.454	2.397	-6.95
52	0.180	0.050	97900.	168443.	6.397	2.613	-8.60
53	0.190	0.060	81583.	182485.	6.570	2.802	-8.56
54	0.150	0.050	97900.	244311.	7.241	2.613	-10.52
55	0.190	0.060	81583.	182485.	6.570	2.802	-8.56
56	0.230	0.080	61187.	167716.	6.388	3.131	-7.40
57	0.220	0.070	69929.	158835.	6.273	2.974	-7.50
58	0.210	0.070	69929.	174508.	6.473	2.974	-7.95
59	0.250	0.090	54389.	160855.	6.299	3.275	-6.87
60	0.210	0.080	61187.	204812.	6.828	3.131	-8.40
61	0.230	0.080	61187.	167716.	6.388	3.131	-7.40
62	0.270	0.100	48950.	154086.	6.210	3.410	-6.36
63	0.250	0.090	54389.	160855.	6.299	3.275	-6.87
64	0.240	0.090	54389.	175921.	6.490	3.275	-7.31
65	0.200	0.090	54389.	276950.	7.550	3.275	-9.71
66	0.210	0.090	54389.	242967.	7.228	3.275	-8.98
67	0.190	0.070	69929.	217595.	6.967	2.974	-9.07
68	0.210	0.070	69929.	174508.	6.473	2.974	-7.95

```
69  0.210 0.070   69929.   174508.   6.473  2.974   -7.95
70  0.200 0.050   97900.   137166.   5.974  2.613   -7.64
71  0.230 0.050   97900.   105952.   5.481  2.613   -6.52
72  0.210 0.050   97900.   125121.   5.793  2.613   -7.23
73  0.150 0.040  122375.   193711.   6.702  2.397   -9.78
74  0.190 0.050   97900.   151128.   6.170  2.613   -8.08
75  0.190 0.040  122375.   124938.   5.791  2.397   -7.71
76  0.230 0.060   81583.   123879.   5.774  2.802   -6.75
77  0.230 0.050   97900.   105952.   5.481  2.613   -6.52
78  0.210 0.060   81583.   148702.   6.137  2.802   -7.58
79  0.190 0.060   81583.   182485.   6.570  2.802   -8.56
80  0.180 0.060   81583.   203593.   6.814  2.802   -9.12
81  0.190 0.070   69929.   217595.   6.967  2.974   -9.07
82  0.190 0.090   54389.   317250.   7.900  3.275  -10.51
83  0.200 0.090   54389.   276950.   7.550  3.275   -9.71
84  0.240 0.090   54389.   175921.   6.490  3.275   -7.31
85  0.230 0.090   54389.   192910.   6.693  3.275   -7.77
86  0.180 0.080   61187.   301389.   7.766  3.131  -10.53
87  0.210 0.070   69929.   174508.   6.473  2.974   -7.95
88  0.170 0.060   81583.   230962.   7.107  2.802   -9.78
89  0.190 0.070   69929.   217595.   6.967  2.974   -9.07
90  0.190 0.070   69929.   217595.   6.967  2.974   -9.07
91  0.190 0.060   81583.   182485.   6.570  2.802   -8.56
92  0.200 0.060   81583.   164334.   6.344  2.802   -8.05
93  0.180 0.040  122375.   137853.   5.984  2.397   -8.15
94  0.200 0.060   81583.   164334.   6.344  2.802   -8.05
95  0.250 0.060   81583.   105826.   5.479  2.802   -6.08
96  0.230 0.070   69929.   145068.   6.086  2.974   -7.07
97  0.220 0.070   69929.   158835.   6.273  2.974   -7.50
98  0.240 0.080   61187.   152696.   6.191  3.131   -6.95
99  0.250 0.080   61187.   140599.   6.023  3.131   -6.57
100 0.240 0.080   61187.   152696.   6.191  3.131   -6.95
101 0.250 0.090   54389.   160855.   6.299  3.275   -6.87
102 0.230 0.070   69929.   145068.   6.086  2.974   -7.07
103 0.240 0.080   61187.   152696.   6.191  3.131   -6.95
104 0.260 0.080   61187.   129802.   5.865  3.131   -6.21
105 0.250 0.080   61187.   140599.   6.023  3.131   -6.57
```

```
STATISTICAL RESULTS SUMMARY:

NUMBER OF DATA POINTS                =    105
MEAN OF OVERLAY                      =  -6.971
STANDARD DEVIATION OF OVERLAY        =   1.971
ZR                                   =   1.645
DESIGN OVERLAY                       =   -3.73
```

APPENDIX E

FORTRAN SOURCE CODE OF THE UTOVER PROGRAM

```
      PROGRAM MAIN
      IMPLICIT REAL(K)
      INTEGER OPTION1
      CHARACTER TITLE*60, FNAMEI*15, FNAMEO*15
      COMMON/C1/TITLE, FNAMEI, FNAMEO
      COMMON/C2/OPTION1
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      COMMON/C4/AMR, DEPTH, DAC, TP, TA
      COMMON/C5/D1, D2, D3, E1, E2, E3, U1, U2, U3, DNEW
      COMMON/C6/W1, W2, W3, W4, W5, RL
C     DS = DESIGN RIGID SLAB THICKNESS
C     AJ = LOAD TRANFER COEFFICIENT
C     KSUB = DESIGN REACTION COEF. OF SUBGRADE
C     AMR= RESILIENT MODULUS
C     D1,D2= THICKNESS OF AC LAYER AND RIGID SLAB
C     D3 = D1+D2
C     E1,E2 = ELASTIC MODULUS OF AC AND RIGID SLAB
C     E3 = EFFECTIVE ELASTIC MODULUS OF NEW COMPOSITE
C     U1,U2 = POISSON RATIO OF AC AND RIGID SLAB
C     U3 = (U1*D1 + U2*D2)/(D1+D2)
C     DNEW = 0.5*D1 + D2
C     P = 1000 LB, THE DYNAFLECT LOAD
CC ****************************************************
CC PURPOSE:   ENTER THE TYPE OF EXISTING PAVEMENT
CC INPUT:     OPTION1
CC ****************************************************
       WRITE(*,10)
    10 FORMAT(' ***************************************************')
       WRITE(*,20)
    20 FORMAT(' *',49X,'*'/' *          WELCOME TO UTOVER',19X,'*'/
     +' * A COMPUTER PROGRAM FOR PAVEMENT OVERLAY DESIGN  *'
     +/' *',49X,'*')
       WRITE(*,10)
    30 WRITE(*,32)
    32 FORMAT(///'          ENTER THE EXISTING PAVEMENT TYPE OR EXIT:')
       WRITE(*,*) '          1. RIGID'
       WRITE(*,*) '          2. FLEXIBLE'
       WRITE(*,*) '          3. COMPOSITE'
       WRITE(*,*) '          4. EXIT'
       WRITE (*,*) ' '
       READ (*,*) OPTION1
C
C***** OVERLAY DESIGN *****
C
       IF(OPTION1 .NE. 1 .AND. OPTION1 .NE. 2 .AND. OPTION1 .NE. 3
      + .AND. OPTION1 .NE. 4) GOTO 30
    34 IF(OPTION1 .EQ. 4) THEN
         WRITE(*,10)
```

```
    WRITE (*,36)
36   FORMAT(' *',49X,'*'/' *      THANK YOU FOR USING THIS',
 +' PROGRAM !',9X,'*'/' *',49X,'*')
    WRITE(*,10)
    STOP
   END IF
   CALL INPUT
   WRITE(*,40)
40 FORMAT(//' EXECUTION IN PROCESS. PLEASE WAIT ...'/)
   OPEN(UNIT=2,FILE=FNAMEI,STATUS='OLD')
   OPEN(UNIT=3,FILE=FNAMEO,STATUS='UNKNOWN')
   WRITE(3,45)TITLE
45 FORMAT('TITLE:',2X,A60)
   IF(OPTION1 .EQ. 1) THEN
    D3=D2
    U3=U2
    E3=E2
    DNEW=D2
    CALL OCOMP
   END IF
   IF(OPTION1 .EQ. 3) THEN
    D3=D1+D2
    U3=(D1*U1+D2*U2)/(D1+D2)
    DNEW=0.5*D1+D2
    A1=((E1/E2)*D1*(0.5*D1+D2)+0.5*D2*D2)/((E1/E2)*D1+D2)
    R1=E1*(D1**3/12.0+D1*(0.5*D1+D2-A1)**2)/(1-U1*U1)
    R2=E2*(D2**3/12.0+D2*(A1-0.5*D2)**2)/(1-U2*U2)
    E3=12*(1-U3*U3)*(R1+R2)/D3**3
    CALL OCOMP
   END IF
   IF(OPTION1 .EQ. 2) CALL OFLEX
   WRITE(*,50)
50 FORMAT(//' EXECUTION FINISHED.'/)
55 WRITE(*,60)
60 FORMAT(///' ENTER THE DESIRED ACTIVITY:'/
 +/' 1. ANOTHER OVERLAY DESIGN.'/' 2. EXIT.'/)
   READ(*,*)I
   IF(I .EQ. 1)GOTO 30
   IF(I .EQ. 2)THEN
    OPTION1=4
    GOTO 34
   END IF
   GOTO 55
   END
CC ***************************************************************************
CC          SUBROUTINE INPUT
CC ***************************************************************************
    SUBROUTINE INPUT
    IMPLICIT REAL(K)
    INTEGER OPTION1
```

```
      CHARACTER TITLE*60, FNAMEI*15, FNAMEO*15
      COMMON/C1/TITLE, FNAMEI, FNAMEO
      COMMON/C2/OPTION1
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      COMMON/C4/AMR, DEPTH, DAC, TP, TA
      COMMON/C5/D1, D2, D3, E1, E2, E3, U1, U2, U3, DNEW
      COMMON/C6/W1, W2, W3, W4, W5, RL
      I=0
    5 WRITE(*,*)'       ENTER THE TITLE OF THE ANALYSIS:'
      WRITE (*,*) ' '
      READ(*,7) TITLE
    7 FORMAT(A60)
      IF(I .NE. 0) GOTO 200
   10 WRITE(*,*)'       ENTER DESIGN E-18(MILLIONS):'
      WRITE (*,*) ' '
      READ(*,*) E18
      E18=E18*1000000
      IF(I .NE. 0) GOTO 200
   20 WRITE(*,*)'       ENTER THE RELIABILITY IN %:'
      WRITE(*,*)'      THE RECOMMENDED VALUES ARE:'
      WRITE(*,*)'                              Urban       Rural'
      WRITE(*,*)' Interstate and Other Freeways    85-99.9     80-99.9'
      WRITE(*,*)' Principal Arterials          80-99       75-95'
      WRITE(*,*)' Collectores                  80-95       75-95'
      WRITE(*,*)' Local                        50-80       50-80'
      WRITE (*,*) ' '
      READ(*,*)R
      IF(I .NE. 0) GOTO 200
   30 WRITE(*,*)'       ENTER THE STANDARD DEVIATION OF TRAFFIC:'
      WRITE(*,*)'      ENTER 0 TO USE 0.10'
      WRITE (*,*) ' '
      READ(*,*)S0
      IF(S0 .EQ. 0.0) S0=0.10
      IF(I .NE. 0) GOTO 200
   40 WRITE(*,*)'       ENTER THE FILE NAME CONTAINING DYNAFLECT DATA:'
      WRITE(*,*)'      (MAX. 15 CHARACTRES, PLEASE)'
      WRITE (*,*) ' '
      READ(*,45)FNAMEI
   45 FORMAT(15A)
      IF(I .NE. 0) GOTO 200
   50 WRITE(*,*)'       ENTER THE OUTPUT FILE NAME:'
      WRITE(*,*)'      (MAX. 15 CHARACTRES, PLEASE)'
      WRITE (*,*) ' '
      READ(*,45)FNAMEO
      IF(I .NE. 0) GOTO 200
      IF(OPTION1 .EQ. 2) GOTO 170
      IF(OPTION1. EQ. 1) GOTO 90
   60 WRITE(*,*)'       ENTER THICKNESS OF EXISTING AC LAYER:'
      WRITE (*,*) ' '
      READ(*,*)D1
```

```
  IF(I .NE. 0) GOTO 200
70 WRITE(*,*)'     ENTER POISSON RATIO OF EXISTING AC LAYER:'
  WRITE(*,*)'     ENTER 0 TO USE 0.35'
  WRITE (*,*) ' '
  READ(*,*)U1
  IF(U1 .EQ. 0.0) U1=0.35
  IF(I .NE. 0) GOTO 200
80 WRITE(*,*)'     ENTER NEW AC RESILIENT MODULUS:'
  WRITE(*,*)'     ENTER 0 TO USE 450000'
  WRITE (*,*) ' '
  READ(*,*)E1
  IF(E1 .EQ. 0) E1 = 450000
  IF(I .NE. 0) GOTO 200
90 WRITE(*,*)'     ENTER THICKNESS OF EXISTING PCC SLAB:'
  WRITE (*,*) ' '
  READ(*,*)D2
  IF(I .NE. 0) GOTO 200
100 WRITE(*,*)'     ENTER POISSON RATIO OF EXISTING PCC SLAB:'
  WRITE(*,*)'     ENTER 0 TO USE 0.15'
  WRITE (*,*) ' '
  READ(*,*)U2
  IF(U2 .EQ. 0.0) U2=0.15
  IF(I .NE. 0) GOTO 200
110 WRITE(*,*)'     ENTER NEW CONCRETE ELASTIC MODULUS:'
  WRITE(*,*)'     ENTER 0 TO USE 5000000'
  WRITE (*,*) ' '
  READ(*,*)E2
  IF(E2 .EQ. 0) E2 = 5000000
  EC=E2
  IF(I .NE. 0) GOTO 200
120 WRITE(*,*)'     ENTER INITIAL PSI FOR NEW PAVEMENT:'
  WRITE(*,*)'     ENTER 0 TO USE 4.5'
  WRITE (*,*) ' '
  READ(*,*)PSII
  IF(PSII .EQ. 0) PSII = 4.5
  IF(I .NE. 0) GOTO 200
130 WRITE(*,*)'     ENTER TERMINAL PSI:'
  WRITE(*,*)'     ENTER 0 TO USE 2.5'
  WRITE (*,*) ' '
  READ(*,*)PSIT
  IF(PSIT .EQ. 0) PSIT = 2.5
  IF(I .NE. 0) GOTO 200
140 WRITE(*,*)'     ENTER NEW CONCRETE MODULUS OF RUPTURE:'
  WRITE(*,*)'     ENTER 0 TO USE 700'
  WRITE (*,*) ' '
  READ(*,*)SC
  IF(SC .EQ. 0) SC = 700
  IF(I .NE. 0) GOTO 200
150 WRITE(*,*)'     ENTER LOAD TRANSFER COEFFICIENT, J:'
  WRITE(*,*)'     ENTER 0 TO USE 3.2'
```

```
    WRITE (*,*) ' '
    READ(*,*)AJ
    IF(AJ .EQ. 0) AJ = 3.2
    IF(I .NE. 0) GOTO 200
160 WRITE(*,*)'      ENTER DRAINAGE COEFFICIENT, Cd:'
    WRITE(*,*)'      ENTER 0 TO USE 1.0'
    WRITE (*,*) ' '
    READ(*,*)CD
    IF(CD .EQ. 0.0) CD = 1.0
    GOTO 200
170 WRITE(*,*)'      ENTER THE THICKNESS OF WHOLE FLEXIBLE PAVEMENT
   +ABOVE SUBGRADE:'
    WRITE(*,*)' '
    READ(*,*)DEPTH
    IF(I .NE. 0) GOTO 200
175 WRITE(*,*)'      ENTER THE THICKNESS OF SURFACE AC LAYER:'
    WRITE(*,*)' '
    READ(*,*)DAC
    IF(I .NE. 0) GOTO 200
180 WRITE(*,*)'      ENTER THE PAVEMENT SURFACE TEMPERATURE:'
    WRITE(*,*)' '
    READ(*,*)TP
    IF(I .NE. 0) GOTO 200
185 WRITE(*,*)'      ENTER THE 5-DAY MEAN AIR TEMPERATURE:'
    WRITE(*,*)' '
    READ(*,*)TA
    IF(I .NE. 0) GOTO 200
190 WRITE(*,*)'      ENTER INITIAL PSI FOR NEW FLEXIBLE PAVEMENT:'
    WRITE(*,*)'      ENTER 0 TO USE 4.2'
    WRITE (*,*) ' '
    READ(*,*)PSII
    IF(PSII .EQ. 0) PSII = 4.2
    IF(I .NE. 0) GOTO 200
195 WRITE(*,*)'      ENTER TERMINAL PSI:'
    WRITE(*,*)'      ENTER 0 TO USE 2.5'
    WRITE (*,*) ' '
    READ(*,*)PSIT
    IF(PSIT .EQ. 0) PSIT = 2.5
C
C****** CHECKVALUE ******
C
 200 I1=1
    WRITE(*,205)I1,TITLE
 205 FORMAT(1X,I2,'. TITLE= ',A60)
    I1=I1+1
    WRITE(*,215)I1,E18
 215 FORMAT(1X,I2,'. DESIGN E-18 =    ', F10.0)
    I1=I1+1
    WRITE(*,225)I1,R
 225 FORMAT(1X,I2,'. RELIABILITY =    ', F10.2, '%')
```

```
  I1=I1+1
  WRITE(*,235)I1,S0
235 FORMAT(1X,I2,'. STANDARD DEVIATION OF TRAFFIC =   ', F10.3)
  I1=I1+1
  WRITE(*,245)I1,FNAMEI
245 FORMAT(1X,I2,'. DYNAFLECT DATA FILE=     ', 15A)
  I1=I1+1
  WRITE(*,255)I1,FNAMEO
255 FORMAT(1X,I2,'. OUTPUT FILE NAME =   ', 15A)
  I1=I1+1
  IF(OPTION1. EQ. 1) GOTO 290
  IF(OPTION1 .EQ. 2) GOTO 370
  WRITE(*,265)I1,D1
265 FORMAT(1X,I2,'. AC LAYER THICKNESS OF EXISTING PAVEMENT =  ',
 +F10.3)
  I1=I1+1
  WRITE(*,275)I1,U1
275 FORMAT(1X,I2,'. POISSON RATIO OF AC MATERIAL =   ', F10.3)
  I1=I1+1
  WRITE(*,285)I1,E1
285 FORMAT(1X,I2,'. RESILIENT MODULUS OF NEW AC MATERIAL =  ', F10.0)
  I1=I1+1
290 WRITE(*,295)I1,D2
295 FORMAT(1X,I2,'. PCC SLAB THICKNESS OF EXISTING PAVEMENT =  ',
 +F10.3)
  I1=I1+1
  WRITE(*,305)I1,U2
305 FORMAT(1X,I2,'. POISSON RATIO OF PCC MATERIAL =   ', F10.3)
  I1=I1+1
  WRITE(*,315)I1,E2
315 FORMAT(1X,I2,'. ELASTIC MODULUS OF NEW PCC MATERIAL =  ', F10.0)
  I1=I1+1
  WRITE(*,325)I1,PSII
325 FORMAT(1X,I2,'. PAVEMENT INITIAL PSI =   ', F10.3)
  I1=I1+1
  WRITE(*,335)I1,PSIT
335 FORMAT(1X,I2,'. TERMINAL PSI = ', F10.3)
  I1=I1+1
  WRITE(*,345)I1,SC
345 FORMAT(1X,I2,'. NEW CONCRETE MODULUS OF RUPTURE =   ', F10.3)
  I1=I1+1
  WRITE(*,355)I1,AJ
355 FORMAT(1X,I2,'. LOAD TRANFER COEF. = ', F10.3)
  I1=I1+1
  WRITE(*,365)I1,CD
365 FORMAT(1X,I2,'. DRAINAGE COEF. =   ', F10.3)
  GOTO 380
370 WRITE(*,372)I1,DEPTH
372 FORMAT(1X,I2,'. THICKNESS OF WHOLE FLEXIBLE PAVEMENT =  ', F10.2)
  I1=I1+1
```

```
  WRITE(*,374)I1,DAC
374 FORMAT(1X,I2,'. THICKNESS OF SURFACE AC LAYER =  ',F10.2)
  I1=I1+1
  WRITE(*,376)I1,TP
376 FORMAT(1X,I2,'. PAVEMENT SURFACE TEMPERATURE = ',F10.2)
  I1=I1+1
  WRITE(*,378)I1,TA
378 FORMAT(1X,I2,'. 5-DAY MEAN AIR TEMPERATURE = ',F10.2)
  I1=I1+1
  WRITE(*,325)I1,PSII
  I1=I1+1
  WRITE(*,335)I1,PSIT
380 WRITE (*,*) ' '
  WRITE(*,*)'  WHICH FACTOR DO YOU WANT TO CHANGE ?'
  WRITE(*,*)'  ENTER 0 FOR NONE'
  WRITE (*,*) ' '
  READ(*,*)I
  IF(I .GT. I1 .OR. I .LT. 0)GOTO 200
  IF(I .EQ. 0) GOTO 400
  IF(I .EQ. 1) GOTO 5
  IF(I .EQ. 2) GOTO 10
  IF(I .EQ. 3) GOTO 20
  IF(I .EQ. 4) GOTO 30
  IF(I .EQ. 5) GOTO 40
  IF(I .EQ. 6) GOTO 50
  IF(OPTION1 .EQ. 1) THEN
   IF(I .EQ. 7) GOTO 90
   IF(I .EQ. 8) GOTO 100
   IF(I .EQ. 9) GOTO 110
   IF(I .EQ. 10) GOTO 120
   IF(I .EQ. 11) GOTO 130
   IF(I .EQ. 12) GOTO 140
   IF(I .EQ. 13) GOTO 150
   IF(I .EQ. 14) GOTO 160
  END IF
  IF(OPTION1 .EQ. 3) THEN
   IF(I .EQ. 7) GOTO 60
   IF(I .EQ. 8) GOTO 70
   IF(I .EQ. 9) GOTO 80
   IF(I .EQ. 10) GOTO 90
   IF(I .EQ. 11) GOTO 100
   IF(I .EQ. 12) GOTO 110
   IF(I .EQ. 13) GOTO 120
   IF(I .EQ. 14) GOTO 130
   IF(I .EQ. 15) GOTO 140
   IF(I .EQ. 16) GOTO 150
   IF(I .EQ. 17) GOTO 160
  END IF
  IF(OPTION1 .EQ. 2) THEN
   IF(I .EQ. 7) GOTO 170
```

```
       IF(I .EQ. 8) GOTO 175
       IF(I .EQ. 9) GOTO 180
       IF(I .EQ. 10) GOTO 185
       IF(I .EQ. 11) GOTO 190
       IF(I .EQ. 12) GOTO 195
      END IF
  400 RETURN
      END
CC ************************************************************************
CC          SUBROUTINE OCOMP
CC ************************************************************************
      SUBROUTINE OCOMP
      IMPLICIT REAL(K)
      INTEGER OPTION1
      CHARACTER TITLE*60, FNAMEI*15, FNAMEO*15
      COMMON/C1/TITLE, FNAMEI, FNAMEO
      COMMON/C2/OPTION1
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      COMMON/C4/AMR, DEPTH, DAC, TP, TA
      COMMON/C5/D1, D2, D3, E1, E2, E3, U1, U2, U3, DNEW
      COMMON/C6/W1, W2, W3, W4, W5, RL
C
C***** RELIABILITY ZR TERM CALCULATION *****
C
      CALL RELI(R,ZR)
C
C***** OUTPUT 1 *****
C
      IF(OPTION1 .EQ. 1)GOTO 20
      WRITE(3,5)
    5 FORMAT(/' EXISTING PAVEMENT TYPE:      COMPOSITE',
     +/' OVERLAY PAVEMENT TYPE:       AC OVERLAY')
      WRITE(3,10)
   10 FORMAT(//'GEOMETRY OF EXISTING PAVEMENT:')
      WRITE(3,15)D1,U1,E1,D2,U2,E2,D3,U3,E3
   15 FORMAT(/' THICKNESS OF AC LAYER   = ',F9.2,
     +/' POISSON RATIO AC        = ',F9.3,
     +/' ELAS. MODULUS OF NEW AC = ',F10.0,
     +/' THICKNESS OF PCC SLAB   = ',F9.2,
     +/' POISSON RATIO OF PCC    = ',F9.3
     +/' ELAS. MODULUS OF NEW PCC= ',F10.0,
     +//' TOTAL DEPTH OF PAVEMENT = ',F9.2,
     +/' EQUIVALENT POISSON RATIO= ',F9.3,
     +/' EQUIVALENT ELAS. MODULUS= ',F10.0/)
      GOTO 35
   20 WRITE(3,25)
   25 FORMAT(/' EXISTING PAVEMENT TYPE:      RIGID',
     +/' OVERLAY PAVEMENT TYPE:       AC OVERLAY')
      WRITE(3,10)
      WRITE(3,30)D2,U2
```

```
 30 FORMAT(/' THICKNESS OF PCC SLAB   = ',F10.2,
  +/' POISSON RATIO OF PCC     = ',F10.2/)
 35 WRITE(3,40)E18,R,ZR,S0,PSII,PSIT,EC,SC,AJ,CD
 40 FORMAT(/'OVERLAY DESIGN:'/
  +/' DESIGN TRAFFIC,            E18 = ',F10.0,
  +/' RELIABILITY,               R = ',F8.1,'%',
  +/'                          ZR = ',F9.3,
  +/' TRAFFIC STANDARD DEVIATION, S0 = ',F9.2,
  +/' INITIAL PSI              Pi = ',F9.2,
  +/' TERMINAL PSI               Pt = ',F9.2,
  +/' ELASTIC MODULUS OF NEW PCC  Ec = ',F10.0,
  +/' NEW PCC MODULUS OF RUPTURE  Sc = ',F9.1,
  +/' LOAD TRANFER COEFFICIENT     J = ',F9.2,
  +/' DRAINAGE FACTOR             Cd = ',F9.2/)
   WRITE(3,45)
 45 FORMAT('____________________________________________________________
  +____________________'/)
   WRITE(3,50)
 50 FORMAT(' LOCA.',' W1   W2   W3   W4   W5   Lk ',1X,
  +'   Ep     k  ',' Deff  Dreq Hover')
   WRITE(3,52)
 52 FORMAT(61X,'(PCC) (PCC)  (AC)')
   WRITE(3,55)
 55 FORMAT(16X,'   (mils)',13X,'(in.)',1X,'  (psi)   (pci) ',
  +8X,'(in.)')
   WRITE(3,45)
C
C***** SET TO ZERO
C
   IA=0
   E1ST=0.0
   E2ND=0.0
C
C***** INPUT DYNAFLECT DATA *****
C
 70 READ(2,75,END=100)PT,W1,W2,W3,W4,W5
 75 FORMAT(2X,F6.3,3X,5F7.2)
   IA=IA+1
   CALL BACKCAL(EEX, KSUB, D3, U3)
C
C***** CALCULATION OF EFFECTIVE THICKNESS OF EXISTING PAVEMENT
C
   A1=DNEW*(EEX/E3)**0.333
   DEFF=MIN(A1,DNEW)
C
C***** DETERMINE THE REQUIRED THICKNESS
C
   CALL DREQ(DF)
C
C****** DETERMINE OVERLAY AC THICKNESS
```

```
C
    ATP=2.2233+0.0099*(DF-DEFF)*(DF-DEFF)-0.1534*(DF-DEFF)
    DOVER=ATP*(DF-DEFF)
C
C***** OUTPUT 2 *****
C
    WRITE(3,80)PT,W1,W2,W3,W4,W5,RL,EEX,KSUB,DEFF,DF,DOVER
 80 FORMAT(F6.3,1X,5F6.3,1X,F5.2,1X,F10.0,F6.1,2(1X,F5.2),F6.2)
C
C***** STATISTICAL CALCULATION
C
    E1ST=E1ST+DOVER
    E2ND=E2ND+DOVER*DOVER
    GOTO 70
100 E1ST=E1ST/IA
    E2ND=E2ND/IA
    DMEAN=E1ST
    DSTD=SQRT(E2ND-E1ST*E1ST)
    DOVER=DMEAN+(-1)*ZR*DSTD
C
C***** OUTPUT 3 *****
C
    ZR=(-1)*ZR
    WRITE(3,45)
    WRITE(3,110)
110 FORMAT(///'STATISTICAL RESULTS SUMMARY:')
    WRITE(3,120)IA,DMEAN,DSTD,R,DOVER
120 FORMAT(/' NUMBER OF DATA POINTS         = ',I10,
   +/' AVG A(Dreq - Deff)          = ',F10.3,
   +/' STD A(Dreq - Deff)          = ',F10.3,/
   +/' DESIGN AC OVERLAY THICKNESS'
   +/' AT ',F5.2,'% RELIABILITY LEVEL    = ',F10.2)
    CLOSE(2)
    CLOSE(3)
    RETURN
    END
CC ***********************************************************************
CC          SUBROUTINE RELIABILITY
CC ***********************************************************************
    SUBROUTINE RELI(R,ZR)
    DIMENSION AR(18), AZR(18)
    DATA AR/50, 60, 70, 75, 80, 85, 90, 91,92, 93, 94, 95, 96, 97,
   +98, 99, 99.9, 99.99/
    DATA AZR/0.0, 0.253, 0.524, 0.674, 0.841, 1.037, 1.282, 1.340,
   +1.405, 1.476, 1.555, 1.645, 1.751, 1.881, 2.054, 2.327, 3.090,
   +3.750/
    DO 50 I=1,18
      IF(R .GE. AR(I) .AND. R .LE. AR(I+1)) THEN
        ZR=AZR(I)+(AZR(I+1)-AZR(I))*(R-AR(I))/(AR(I+1)-AR(I))
        GOTO 100
```

```
      END IF
   50 CONTINUE
  100 ZR=(-1)*ZR
      RETURN
      END
CC ************************************************************************
CC          SUBROUTINE BACKCALCULATION
CC ************************************************************************
      SUBROUTINE BACKCAL(EEX, KSUB, TK, PS)
      IMPLICIT REAL(K)
      COMMON/C6/W1, W2, W3, W4, W5, RL
      DIMENSION RADIUS(19), AREA(19)
C***** P = TESTING LOADING *****
      P=1000
C***** AR = RADIUS OF CONTACT AREA *****
      AR=2.257
C**** AREA/STIFFNESS RADIUS CURVE *****
      DATA RADIUS/10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60,
     $65, 70, 75, 80, 85, 90, 95, 100/
      DATA AREA/10.628, 16.989, 21.865, 25.438, 28.032, 29.941,
     $31.376, 32.479, 33.345, 34.036, 34.598, 35.061, 35.447,
     $35.773, 36.052, 36.291, 36.499, 36.681, 36.841/
C***** CALCULATE AREA AND INTERPOLATE FOR STIFFNESS RADIUS *****
      AREA1=(2.81*(W1+W2)+5.19*(W2+W3)+5.68*(W3+W4)+
     $5.835*(W4+W5))/W1
      DO 50 I=1,18
        IF(AREA1.GT.AREA(I).AND.AREA1.LE.AREA(I+1))THEN
          RL=RADIUS(I)+(RADIUS(I+1)-RADIUS(I))*(AREA1-AREA(I))/
     $      (AREA(I+1)-AREA(I))
        GOTO 80
        END IF
   50 CONTINUE
      WRITE(*,60)AREA1
   60 FORMAT(/' AREA=',F10.3,' OUT OF RANGE!')
      GOTO 100
   80 S=10.0/RL
      AL=AR/RL
      CALL INTERP(S,AL,W11)
      EEX=1000*12*P*RL*RL*(1-PS*PS)*W11/(TK**3*W1)
      KD=1000*W11*P/(W1*RL*RL)
      KSUB=0.5*KD
  100 RETURN
      END
CC ************************************************************************
CC          SUBROUTINE INTERPOLATE
CC ************************************************************************
      SUBROUTINE INTERP(S,AL,W)
      Y1=0.12592-1.9334*0.01*S-4.4026*0.01*S*S+2.2903*0.01*S**3-
     $4.3265*0.001*S**4+2.9147*0.0001*S**5
      Y2=0.11399-5.8421*0.001*S-4.6153*0.01*S*S+2.1074*0.01*S**3-
```

```
     $3.6447*0.001*S**4+2.2743*0.0001*S**5
      Y3=9.5961*0.01+1.2830*0.0001*S-3.7181*0.01*S*S+1.5007*0.01*S**3-
     $2.3239*0.001*S**4+1.3040*0.0001*S**5
      Y4=6.2771*0.01+4.1902*0.0001*S-1.1447*0.01*S*S+1.3215*0.001*S**3+
     $3.7434*0.0001*S**4-5.6973*0.00001*S**5
      Y5=3.8249*0.01-3.2254*0.001*S+2.4954*0.001*S*S-3.0040*0.001*S**3+
     $7.1804*0.0001*S**4-4.9843*0.00001*S**5
      IF(AL.GT.0.0.AND.AL.LE.0.5)THEN
       W=Y1+(Y2-Y1)*AL/0.5
       GOTO 100
      END IF
      IF(AL.GT.0.5.AND.AL.LE.1.0)THEN
       W=Y2+(Y3-Y2)*(AL-0.5)/0.5
       GOTO 100
      END IF
      IF(AL.GT.1.0.AND.AL.LE.2.0)THEN
       W=Y3+(Y4-Y3)*(AL-1.0)
       GOTO 100
      END IF
      IF(AL.GT.2.0.AND.AL.LE.3.0)THEN
       W=Y4+(Y5-Y4)*(AL-2.0)
       GOTO 100
      END IF
      WRITE(*,20)
   20 FORMAT(' THE a/l ratio is out of range(0 - 3).')
  100 RETURN
      END
CC ***************************************************************************
CC            SUBROUTINE DREQUIRED
CC ***************************************************************************
      SUBROUTINE DREQ(DF)
      IMPLICIT REAL(K)
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      DPSI=PSII-PSIT
      A1=20
   10 D=A1
      CALL AASHTOR(E18A, D)
      IF(E18A .LT. E18)THEN
       A1=A1+3
       GOTO 10
      END IF
C***** ITERATION BY INTERVAL HALVING *****
      A2=0.0
   50 IF((A1-A2) .LT. 0.003) GOTO 60
      A3=(A1+A2)/2.0
      CALL AASHTOR(E18A, A3)
      IF(E18A .LT. E18) THEN
       A2=A3
      ELSE
       A1=A3
```

```
      END IF
      GOTO 50
   60 DF=(A1+A2)/2
      RETURN
      END
CC ************************************************************************
CC          SUBROUTINE AASHTORIGID
CC ************************************************************************
      SUBROUTINE AASHTOR(E18A, D)
      IMPLICIT REAL(K)
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      DPSI=PSII-PSIT
      A1=ZR*S0+7.35*LOG10(D+1)-0.06
      A2=LOG10(DPSI/3.0)/(1.0+1.624*10**7/((D+1)**8.46))
      A3=4.22-0.32*PSIT
      A4=SC*CD*(D**0.75-1.132)
      A5=215.63*AJ*(D**0.75-18.42/((EC/KSUB)**0.25))
      E18A=A1+A2+A3*LOG10(A4/A5)
      E18A=10**E18A
      RETURN
      END
CC ************************************************************************
CC
CC          SUBROUTINE OFLEXIBLE
CC
CC ************************************************************************
      SUBROUTINE OFLEX
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      COMMON/C4/AMR, DEPTH, DAC, TP, TA
      CALL RELI(R,ZR)
      IA=0
      E1ST=0.0
      E2ND=0.0
C
C***** TEMPERATURE CORRECTION *****
C
      IF(DAC .LT. 2) THEN
        AJ=1
        GOTO 10
      END IF
      T1=TA+TP
      CALL TEMP(DAC,T1,TMEAN,AJ)
C
C***** OUTPUT 1 *****
C
   10 WRITE(3,*)' '
      WRITE(3,*)'EXISTING PAVEMENT TYPE:      FLEXIBLE'
      WRITE(3,*)'OVERLAY PAVEMENT TYPE:        AC OVERLAY'
      WRITE(3,12)
   12 FORMAT(//'GEOMETRY OF EXISTING PAVEMENT:')
```

```
      WRITE(3,15)DEPTH,DAC
   15 FORMAT(/' TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE  = ',F6.2,
     +/' SURFACE AC LAYER THICKNESS             = ',F6.2/)
      WRITE(3,17)
   17 FORMAT(/'TEMPERATURE ADJUSTMENT: ')
      WRITE(3,20)TP,TA,TMEAN,AJ
   20 FORMAT(/' PAVEMENT SURFACE TEMPERATURE   = ',F5.1,
     +/' 5-DAY MEAN AIR TEMPERATURE     = ',F5.1,
     +/' PAVEMENT MEAN TEMPERATURE      = ',F5.1,
     +/' W1 ADJUSTMENT FACTOR, AJ       = ',F5.3/)
      WRITE(3,22)
   22 FORMAT(/'OVERLAY DESIGN:')
      WRITE(3,25)E18,R,ZR,S0,PSII,PSIT
   25 FORMAT(/' DESIGN TRAFFIC,           E18 = ',F10.0,
     +/' RELIABILITY,              R = ',1X,F7.1,'%',
     +/'                        ZR = ',2X,F7.3,
     +/' TRAFFIC STANDARD DEVIATION, S0 = ',2X,F7.2,
     +/' INITIAL PSI               = ',2X,F7.2,
     +/' TERMINAL PSI                 = ',2X,F7.2/)
      WRITE(3,27)
   27 FORMAT(/'________________________________________________________________
     +______________'/)
      WRITE(3,30)
   30 FORMAT(' No',3X,' W1  ',2X,' W5  ',4X,'   MR   ',2X,
     +'   Ep    ',3X,' SNeff',2X,' SNreq',4X,' Dover')
      WRITE(3,35)
   35 FORMAT(5X,'(mils)',1X,'(mils)',4X,' (psi)  ',2X,'  (psi)   ',
     +22X,'(in.) ')
      WRITE(3,27)
C
C***** INPUT DYNAFLECT DATA *****
C
   50 READ(2,60) PT,W1,W5
      W1A=AJ*W1
   60 FQRMAT(2X,F6.3,3X,F7.2,21X,F7.2)
      IF(PT .EQ. 0) GOTO 500
C
C***** CALCULATION OF AMR *****
C
      IA=IA+1
      AMRC=4895/W5
C
C***** DETERMINE PAVEMENT ELASTIC MODULUS, Ep
C
  100 A1=0.0
      A2=6.0E6
  110 CALL FBACK(AMRC,DEPTH,A2,W0)
      IF(W0 .GT. W1A) THEN
        A2=A2+1.0E6
        GOTO 110
```

```
    END IF
 120 IF((A2-A1) .LT. 10) GOTO 200
    A3=(A1+A2)/2
    CALL FBACK(AMRC,DEPTH,A3,W0)
    IF(W0 .GT. W1A) THEN
     A1=A3
    ELSE
     A2=A3
    END IF
    GOTO 120
 200 EP=(A1+A2)/2
C
C***** SNEFF=EFFECTIVE SN OF EXISTING PAVEMENT
C
    SNEFF=0.0045*DEPTH*EP**0.3333
C
C***** SNREQ=REQUIRED SN DETERMINATION
C
    AMR=AMRC/3
    SN1=0.0
    SN2=10.0
 210 CALL AASHTOF(SN2,E18A)
    IF(E18A .LT. E18) THEN
     SN2=SN2+3
     GOTO 210
    END IF
C
C***** ITERATION BY INTERVAL HALVING
C
 220 IF((SN2-SN1) .LT. 0.001) GOTO 230
    SN3=(SN1+SN2)/2
    CALL AASHTOF(SN3, E18A)
    IF(E18A .LT. E18) THEN
     SN1=SN3
    ELSE
     SN2=SN3
    END IF
    GOTO 220
 230 SNREQ=(SN1+SN2)/2
C
C***** OVERLAY THICKNESS DETERMINATION
C
    DOVER=(SNREQ-SNEFF)/0.44
C
C***** OUTPUT 2 *****
C
    WRITE(3,250) IA,W1,W5,AMRC,EP,SNEFF,SNREQ,DOVER
 250 FORMAT(I3,2(2X,F5.3),4X,F8.0,2X,F10.0,4X,F6.3,2X,F6.3,4X,F6.2)
C
C***** STATISTICAL CALCULATION *****
```

```
C
    E1ST=E1ST+DOVER
    E2ND=E2ND+DOVER*DOVER
    GOTO 50
 500 E1ST=E1ST/IA
    E2ND=E2ND/IA
    DMEAN=E1ST
    DSTD=SQRT(E2ND-E1ST*E1ST)
    DOVER=DMEAN+(-1)*ZR*DSTD
C
C***** OUTPUT 3 *****
C
    ZR=(-1)*ZR
    WRITE(3,27)
    WRITE(3,505)
 505 FORMAT(///'STATISTICAL RESULTS SUMMARY:')
    WRITE(3,510)IA,DMEAN,DSTD,ZR,DOVER
 510 FORMAT(/' NUMBER OF DATA POINTS          = ',I10,
   +/' MEAN OF OVERLAY                = ',F10.3,
   +/' STANDARD DEVIATION OF OVERLAY  = ',F10.3,
   +/' ZR                   = ',F10.3
   +/' DESIGN OVERLAY                 = ',F10.2)
    CLOSE(2)
    CLOSE(3)
    RETURN
    END
CC  ***************************************************************************
CC
CC          SUBROUTINE TEMPERATURE ADJUSTMENT
CC
CC  ***************************************************************************
    SUBROUTINE TEMP(D,T1,TMEAN,AJ)
C
C***** DETERMINE PAVEMENT MEAN TEMPERATURE
C***** BASED ON 1986 AASHTO GUIDE
C
    A1=0.6*T1-6
    A2=0.56*T1-3.53
    A4=0.51*T1-1.53
    A6=0.473*T1+3
    A8=0.458*T1+5
    A12=0.427*T1+9
C
C***** TS=TEMPERATURE AT 1 INCH DEPTH
C
    TS=A1
C
C***** TM=TEMPERATURE AT MID THICKNESS
C
    D1=D/2
```

```
    IF(D1 .LE. 1) THEN
     TM=A1
    ELSE IF(D1 .GT. 1 .AND. D1 .LE. 2) THEN
     TM=A1+(D1-1)*(A2-A1)
    ELSE IF(D1 .GT. 2 .AND. D1 .LE. 4) THEN
     TM=A2+(A4-A2)*(D1-2)/2
    ELSE IF(D1 .GT. 4 .AND. D1 .LE. 6) THEN
     TM=A4+(A6-A4)*(D1-4)/2
    ELSE IF(D1 .GT. 6 .AND. D1 .LE. 8) THEN
     TM=A6+(A8-A6)*(D1-6)/2
    ELSE IF(D1 .GT. 8 .AND. D1 .LE. 12) THEN
     TM=A8+(A12-A8)*(D1-8)/4
    ELSE IF(D1 .GT. 12) THEN
     TM=A12
    END IF
C
C***** TB=TEMPERATURE AT BOTTOM OF THICKNESS
C
    IF(D .LE. 1) THEN
     TB=A1
    ELSE IF(D .GT. 1 .AND. D .LE. 2) THEN
     TB=A1+(D-1)*(A2-A1)
    ELSE IF(D .GT. 2 .AND. D .LE. 4) THEN
     TB=A2+(A4-A2)*(D-2)/2
    ELSE IF(D .GT. 4 .AND. D .LE. 6) THEN
     TB=A4+(A6-A4)*(D-4)/2
    ELSE IF(D .GT. 6 .AND. D .LE. 8) THEN
     TB=A6+(A8-A6)*(D-6)/2
    ELSE IF(D .GT. 8 .AND. D .LE. 12) THEN
     TB=A8+(A12-A8)*(D-8)/4
    ELSE IF(D .GT. 12) THEN
     TB=A12
    END IF
C
C***** TMEAN=PAVEMENT MEAN TEMPERATURE
C
    TMEAN=(TS+TM+TB)/3
C
C***** DETERMINATION OF TEMP. ADJUSTMENT FACTOR, AJ
C
    A2=-4.211*0.001*TMEAN+1.2863
    B2=-3.846*0.001*TMEAN+1.2615
    A4=-7.368*0.001*TMEAN+1.501
    B4=-6.538*0.001*TMEAN+1.445
    A8=-8.684*0.001*TMEAN+1.591
    B8=-9.615*0.001*TMEAN+1.654
    A12=-9.474*0.001*TMEAN+1.644
    B12=-1.154*0.01*TMEAN+1.785
    IF(D .LE. 2) GOTO 10
    IF(D .GT. 2 .AND. D .LE. 4) GOTO 20
```

```
    IF(D .GT. 4 .AND. D .LE. 8) GOTO 30
    IF(D .GT. 8 .AND. D .LE. 12) GOTO 40
    GOTO 50
 10 IF(TMEAN .LE. 68) THEN
     AJ=A2
    ELSE
     AJ=B2
    END IF
    GOTO 100
 20 IF(TMEAN .LE. 68) THEN
     AJ=A2+(A4-A2)*(D-2)/2
    ELSE
     AJ=B2+(B4-B2)*(D-2)/2
    END IF
    GOTO 100
 30 IF(TMEAN .LE. 68) THEN
     AJ=A4+(A8-A4)*(D-4)/4
    ELSE
     AJ=B4+(B8-B4)*(D-4)/4
    END IF
    GOTO 100
 40 IF(TMEAN .LE. 68) THEN
     AJ=A8+(A12-A8)*(D-8)/4
    ELSE
     AJ=B8+(B12-B8)*(D-8)/4
    END IF
    GOTO 100
 50 IF(TMEAN .LE. 68) THEN
     AJ=A12
    ELSE
     AJ=B12
    END IF
100 RETURN
    END
CC ****************************************************************************
CC
CC          SUBROUTINE CALCULATION OF SURFACE DEFLECTION
CC
CC ****************************************************************************
    SUBROUTINE FBACK(AMR,D,EP,W0)
    CALL FVALUE(0.0,F0)
    CALL FVALUE(D,FD)
    WP=70531.*(F0-FD)/EP
    DE=D*(EP/AMR)**0.3333
    CALL FVALUE(DE,FDE)
    WS=70531*FDE/AMR
    W0=WP+WS
    RETURN
    END
```

```
CC *************************************************************************
CC
CC          SUBROUTINE F(Z) VALUE INTERPOLATION
CC
CC *************************************************************************
      SUBROUTINE FVALUE(D,FZ)
      DIMENSION Z(20),F(20)
      DATA Z/0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, 28, 30, 35,
     +40, 60, 80, 100, 1000/
      DATA F/0.4027, 0.4027, 0.4097, 0.4105, 0.4034, 0.3878, 0.3679,
     +0.3467, 0.3254, 0.3048, 0.2857, 0.2517, 0.2240, 0.2113, 0.1857,
     +0.1652, 0.1141, 0.0865, 0.0695, 0.00638/
      DO 50 I=1,20
        IF(D .GE. Z(I) .AND. D .LT. Z(I+1)) THEN
          FZ=F(I)+(F(I+1)-F(I))*(D-Z(I))/(Z(I+1)-Z(I))
          GOTO 100
        END IF
   50 CONTINUE
  100 RETURN
      END
CC *************************************************************************
CC
CC          SUBROUTINE FLEXIBLE AASHTO EQUATION
CC
CC *************************************************************************
      SUBROUTINE AASHTOF(SN, E18A)
      COMMON/C3/E18, R, ZR, S0, DS, PSII, PSIT, EC, SC, AJ, CD, KSUB
      COMMON/C4/AMR, DEPTH, DAC, TP, TA
      DPSI=PSII-PSIT
      A1=ZR*S0+9.36*LOG10(SN+1)-0.20
      A2=LOG10(DPSI/2.7)/(0.40+1094/(SN+1)**5.19)
      A3=2.32*LOG10(AMR)-8.07
      E18A=A1+A2+A3
      E18A=10**E18A
      RETURN
      END
```