EVERSERIES© USER'S GUIDE
Pavement Analysis Computer Software and Case Studies

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FOREWORD

This user's guide includes descriptions of four computer software programs and three case studies, which will highlight hot mix asphalt overlay and design procedures.

The units used in this guide will be US customary. The three WSDOT computer programs – Everstress©, Evercalc©, and Everpave© – are capable of calculating in both US customary and in metric units. The AASHTO computer program AASHTO DARWin®, at the writing of this user's guide, was only capable of using US customary units.

Additional References

Additional references for the Everseries© pavement analysis software programs can be found in the following publications:

1. Bu-Bushait, A., "Development of a Flexible Pavement Fatigue Model for Washington State", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1985.

2. Newcomb, D. E., "Development and Evaluation of a Regression Method to Interpret Dynamic Pavement Deflections", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1986.

3. Lee, S. W., "Backcalculation of Pavement Moduli by Use of Pavement Surface Deflections", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1988.

4. Lee, S. W., Mahoney, J. P., and Jackson, N. C., "A Verification of Backcalculation of Pavement Moduli", *Transportation Research Board* No. 1196, Transportation Research Board, Washington DC, 1988.

5. Sivaneswaran, N., Kramer, S. L., and J. P. Mahoney, "Advanced Backcalculation Using a Nonlinear Least Squares Optimization Technique", *Transportation Research Board* No. 1293, Transportation Research Board, Washington DC, 1991.

6. Sivaneswaran, N., "Applications of System Identification in Geotechnical Engineering", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1993.

7. Mahoney, J. P., Winters, B. C., Jackson, N. C., and Pierce, L. M., "Some Observations about Backcalculation and Use of a Stiff Layer Condition", *Transportation Research Board* No. 1384, Transportation Research Board, Washington DC, 1993.

8. Pierce, L. M., Jackson, N. C., and Mahoney, J. P., "Development and Implementation of a Mechanistic-Empirical Based Overlay Design Procedure for Flexible Pavements", *Transportation Research Board* No. 1388, Transportation Research Board, Washington DC, 1993.

9. Mahoney, J. P. and Pierce, L. M., "An Examination of WSDOT Transfer Functions for Mechanistic-Empirical AC Overlay Design", *Transportation Research Board* No. 1539, Transportation Research Board, Washington DC, 1996.

10. Pierce, L. M. and Mahoney, J. P., "Asphalt Concrete Overlay Design Case Studies", *Transportation Research Board* No. 1543, Transportation Research Board, Washington DC, 1996.

Software Disclaimer

The Washington State Department of Transportation does not warrantee anything concerning any of the programs or files, which make up the Everseries© Pavement Analysis Programs. We accept no responsibility for any loss or damage of any kind, which results from the use or purported use of the Everseries© Pavement Analysis Programs, or any files in the package, for any purpose whatsoever.

1.1 INTRODUCTION

The Everstress© program is capable of determining the stresses, strains, and deflections in a layered elastic system (semi-infinite) under circular surface loads. The program can analyze a pavement structure containing up to five layers, 20 loads and 50 evaluation points. The Everstress© program will also take into account any stress dependent stiffness characteristics.

1.2 CHARACTERISTICS OF EVERSTRESS©

The program can be used to estimate stress, strain or deflection within a layered pavement system due to a static load(s). The modulus of elasticity, Poisson's ratio and thickness must be defined for each layer. Further, the load magnitude, contact pressure (or load radius) and location must be defined for each load (wheel) considered.

Everstress© was developed from WESLEA layered elastic analysis program (provided by the Waterways Experiment Station, U.S. Army Corps of Engineers). The pavement system model is multi-layered elastic using multiple wheel loads (up to 20). The program can analyze hot mix asphalt (HMA) pavement structure containing up to five layers and can consider the stress sensitive characteristics of unbound pavement materials.

The consideration of the stress sensitive characteristics of unbound materials can be achieved through adjusting the layer moduli in an iterative manner by use of stress-modulus relationships as follows [1]:

$Eb = K_1\theta K_2$ for granular soils, Equation 1

$Es = K_3\sigma_d K_4$ for fine grained soils, Equation 2

where,

E_b	=	resilient modulus of granular soils (ksi or MPa),
E_s	=	resilient modulus of fine grained soils (ksi or MPa),
θ	=	bulk stress (ksi or MPa),
σ_d	=	deviator stress (ksi of MPa), and
K_1, K_2, K_3, K_4	=	regression constants

K1 and K3 are dependent on moisture content, which can change with the seasons. K2 and K4 are related to soil types, either coarse grained or fine-grained soil. K2 is positive and K4 is negative and remain relatively constant with the seasons.

Each iteration of the program, when stress dependent layers are used includes pavement analysis, modulus calculation and comparison, and modulus adjustment. The pavement analysis provides the stresses, strains, and deflections. The inspection points for the pavement analysis are typically, vertically at the bottom of the HMA layers, at mid-depth of unbound base and subbase courses, and at the top of subgrade. Inspection points can be placed as necessary by the user and are limited to a total of 50 inspection points.

Bulk stress is calculated for coarse-grained soil layers, and deviator stress for fine-grained soil layers. Required moduli are determined by use of the stress-modulus relationships (Equations 1 and 2), and compared to the moduli used for the pavement analysis. If the sum of the modulus difference is less than the allowable tolerance (an input requirement), then the program produces a solution. Otherwise, the iteration process is repeated until the modulus difference becomes less than the allowable tolerance or the iteration reaches the maximum allowable iteration (input requirement).

1.2.1 Hardware Requirements

The Everstress© program is coded in Microsoft Visual Basic and Microsoft FORTRAN Power Station 4.0 and is designed to run on IBM or compatible personal computers with Microsoft Windows 95/NT 4.0 or higher.

1.2.2 Installation of the Program

To install the program, start Windows, click on the **Start** button, select Run and type a:\setup or select **Browse** and locate the SETUP.EXE. Prior to installation of the program(s) the user will be shown the README.TXT. It is highly recommended that this file be reviewed prior to the installation of the program(s). Once README.TXT has been reviewed, the user is asked to select the source directory (default - a:\), the target directory (default = C:\EVERSERS), and which programs are to be installed. The user has the option of selecting Everstress©, Evercalc©, Everpave©, or any combination of the above. Once satisfied with the selection, select **Start Install**.

1.2.3 Program Contents

The following paragraphs describe each of the various menus and inputs of the program.

1.2.3.1 File

Prepare Input Data - This menu option provides a form to create an INPUT DATA File or edit an existing file. INPUT DATA File contains layer information, load information, and evaluation points.

Analyze Pavement - This menu option performs the actual analysis and requires the INPUT DATA File. The analysis is carried out in a DOS window and it is advised that you don't switch windows until the completion of the Analysis.

Print/View Output - This menu option lets the user view the output on the screen and optionally prints it on the Windows default printer.

Exit – This menu option closes the program and returns the user to the Windows desktop.

1.2.3.2 Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

About Everstress© - lists program version information, responsible agency and personnel contacts, system memory and resources.

1.2.3.3 Prepare Input Data

File

Open – Open previously saved Data File.

Save - Save the current INPUT DATA File under the same name.

Save As - Save the current INPUT DATA File under a different name.

NOTE: The user must save all data entry files, the program will not automatically save any entries or prompt user to save file.

Exit - Exit Input Data Entry. Selecting exit will not prompt for saving. The user must save the data prior to exiting this screen.

Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

Entry Data

Title - Text for identification purposes.

No of Layers - Total number of layers in the pavement structure. The maximum number of layers is limited to five.

Units - Units of measurement, either metric or US Customary.

Layer Information

No - Layer number. The upper most layer is designated as number 1 and proceeds sequentially downward. This entry is for Everstress© file structure only and cannot be edited by the user.

Layer ID - Identifies whether the moduli of the layer is stress sensitive

0 - Moduli is stress insensitive (HMA material)

1 - Moduli varies with bulk stress (coarse grained soil)

$$E = \text{Multiplier} \times (\text{Bulk Stress}/\text{Atmospheric Pressure})^{\text{Power}} \quad \text{Equation 3}$$

2 - Moduli varies with deviator stress (fine grained soil)

$$E = \text{Multiplier} \times (\text{Deviator Stress}/\text{Atmospheric Pressure})^{\text{Power}} \quad \text{Equation 4}$$

Note: It was customary to use the following form of the equation to describe stress sensitive moduli:

Coarse Grained Material

$E = \text{Multiplier} * (\text{Bulk Stress})^{\text{Power}}$ Equation 5

Fine Grained Material

$E = \text{Multiplier} * (\text{Deviator Stress})^{\text{Power}}$ Equation 6

The new coefficients are related to these coefficients by the following relationships:

Power New = Power Old

$\text{Multiplier New} = (\text{Multiplier Old})(\text{Atmospheric Pressure})^{\text{Power Old}}$

Example:

$E = 8500 \times (\text{Bulk Stress})^{0.375}$ would be equivalent to

$E = 8500 \times (14.696)^{0.375} \times (\text{Bulk Stress/Atmospheric Pressure})^{0.375}$

The atmospheric pressure is in the same units as the stress (14.696 psi or 101.4 kPa). The bulk and deviator stress includes static (overburden) stress. The stresses used are calculated at X = 0, Y = 0 and at the bottom of the 1st layer, at the middle of the intermediate layers, and at the top of the last layer. The loading locations should be specified with this in mind.

Interface Contact – Describes the frictional contact between layers.

Value	Description
0	Full slip at the layer interface
1	Complete adhesion at the layer interface (no slip)
2 - 1000	Partial slip (also varies with E and Poisson's ratio)

Poisson's Ratio - Enter the Poisson's ratio for each layer. The following are typical values for Poisson's Ratio:

Hot mix asphalt	0.35
Crushed surfacing base	0.40
Subgrade	0.45

Thickness - Enter the thickness of each layer (inch or cm).

Moduli - Resilient modulus for each layer. If this layer is stress sensitive, this will be used as the initial moduli and the program will compute a stress compatible moduli iteratively (ksi or MPa).

Multiplier - If this layer is stress sensitive, use the multiplier regression coefficients as described in Layer ID above. If Layer ID is equal to zero, then this entry will not apply and the program will automatically remove the data box.

Power - If this layer is stress sensitive, use K2 or K4 regression coefficients. If Layer ID is equal to zero, then this entry will not apply and the program will automatically remove the data box.

Max. Iteration - If any of the layers are stress sensitive, the maximum number of iterations allowed in obtaining stress compatible moduli. A value of five is typical used.

Modulus Tol. (%) - If any of the layers are stress sensitive, modulus percentage tolerance in successive iterations. A value of 1.0 is typically used.

Load/Evaluation Locations

No. of Loads - Number of loads applied to the pavement structure. Currently the program is limited to a maximum of 20 loads.

No of X-Y Evaluation Points - Number of X-Y evaluation points. Currently the program is limited to a maximum of 50 points, this includes all combinations of X-Y and Z locations. For example, if the user enters five X-Y locations and three Z locations for each X-Y location, then the number of evaluation points is 5 (X-Y) x 3 (Z) = 15. Each X-Y point can have up to five points in the Z direction. If more than five points in the Z direction are needed at the same X-Y locations, then the next evaluation point can be used with the same X-Y locations.

X-Position - X coordinate of the load/evaluation point (inch or cm).

Y-Position - Y-coordinate of the load/evaluation point (inch or cm).

Z-Position - Z-coordinate of the evaluation point (inch or cm).

Load - Magnitude of the load (lb. or N).

Pressure - Contact pressure of the applied load (psi or kPa).

Radius - Radius of the loaded area.

Note: Only two of the above three (load, pressure, radius) are required, the third value will be automatically calculated (inch or cm).

Unit Weight

The unit weight of each material layer is required if any of the layer moduli are stress sensitive for the calculation of the overburden pressures. The program provides the following default values, which may be modified as necessary.

Table 1. Material Unit Weight

Layer No.	Layer Description	Unit Weight	
		(lbs/ft^3)	(kN/m^3)
1	Hot mix asphalt	145.0	22.8
2	Crushed Stone Base	130.0	20.5
3	Subgrade	125.0	19.7
4	Subgrade	120.0	18.9
5	Subgrade	120.0	18.9

1.2.3.4 Analyze Pavement

Performs the actual analysis. The program will prompt for the INPUT DATA File and an OUTPUT DATA File. The analysis is carried out in a DOS window and it is advised that you don't switch to other windows until the analysis is completed.

1.2.3.5 Print/View Results

This menu item allows the user to select the output Filename to be either reviewed on the screen or printed to the default Windows printer.

Options – Standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

Output Description - Most of the output quantities are self explanatory, except for the following:

Stresses - stresses due to input wheel load(s) (does not include overburden components).

Strains - strains do not include the static components.

Moduli (1) - moduli specified in the input data.

Moduli (2) - stress compatible moduli calculated (only for stress sensitive materials).

Maximum Error in Modulus - maximum error in the calculated moduli (stress compatible) at the end of the last iteration.

Sxx, Syy, Szz, Syz, Sxy, Sxz - normal stresses in the X-Y-Z directions.

Exx, Eyy, Ezz - normal strains in the X-Y-Z directions.

Ux, Uy, Uz - deflections in the X-Y-Z directions.

S1, S2, S3 - principal stress.

E1, E2, E2 - principal strains.

1.2.4 Execution of the Program

As a general note, any time you save a file in Everstress©, use the same extension as designated by the program. The program calls the required files according to their extension. It will save the user time and keystrokes if the program extension protocols are followed.

After the user has started Windows, the program can be initiated by double clicking onto the Everstress© icon. The screen as shown in Figure 1 will be displayed.

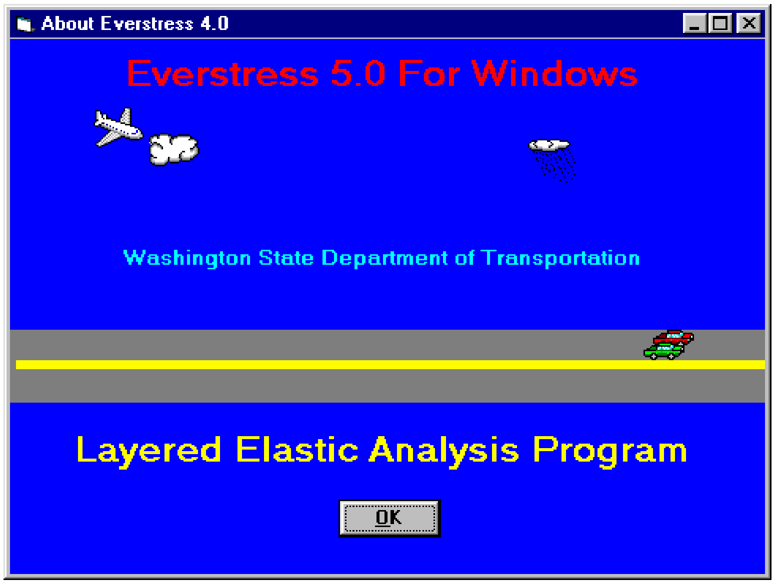


Figure 1. About Everstress© Screen

Press the **OK** button and the screen as shown in Figure 2 will be displayed.

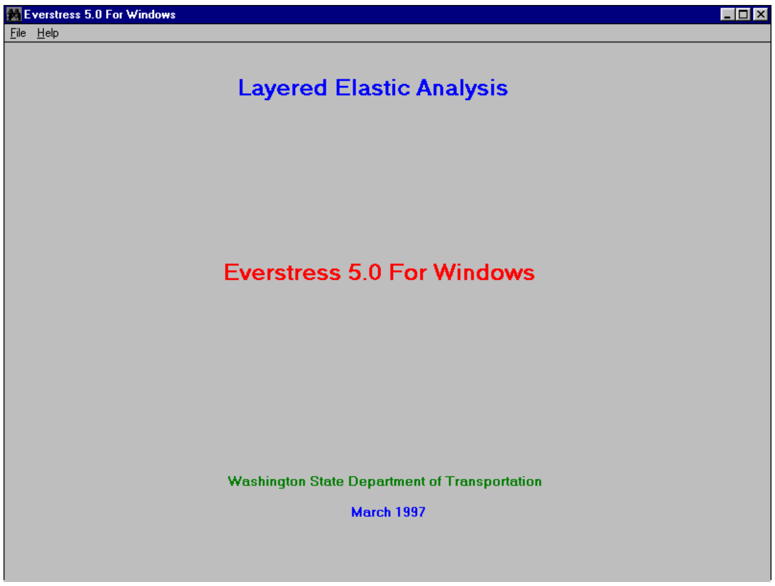


Figure 2. Everstress© Main Screen

To begin the analysis, select **File** and then select **Prepare Input Data**. The screen in Figure 3 will be shown.

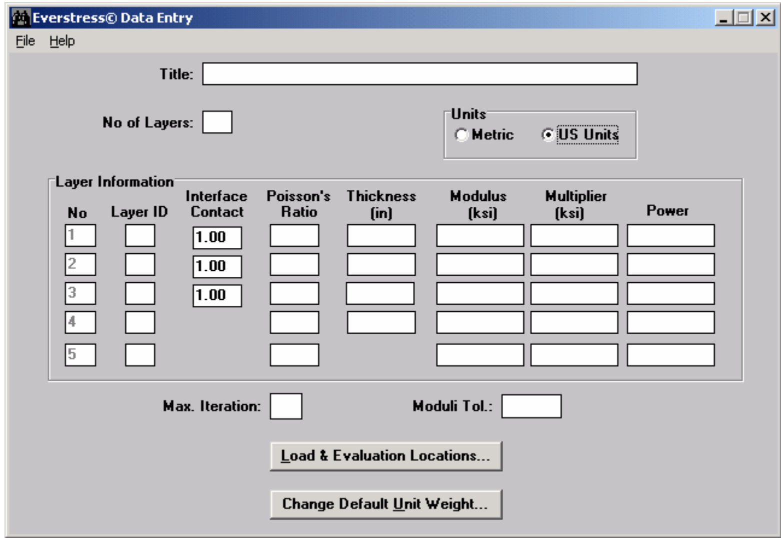


Figure 3. Everstress© Data Entry Screen

Begin by entering a job title, number of layers, type of units and the necessary layer data. Once all inputs have been entered, select **Load & Evaluation Locations** and the screen in Figure 4 will be shown.

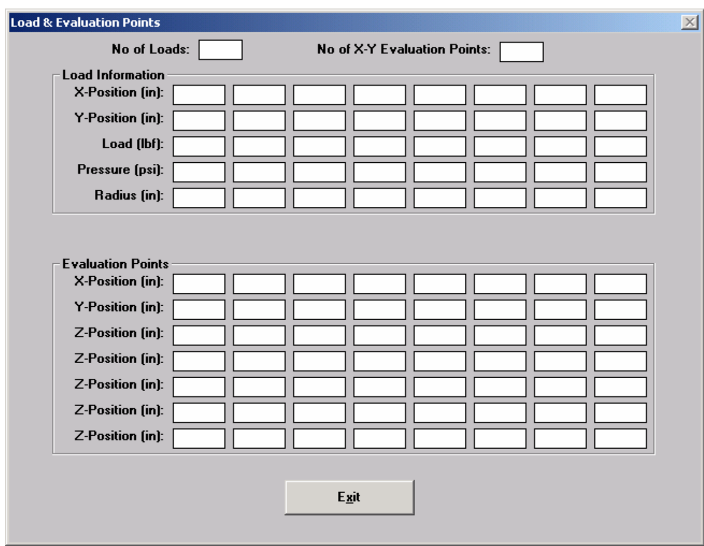


Figure 4. Everstress© Load & Evaluation Points Screen

This screen requires the number of loads, the number of X-Y evaluation points and the X-Y location of each load and evaluation point. The evaluation points will automatically be calculated from the layer thickness entered in the Data Entry Screen. The Z coordinates are set as default locations at the bottom of the HMA layer, at mid-depth of the base course and at the top of the subgrade. In order to insure that the evaluation points are within the HMA layer and the subgrade, 0.001 is subtracted from the HMA depth and 0.001 is added to the HMA plus Base depth. Once all data has been entered, select **Exit** to return to the Data Entry Screen.

To make changes to the default material unit weights, Select **Change Default Unit Weight**. The screen in Figure 5 will be shown. Unit weight values are recommended default values and can be modified as necessary. Select **Exit** to return to the Data Entry Screen.

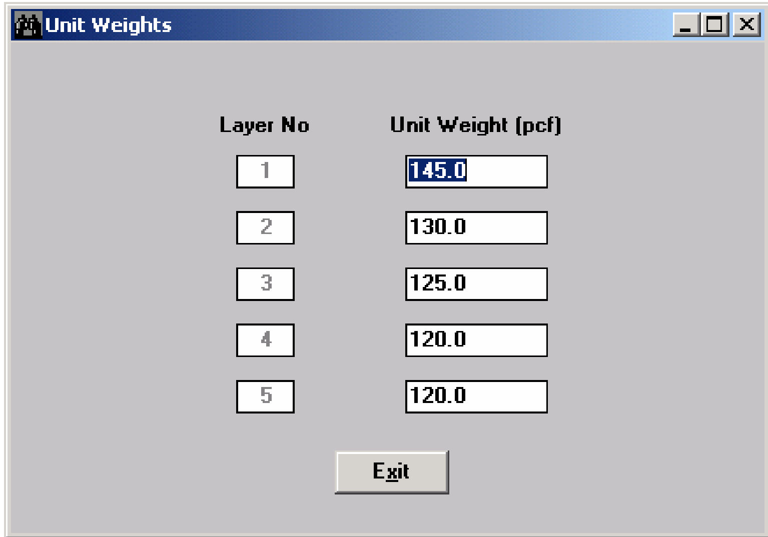


Figure 5. Everstress© Unit Weights Screen

After all data has been entered, the data must be saved. To save the data as a file, select **File** and then select **Save** and enter a filename (using the same extension as shown) and select **OK**.

To analyze the data, select **File** and then select **Analyze Pavement**. The program will then ask the user to select the INPUT DATA Filename. If the file was saved using the Everstress© protocol, then the filename will be shown on the screen. The user can then select the file by double clicking on the filename or by selecting the filename and then selecting **OK**. The program will then automatically create an output filename with ".OUT" as the extension, if this is correct, select **OK**. The program will begin the analysis and inform the user that it is processing the data. Once the analysis has been completed, a version of the following screen will be shown (see Figure 6). Note the program will display the word "Finished" in the lower left hand corner of the screen indicating that the analysis is complete. To exit this screen the user can either select **File** and **Exit** or click on the "X" box in the upper right hand corner of the screen.

To view/print the data, select **File** and then select **Print/View Results**. The computer program will ask the user to select the output filename to be viewed. Select the file by double clicking on the filename or by selecting the filename and then selecting **OK**. The file will be displayed on the screen and can be viewed by pressing the up and down arrows to scroll through a page or by pressing the page up and page down to move from one page to the next, or by pressing the left or right arrow buttons to move from one page to the next. The program allows the user to zoom in and out to better view the data. The preferred font may also be selected for viewing and printing of the data (this font will be set as the default font for future analysis). To print the file, select **Options** and **Print**. To return back to the Main screen, select **Options** and **Exit**.

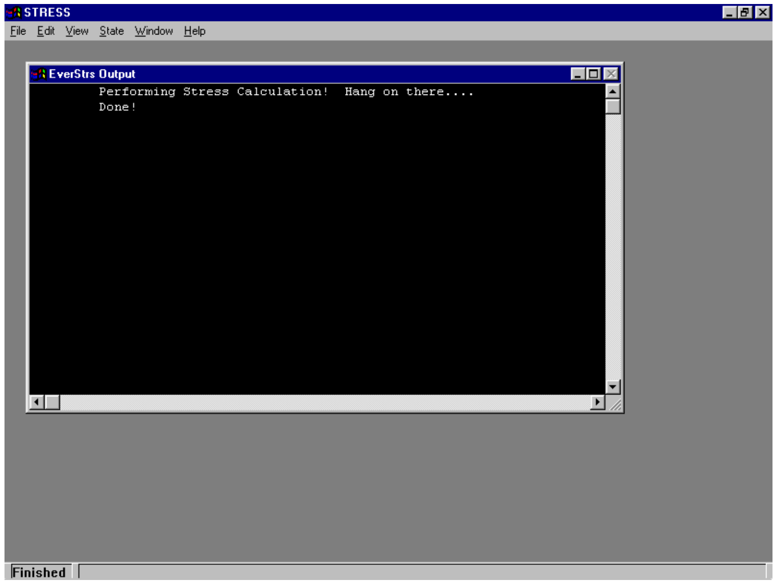


Figure 6. Analysis Completed Screen

To exit the Everstress© program, select **File** and then select **Exit**.

1.2.5 Example

Number of Layers = 3

Layer	Poisson's Ratio	Thickness (in)	Modulus (psi)
HMA	0.35	4	300,000
Base	0.40	6	25,000
Subgrade	0.45		12,000

Number of Loads = 2

Load	X-Position (in)	Y-Position (in)	Load (lb)	Pressure (psi)
1	0	0	4,500	100
2	0	15	4,500	100

Number of Evaluation Points = 3

X-Position (in)	Y-Position (in)	Z-Position #1 (in)	Z-Position #2 (in)	Z-Position #3 (in)
0	0	3.999	6.999	10.001
0	7.5	3.999	6.999	10.001
0	15	3.999	6.999	10.001

1.2.5.1 Printout of Results

Layered Elastic Analysis by Everstress© for Windows

Title: EXAMPLE
No of Layers: 3 No of Loads: 2 No of X-Y Evaluation Points:
3

Layer	Poisson's Ratio	Thickness (in)	Moduli (1) (ksi)
1	.35	4.000	300.00
2	.40	6.000	25.00
3	.45		12.00

Load No	X-Position (in)	Y-Position (in)	Load (lbf)	Pressure (psi)	Radius (in)
1	.00	.00	4500.0	100.00	3.785
2	.00	15.00	4500.0	100.00	3.785

Location No: 1 X-Position (in): .000 Y-Position (in): .000

Normal Stresses

Z-Position (in)	Layer	Sxx (psi)	Syy (psi)	Szz (psi)	Syz (psi)	Sxz (psi)	Sxy (psi)
3.999	1	153.01	131.72	-25.34	2.03	.00	.00
7.000	2	2.35	.32	-14.80	2.00	.00	.00
10.001	3	-.92	-2.09	-9.78	1.38	.00	.00

Normal Strains and Deflections

Z-Position (in)	Layer	Exx (psi)	Eyy (psi)	Ezz (psi)	Ux (mils)	Uy (mils)	Uz (mils)
3.999	1	385.92	290.13	-416.66	.00	-.636	21.870
7.000	2	325.70	211.88	-634.61	.00	-1.068	19.589
10.001	3	368.62	227.14	-702.37	.00	-1.506	17.830

Principal Stresses and Strains

Z-Position (in)	Layer	S1 (psi)	S2 (psi)	S3 (psi)	E1 (10^{-6})	E2 (10^{-6})	E3 (10^{-6})
3.999	1	-25.37	131.75	153.01	-416.78	290.25	385.92
7.000	2	-15.06	.58	2.35	-649.24	226.46	325.70
10.001	3	-10.02	-1.85	-.92	-731.21	255.97	368.62

Location No: 2 X-Position (in): .000 Y-Position (in): 7.500

Normal Stresses

Z-Position (in)	Layer	Sxx (psi)	Syy (psi)	Szz (psi)	Syz (psi)	Sxz (psi)	Sxy (psi)
3.999	1	80.42	-5.08	-13.13	.00	.00	.00
7.000	2	2.52	-1.85	-11.72	.00	.00	.00
10.001	3	-1.00	-2.83	-9.75	.00	.00	.00

Normal Strains and Deflections

Z-Position (in)	Layer	Exx (psi)	Eyy (psi)	Ezz (psi)	Ux (mils)	Uy (mils)	Uz (mils)
3.999	1	289.31	-95.45	-131.62	.00	.00	21.622
7.000	2	31f.03	73.13	-479.51	.00	.00	20.319
10.001	3	388.49	167.47	-669.06	.00	.00	18.775

Principal Stresses and Strains

Z-Position (in)	Layer	S1 (psi)	S2 (psi)	S3 (psi)	E1 (10^{-6})	E2 (10^{-6})	E3 (10^{-6})
3.999	1	-13.13	-5.08	80.42	-131.65	-95.45	289.31
7.000	2	-11.72	-1.85	2.52	-479.57	73.13	318.03
10.001	3	-9.75	-2.83	-1.00	-669.06	167.47	388.49

Location No: 3 X-Position (in): .000 Y-Position (in): 15.000

Normal Stresses

Z-Position (in)	Layer	Sxx (psi)	Syy (psi)	Szz (psi)	Syz (psi)	Sxz (psi)	Sxy (psi)
3.999	1	153.01	131.72	-25.34	-2.03	.00	.00
7.000	2	2.35	.32	-14.80	-2.00	.00	.00
10.001	3	-.92	-2.09	-9.78	-1.38	.00	.00

Normal Strains and Deflections

Z-Position (in)	Layer	Exx (psi)	Eyy (psi)	Ezz (psi)	Ux (mils)	Uy (mils)	Uz (mils)
3.999	1	385.92	290.13	-416.66	.00	.636	21.870
7.000	2	325.70	211.88	-634.61	.00	1.068	19.589
10.001	3	368.62	227.14	-702.37	.00	1.506	17.380

Principal Stresses and Strains

Z-Position (in)	Layer	S1 (psi)	S2 (psi)	S3 (psi)	E1 (10^{-6})	E2 (10^{-6})	E3 (10^{-6})
3.999	1	-25.37	131.75	153.01	-416.78	290.25	385.92
7.000	2	-15.06	.58	2.35	-649.18	226.46	325.70
10.001	3	-10.02	-1.85	-.92	-731.21	255.97	368.62

1.2.6 Interpretation of Example Results

Though all data results can provide insight into pavement behavior, the primary output to review is the normal horizontal strain (Exx or Eyy) at the bottom of the HMA layer (which indicates the potential for fatigue cracking), the normal vertical strain (Ezz) at the middle of the base course (which indicates the potential for rutting in the base course), and the normal vertical strain (Ezz) at the top of subgrade (which indicates the potential for rutting in the subgrade).

2.1 FUNDAMENTALS OF BACKCALCULATION

Backcalculation is essentially a mechanistic evaluation, usually an elastic analysis of pavement surface deflection basins generated by various pavement deflection devices. Backcalculation is where measured and calculated surface deflection basins are matched (to within some tolerable error) and the associated layer moduli required to achieve that match are determined. The backcalculation process is usually iterative and normally done with software that can run on microcomputers. General backcalculation guidelines are contained in paragraph 2.5. An illustration of the backcalculation process is shown in Figure 7 and Figure 8.

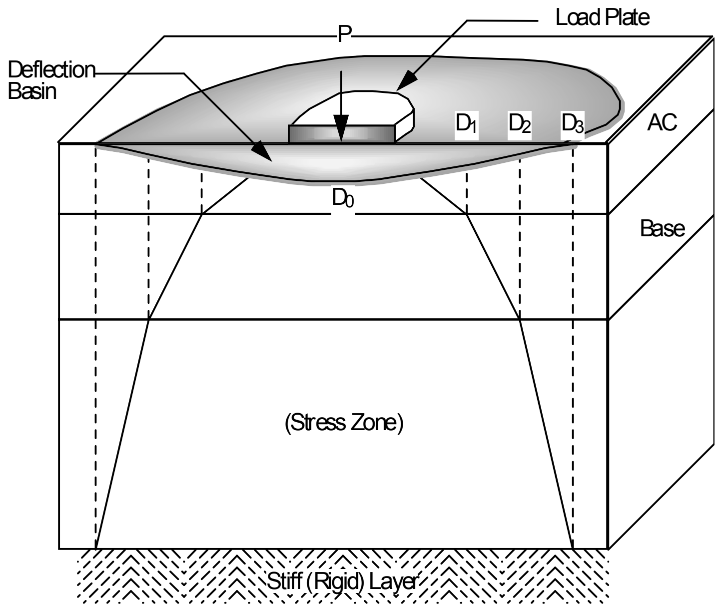


Figure 7. Illustration of Backcalculation to Estimate Layer Moduli

2.1.1 Typical Flowchart

A basic flowchart which represents the fundamental elements in all known backcalculation programs is shown in Figure 9. This flowchart was patterned after one shown by Lytton [2]. Briefly, these elements include:

(a) Measured deflections:
Includes the measured pavement surface deflections and associated distances from the load.

(b) Layer thicknesses and loads:
Includes all layer thicknesses and load levels for a specific test location.

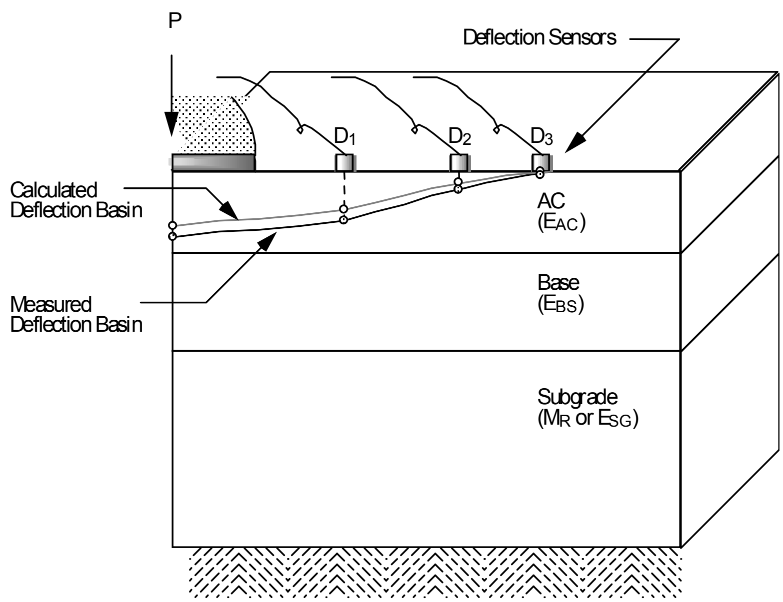


Figure 8. The Backcalculation Process – Matching Measured and Calculated Deflection Basins

(c) Seed moduli:
The seed moduli are the initial moduli used in the computer program to calculate surface deflections. These moduli are usually estimated from user experience or various equations.

(d) Deflection calculation:
Layered elastic computer programs such as CHEVRON, BISAR, or ELSYM5 are generally used to calculate a deflection basin.

(e) Error check:
This element simply compares the measured and calculated basins. There are various error measures, which can be used to make such comparisons.

(f) Search for new moduli:
Various methods have been employed within the various backcalculation programs to converge on a set of layer moduli, which produces an acceptable error between the measured and calculated deflection basins.

(g) Controls on the range of moduli:
In some of the backcalculation programs, a range (minimum and maximum) of moduli are selected or calculated to prevent program convergence to unreasonable moduli levels (could be too high or low).

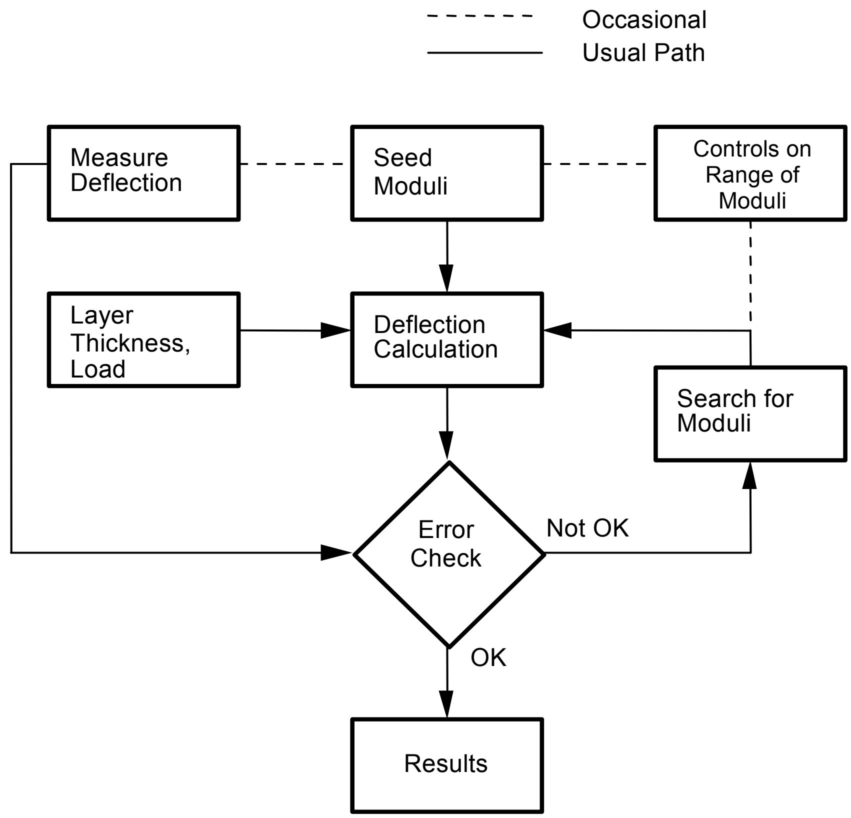


Figure 9. Common Elements of Backcalculation Programs

2.2 MEASURE OF CONVERGENCE

2.2.1 Measure of Deflection Basin Convergence

The primary measure of convergence will be Root Mean Square (RMS) or Root Mean Square Error (RMSE). Both terms are taken to be the same.

$$RMS\ (\%) = \sqrt{\frac{1}{n_d}\sum_{i=1}^{n}\left(\frac{d_{ci} - d_{mi}}{d_{mi}}\right)^2} \times (100) \qquad \text{Equation 7}$$

where,

RMS = root mean square error,
d_{ci} = <u>calculated</u> pavement surface deflection at sensor i,
d_{mi} = <u>measured</u> pavement surface deflection at sensor i, and
n_d = number of deflection sensors used in the backcalculation process.

Example RMS calculation

N_d	Deflections (mils)	
	Measured	Calculated
1 (0")	5.07	4.90
2 (8")	4.32	3.94
3 (12")	3.67	3.50
4 (18")	2.99	3.06
5 (24")	2.40	2.62
6 (36")	1.69	1.86
7 (60")	1.01	0.95

$$\text{RMS (\%)} = \frac{1}{7}\left(\frac{4.90-5.07}{1.01}\right)^2 + \ldots + \left(\frac{0.95-1.01}{1.01}\right)^2$$

= 6.9% (which is very high)

Generally an adequate range of RMS is 1 to 2 percent.

2.3 DEPTH OF STIFF LAYER

Recent literature provides at least two approaches for estimating the depth to stiff layer [3, 4]. The approach used by Rohde and Scullion [3] will be summarized below. There are two reasons for this selection: (1) initial verification of the validity of the approach is documented, and (2) the approach is used in MODULUS 4.0 — a backcalculation program widely used in the U.S.

(a) Basic Assumptions and Description

A fundamental assumption is that the measured pavement surface deflection is a result of deformation of the various materials in the applied stress zone; therefore, the measured surface deflection at any distance from the load plate is the direct result of the deflection below a specific depth in the pavement structure (which is determined by the stress zone). This is to say that only that portion of the pavement structure which is stressed contributes to the measured surface deflections. Further, no surface deflection will occur beyond the offset (measured from the load plate) which corresponds to the intercept of the applied stress zone and the stiff layer (the stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which a zero surface deflection occurs. This is illustrated in Figure 10 where the surface deflection D_C is zero.

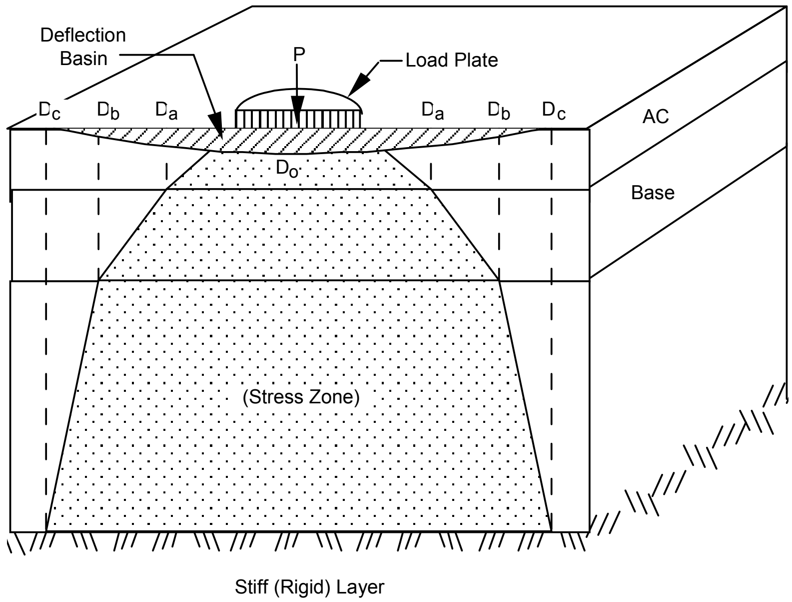


Figure 10. Illustration of Zero Deflection Due to a Stiff Layer

An estimate of the depth at which zero deflection occurs can be obtained from a plot of measured surface deflections and the inverse of the corresponding offsets $\left(\frac{1}{r}\right)$. This is illustrated in Figure 11. The middle portion of the plot is linear with either end curved due to nonlinearities associated with the upper layers and the subgrade. The zero surface deflection is estimated by extending the linear portion of the D vs. $\frac{1}{r}$ plot to a D = 0, the $\frac{1}{r}$ intercept being designated as r_0. Due to various pavement section-specific factors, the depth to stiff layer cannot be directly estimated from r_0 — additional factors must be considered. To do this, regression equations were developed based on BISAR computer program generated data for the following factors and associated values:

Load = P = 9000 lbs (40 kN) (only load level considered)

Moduli ratios: $\frac{E_1}{E_{SG}}$ = 10, 30, 100

$\frac{E_2}{E_{SG}}$ = 0.3, 1.0, 3.0, 10.0

$\frac{E_{rigid}}{E_{SG}}$ = 100

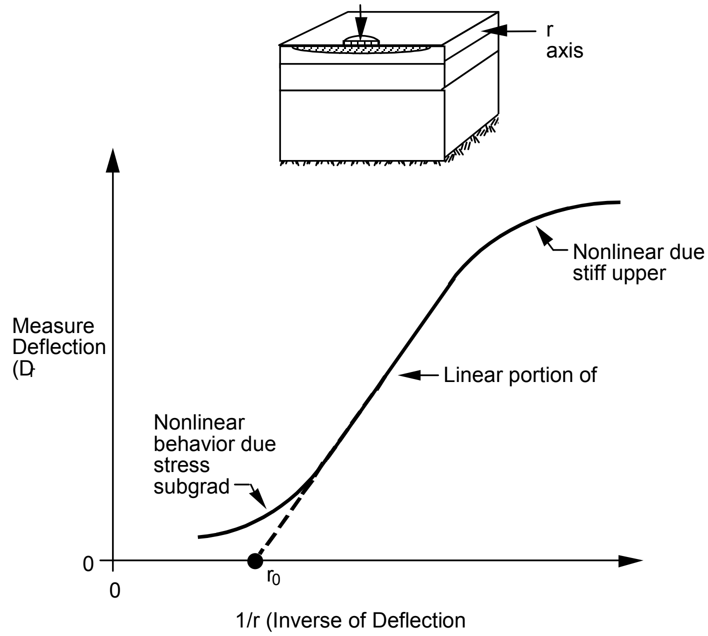


Figure 11. Plot of Inverse of Deflection Offset vs. Measured Deflection

Thickness levels:	T_1	=	1, 3, 5, and 10 inches (25, 75, 125, 250 mm)
	T2	=	6, 10, and 15 inches (150, 250, 375 mm)
	B	=	5, 10, 15, 20, 25, 30, and 50 feet (1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 15.0 m)

where

Ei = elastic modulus of layer i,
Ti = thickness of layer i,
B = depth of the rigid (stiff) layer measured from the pavement surface (feet).

The resulting regression equations follow in (b).

(b) Regression Equations

Four separate equations were developed for various HMA layer thicknesses. The dependent variable is $\frac{1}{B}$ and the independent variables are r_0 (and powers of r_0) and various deflection basin shape factors such as SCI, BCI, and BDI (see Appendix A).

(i) HMA less than 2 inches (50 mm) thick:

$$\frac{1}{B} = 0.0362 - 0.3242\,(r_0) + 10.2717\,(r_0^2) - 23.6609\,(r_0^3) - 0.0037\,(BCI) \qquad \text{Equation 8}$$

$R^2 = 0.98$

(ii) HMA 2 to 4 inches (50 to 100 mm) thick:

$$\frac{1}{B} = 0.0065 + 0.1652\,(r_0) + 5.4290\,(r_0^2) - 11.0026\,(r_0^3) - 0.0004\,(BDI) \qquad \text{Equation 9}$$

$R2 = 0.98$

(iii) HMA 4 to 6 inches (100 to 150 mm) thick:

$$\frac{1}{B} = 0.0413 + 0.9929\,(r_0) - 0.0012\,(SCI) + 0.0063\,(BDI) - 0.0778\,(BCI) \qquad \text{Equation 10}$$

$R2 = 0.94$

(iv) HMA greater than 6 inches (150 mm) thick:

$$\frac{1}{B} = 0.0409 + 0.5669\,(r_0) + 3.0137\,(r_0^2) + 0.0033\,(BDI) - 0.0665\log(BCI) \qquad \text{Equation 11}$$

$R2 = 0.97$

where

r_0	=	$\frac{1}{r}$ intercept (extrapolate steepest section of D vs $\frac{1}{r}$ plot) in units of $\frac{1}{ft}$
SCI	=	D0 - D12" (D0 - D305 mm), Surface Curvature Index
BDI	=	D12" - D24" (D305 - D610 mm), Base Damage Index
BCI	=	D24" - D36" (D610 - D914 mm) Base Curvature Index
Di	=	surface deflections (mils) normalized to a 9,000 lb (40 kN) load at an offset i in feet

(c) Example

Use some typical deflection data to estimate B (depth to stiff layer). The drillers log suggests a stiff layer might be encountered at a depth of 198 inches (5.0 m) (deflection data originally from SHRP).

(i) First, calculate normalized deflections (9,000 lb (40 kN) basis):

	Load Level	Deflections (mils)						
		D_0	D_8	D_{12}	D_{18}	D_{24}	D_{36}	D_{60}
	9,512 lb	5.07	4.32	3.67	2.99	2.40	1.69	1.01
(normalized)	9,000 lb	4.76	4.04	3.44	2.80	2.26	1.59	0.95
	6,534 lb	3.28	2.69	2.33	1.88	1.56	1.09	0.68

(ii) Second, estimate r0. Plot Dr vs. $\frac{1}{r}$ (refer to Figure 12):

D_r (mils)	r (inch)	$\frac{1}{r}$ ($\frac{1}{ft}$)
4.76	0	—
4.04	8	1.50
3.44	12	1.00
2.80	18	0.67
2.26	24	0.50
1.59	36	0.33
0.95	60	0.20

where all D_r normalized to 9,000 lb (40 kN)

(iii) Third, use regression equation in (b)(iv) (for HMA = 7.65 inches (194 mm)) to calculate B:

$$\frac{1}{B} = 0.0409 + 0.5669\,(r_0) + 3.0137\,(r_0^2) + 0.0033\,(BDI) - 0.0665 \log (BCI)$$

where

r_0 = $\frac{1}{r}$ intercept (refer to Figure 12)

≅ 0 (used steepest part of deflection basin which is for Sensors at 36 and 60 inches)

BDI = $D_{12"} - D_{24"}$ = 3.44 - 2.26 = 1.18 mils

BCI = $D_{24"} - D_{36"}$ = 2.26 - 1.59 = 0.67 mils

$$\frac{1}{B} = 0.0409 + 0.5669\,(0) + 3.0137\,(02) + 0.0033\,(1.18) - 0.0665 \log (0.67)$$

$$= 0.0564$$

$$\frac{1}{B} = \frac{1}{0.0564} = 17.7 \text{ feet (213 inches or 5.4 m)}$$

This value agrees fairly well with "expected" stiff layer conditions at 16.5 feet (5.0 m) as indicated by the drillers log even though the $\frac{1}{r}$ value equaled zero.

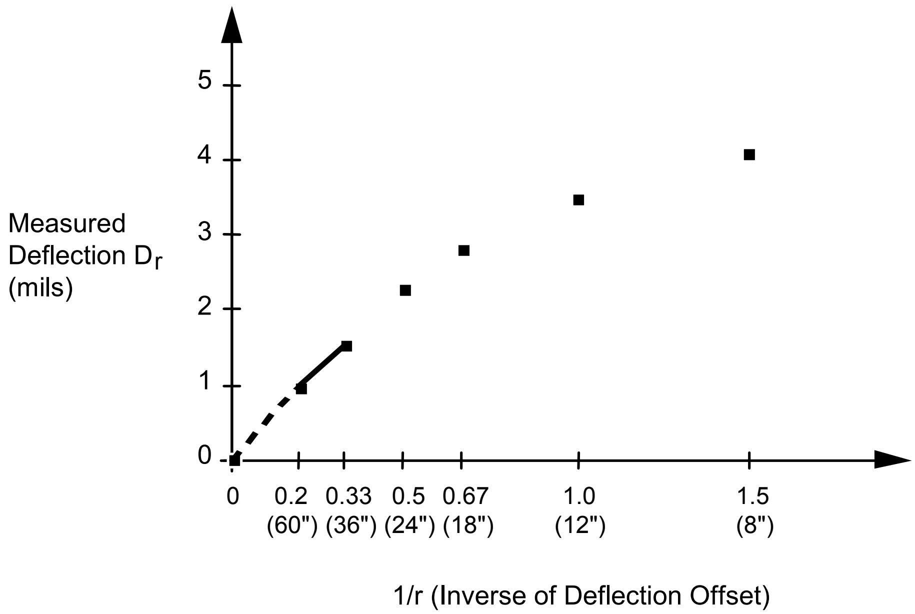


Figure 12. Plot of Inverse of Deflection Offset vs. Measured Deflection

2.3.1 Example of Depth to Stiff Layer Estimates — Road Z-675 (Sweden)

(a) Overview

This road located in south central Sweden is used to illustrate calculated and measured depths to stiff layers (the stiff layer apparently being rock for the specific road).

(b) Measurement of Measured Depth

The depth to stiff layer was measured using borings (steel drill) and a mechanical hammer. The hammer was used to drive the drill to "refusal." Thus, the measured depths could be to bedrock, a large stone, or hard till (glacially deposited material). Further, the measured depths were obtained independently of the FWD deflection data (time difference of several years).

(c) Deflection Measurements

A KUAB 50 FWD was used to obtain the deflection basins. All basins were obtained within ± 16 feet (5 m) of a specific borehole. The deflection sensor locations were set at 0, 7.9, 11.8, 17.7, 23.6, 35.4, and 47.2 inches (0, 200, 300, 450, 600, 900, and 1200 mm) from the center of the load plate.

(d) Calculations

The equations described in Paragraph 2.3 were used to calculate the depth to stiff layer. Since the process requires a 9000 lb (40 kN) load and 1 foot (305 mm) deflection sensor spacings, the measured deflections were adjusted linearly according to the ratio of the actual load to a 9000 lb (40 kN) load.

(e) Results

The results of this comparison are shown in Figure 13. Given all the uncertainties concerning the measured depths, the agreement is quite good.

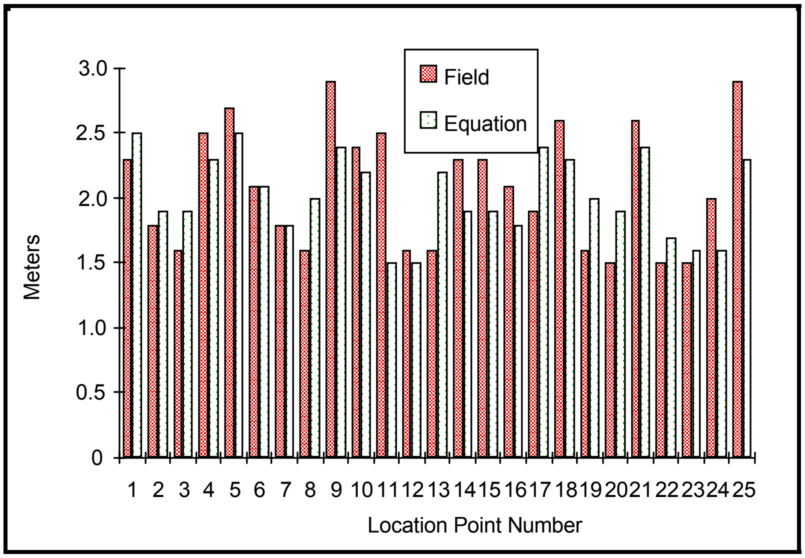


Figure 13. Plot of Measured and Calculated Depths to Stiff Layer (Road Z-675, Sweden)

2.4 VERIFICATION OF BACKCALCULATION RESULTS

There have been and, undoubtedly, will be a number of attempts to verify that backcalculated layer moduli are "reasonable." One way to do this is to compare measured, in-situ strains to calculated (theoretical) strains based on layered elastic analyses.

Two recent studies have done this. The first study summarized [5] was conducted at the PACCAR Technical Center located at Mt. Vernon, Washington. Horizontal strains were measured on HMA instrumented cores (inserted into the original HMA surface material). The HMA layer was approximately 5.5 inch thick over a 13.0 inch thick base course. The WSDOT FWD was used to apply a known load to induce the strain response (measured strain). The calculated strains were determined by use of the EVERCALC program (which used FWD deflection basins to backcalculate layer moduli which, in turn, were used to calculate the corresponding strains.)

Figure 14 and Figure 15 show the measured and calculated strains in the two horizontal directions at the bottom of the HMA layer (longitudinal and transverse). This specific testing was conducted during February 1993. In general, the agreement is good.

The second study was reported by Lenngren [6]. That work was conducted for RST Sweden and used backcalculated layer moduli (from a modified version of the EVERCALC program) to estimate strains at the bottom of two thicknesses of HMA (3.1 and 5.9 n. thick). The pavement structures were located in Finland. Table 2 and Table 3 are used as summaries. The backcalculated strains are generally within ± 5 percent of the measured strains.

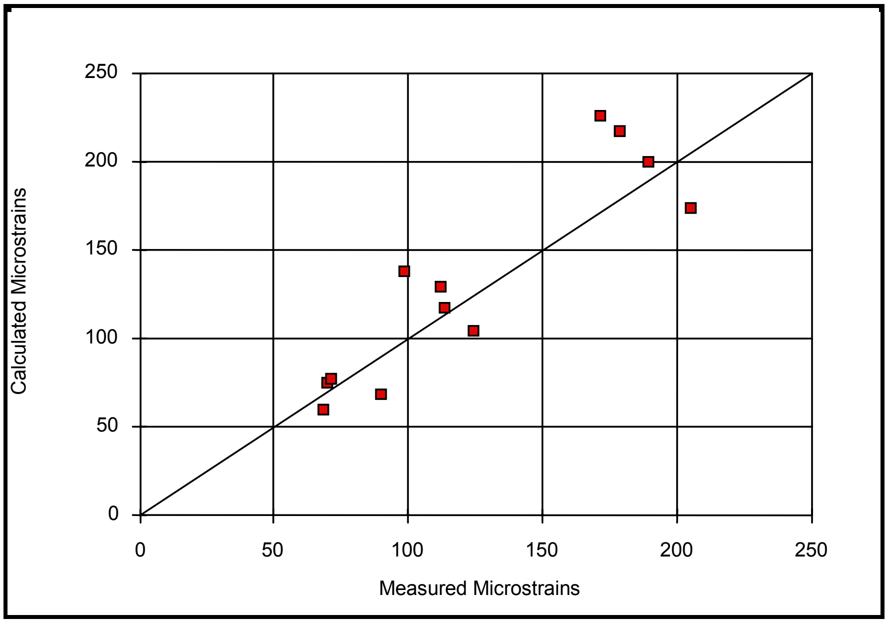


Figure 14. Measured vs. Calculated Strain for Axial Core Bottom Longitudinal Gauges – February 1993 FWD Testing [6]

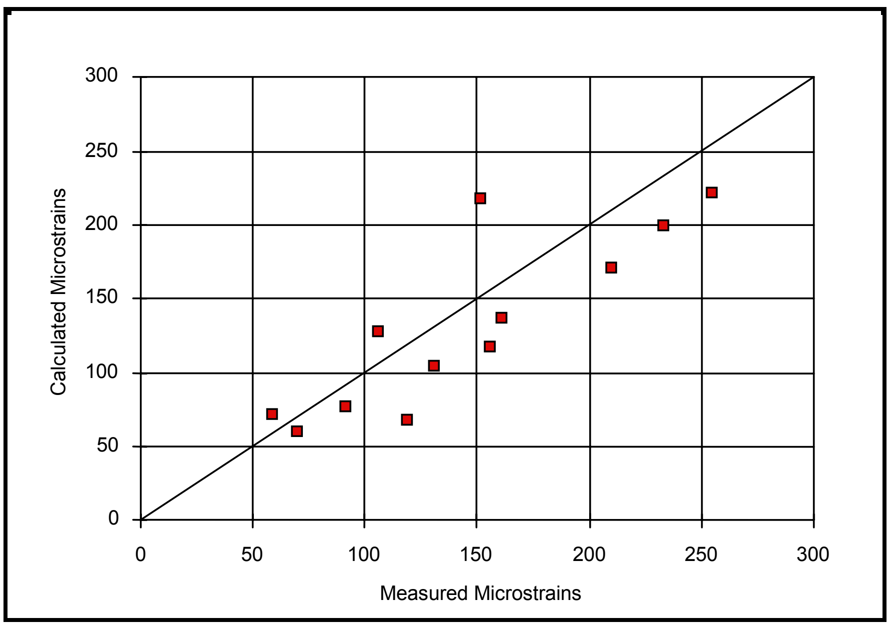


Figure 15. Measured vs. Calculated Strain for Axial Core Bottom Transverse Gauges – February 1993 FWD Testing [6]

Table 2. Backcalculated and Measured Tensile Strains — 3.1 inch HMA Section [6]

Time of Day (a.m. or p.m.)	Tensile Strain Bottom of HMA (x 10^{-6})		
	Backcalculated*	Measured	% Difference
a.m.	119	123	-3
a.m.	119	122	-2
a.m.	74	65	+14
a.m.	60	65	-8
p.m.	284	292	-3
p.m.	284	283	~0
p.m.	167	159	+5
p.m.	167	158	+6
p.m.	87	85	+2
p.m.	81	84	-4

*Backcalculation process used sensors @ D_0, D_{12}, D_{24}, D_{36}, and D_{48}

Table 3. Backcalculated and Measured Tensile Strains — 5.9 inch Section [6]

Time of Day (a.m. or p.m.)	Tensile Strain Bottom of HMA (x 10^{-6})		
	Backcalculated*	Measured	% Difference
a.m.	66	70	-6
a.m.	71	69	+3
a.m.	68	69	-1
a.m.	38	35	+9
a.m.	127	130	-2
a.m.	119	130	-8
p.m.	178	185	-4
p.m.	182	183	-1
p.m.	104	96	+8
p.m.	51	48	+6
p.m.	56	49	+14

*Backcalculation process used sensors @ D_0, D_{12}, D_{24}, D_{36}, and D_{48}

2.5 BACKCALCULATION GUIDELINES

The general guidelines, which follow, are rather broad in scope and should be considered only "rules-of-thumb" at best. These guidelines were developed from WSDOT experience and the SHRP LTPP Expert Task Group for Deflection Testing and Backcalculation. Undoubtedly, they will change and software such as Evercalc© will continue to be improved.

2.5.1 Number of Layers

Generally, one should use no more than 3 or 4 layers of unknown moduli in the backcalculation process (preferably, no more than 3 layers).

If a three-layer system is being evaluated, and questionable results are being produced (extremely weak base moduli, for example), it is sometimes advantageous to evaluate this pavement structure as a two-layer system. This modification would possibly indicate that the base material has been contaminated by the underlying subgrade and is weaker due to the presence of fine material. Alternatively, a stiff layer should be considered if not done so previously.

If a pavement structure consists of a stiffer layer between two weak layers, it may be difficult to obtain realistic backcalculated moduli, such as HMA over a cement treated base.

2.5.1 Thickness of Layers

2.5.1.2 Surfacing

It can be rather difficult to "accurately" backcalculate HMA/BST moduli for bituminous surface layers less than 3 inches (75 mm) thick. Such backcalculation can be attempted for layers less than 3 inches (75 mm), but caution is suggested. In theory, it is possible to backcalculate separate layer moduli for various types of bituminous layers within a flexible pavement. Generally, it is not advisable to do this since one can quickly be attempting to backcalculate too many unknown layer moduli (i.e., greater than 3 or 4). By necessity, one should expect to combine all bituminous layers (seal coats, HMA, etc.) into "one" layer unless there is evidence (or the potential) for distress, such as stripping, in an HMA layer or some other such distress, which is critical to pavement performance.

2.5.1.3 Unstabilized Base/Subbase Course

"Thin" base course beneath "thick" surfacing layers (say HMA or PCC) often result in low base moduli. There are a number of reasons why this can occur. One, a thin base is not a "significant" layer under a very stiff, thick layer. Second, the base modulus may be relatively "low" due to the stress sensitivity of granular materials. The use of a stiff layer generally improves the modulus estimate for base/subbase layers.

2.5.1.4 Subgrade

If unusually high subgrade moduli are calculated, check to see if a stiff layer is present. Stiff layers, if unaccounted for in the backcalculation process, will generally result in unrealistically high subgrade moduli. This is particularly true if a stiff layer is within a depth of about 20 to 30 feet (6 to 9 m) below the pavement surface.

2.5.1.5 Stiff Layer

Often, stiff layers are given "fixed" stiffness ranging from 100,000 to 1,000,000 psi (700 to 7000 MPa) with semi-infinite depth. This, in effect, makes the "subgrade" a layer with a "fixed" depth (instead of the normally assumed infinite depth). Currently, it appears advisable to use backcalculation software, which uses an algorithm such as described and illustrated in Paragraph 2.3, "Depth to Stiff Layer." What is not so clear is whether one should always fix the depth to stiff layer at say 20, 30, or possibly 50 feet (6, 9, or 15 m) if no stiff layer is otherwise indicated (i.e., use a semi-infinite depth for the subgrade). The depth to stiff layer should be verified whenever possible with other non-destructive testing (NDT) data or borings.

The stiffness (modulus) of the stiff layer apparently can vary. If the stiff layer is due to saturated conditions (e.g. water table) then moduli of about 50,000 psi (345 MPa) appear more appropriate. If rock or stiff glacial tills are the source of the stiff layer then moduli of about 1,000,000 psi (6 900 MPa) appear to be more appropriate.

2.5.2 Initial Moduli and Moduli Ranges

2.5.2.1 HMA - Initial Moduli

There are several ways one can estimate the initial HMA modulus (often referred to as “seed modulus”). One can use a modulus-temperature plot as illustrated in Figure 16, if the HMA temperature at the time of testing is known; however, data such as shown in Figure 16 are based on laboratory resilient moduli (load pulse = 100 msec).

2.5.2.2 Cracked HMA Initial Moduli

Generally, fatigue cracked HMA (less than 10 percent wheel path hairline cracks) is often observed to have backcalculated moduli of about 100,000 to 200,000 psi (700 to 1400 MPa). What is most important in the backcalculation process, assuming surface fatigue cracking is present, is to determine whether the cracks are confined to only the immediate wearing course or go through the whole depth of the HMA layer? For HMA layers greater than 6 inches (150 mm) thick, WSDOT has observed that the cracking is confined to the upper wearing course (top-down cracking).

2.5.2.3 HMA Moduli Ranges

If an HMA modulus range is required, use your best estimate of the E_{ac}, then 0.25 E_{ac} to 5.00 E_{ac}

2.5.2.4 Unstabilized Bases and Subbases

Material Type	Initial Modulus ksi (MPa)	Moduli Range ksi (MPa)
Crushed Stone or Gravel Bases	35 (240)	10 to 150 (70 to 7000)
Crushed Stone or Gravel Subbases	30 (210)	10 to 100 (70 to 700)
Sand Bases	20 (140)	5 to 80 (35 to 550)
Sand Subbases	15 (100)	5 to 80 (35 to 550)

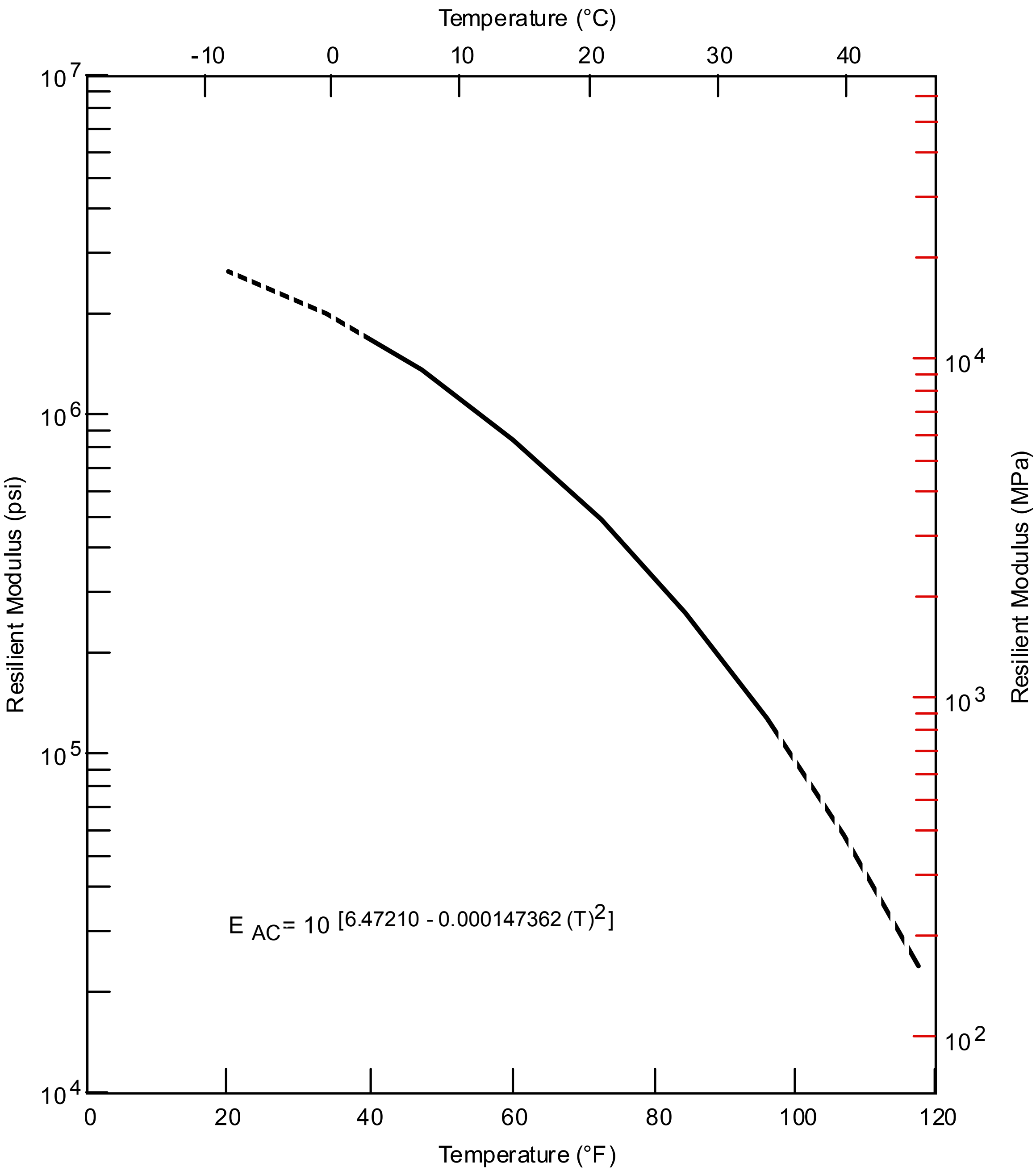


Figure 16. General Stiffness-Temperature Relationship for Class B (Dense Graded) Hot Mix Asphalt in Washington State

2.5.2.5 Stabilized Bases and Subbases

If unconfined compressive strength data is available:

Material Type	Unconfined Compressive Strength ksi (MPa)	Initial Modulus ksi (MPa)	Moduli Range ksi (MPa)
Lime Stabilized	< 250 (< 1.7)	30 (200)	5 to 100 (35 to 690)
	250 to 500 (1.7 to 3.4)	50 (340)	15 to 150 (100 to 1000)
	> 500 (> 3.4)	70 (480)	20 to 200 (140 to 1400)
Cement Stabilized	< 750 (< 5.2)	400 (2800)	100 to 1500 (700 to 10000)
	750 to 1250 (5.2 to 8.6)	1000 (7000)	200 to 3000 (1400 to 20000)
	> 1250 (> 8.6)	1500 (10000)	300 to 4000 (2000 to 28000)

If not, assume unconfined compressive strength is 250 to 500 psi (1.7 to 3.4 MPa) for lime stabilized and 750 to 1250 psi (5.2 to 8.6 MPa) for cement stabilized and use corresponding moduli values.

2.5.2.6 Subgrade

The resilient modulus of the subgrade can be determined by

- NDT and backcalculation,
- laboratory testing, or
- other sources/correlations.

WSDOT will normally use the FWD and appropriate equations to estimate M_R. The basic equation for subgrade modulus is [7]:

$$M_R = \frac{P\ (1 - \mu 2)}{(p)\ (r)\ (dr)} \qquad \text{(Equation 12)}$$

If μ = 0.5, then the equation reduces to

$$MR = \frac{0.24\ (P)}{(r)\ (dr)} \qquad \text{(Equation 13)}$$

where

M_R = elastic modulus of subgrade (psi),
P = load (lbs),
r = radial distance from the center of the load plate (inch) and
dr = pavement deflection at distance r from the applied load (inch).

Refer to Table 4 for suggested typical values or the following discussion and equations to use in estimating E_{sg} (or M_R) from the deflection basin.

Table 4. Typical Values of Subgrade Moduli [7]

Material	Climate Condition			
	Dry	Wet — No Freeze	Wet - Freeze	
			Unfrozen	Frozen
	psi (MPa)	psi (MPa)	psi (MPa)	psi (MPa)
Clay	15,000 (103)	6,000 (41)	6,000 (41)	50,000 (345)
Silt	15,000 (103)	10,000 (69)	5,000 (34)	50,000 (345)
Silty or Clayey Sand	20,000 (138)	10,000 (69)	5,000 (34)	50,000 (345)
Sand	25,000 (172)	25,000 (172)	25,000 (172)	50,000 (345)
Silty or Clayey Gravel	40,000 (276)	30,000 (207)	20,000 (138)	50,000 (345)
Gravel	50,000 (345)	50,000 (345)	40,000 (276)	50,000 (345)

Several researchers have developed regression equations to predict E_{SG} from plate load and deflections measured at distances from about 24 inches (600 mm) to 48 inches (1200 mm) from the center of the plate load. Newcomb developed such regression equations to predict E_{SG} as part of an overall effort to develop a mechanistic empirical overlay design procedure for WSDOT [8]. For two layer cases, the subgrade modulus can be estimated from:

$E_{SG} = -466 + 0.00762\ (P/D3)$ Equation 14

$E_{SG} = -198 + 0.00577\ (P/D4)$ Equation 15

$E_{SG} = -371 + 0.00671\ (2P/(D3 + D4))$ Equation 16

and for three layer cases

$E_{SG} = -530 + 0.00877\ (P/D3)$ Equation 17

$E_{SG} = -111 + 0.00577\ (P/D4)$ Equation 18

$E_{SG} = -346 + 0.00676\ (2P/(D3 + D4))$ Equation 19

The $R^2 \approx 99\%$ for all equations and the sample sizes were 180 (two layer case) and 1,620 (three layer case). These equations were developed from generated data (ELSYM5) with the following levels of input data:

Two Layer Case	Load, P, lb (kN)	Surface Thickness, h_{HMA}, inch (mm)	Surface Modulus, E_{HMA}, psi (MPa)	Subgrade Modulus, E_{SG}, psi (MPa)
	5,000 (22)	2 (50)	2,000,000 (13800)	50,000 (345)
	10,000 (44)	6 (150)	500,000 (3450)	30,000 (207)
	15,000 (67)	12 (300)	100,000 (690)	10,000 (69)
		18 (450)		5,000 (35)
				2,500 (17)

Three Layer Case	Load, P, lb (kN)	Surface Thickness, h_{HMA}, inch (mm)	Base Thickness, h_B, inch (mm)	Surface Modulus, E_{HMA}, psi (MPa)	Base Modulus, E_B, psi (MPa)	Subgrade Modulus, E_{SG}, psi (MPa)
	5,000 (22)	2 (50)	4 (100)	2,000,000 (13800)	100,000 (690)	50,000 (345)
	10,000 (44)	6 (150)	10 (250)	500,000 (3450)	50,000 (345)	30,000 (207)
	15,000 (67)	12 (300)	18 (450)	100,000 (690)	30,000 (207)	10,000 (69)
					10,000 (69)	5,000 (35)
						2,500 (17)

(assumed that load applied on a 12.0 inch diameter load plate)

From this generated data (no rigid base), regression equations were also developed for estimating the surface modulus (HMA) for a two layer case (for example a "full-depth" pavement):

$$\log E_{HMA} = -0.53740 - 0.95144 \log_{10} E_{SG} - 1.21181 \sqrt[3]{h_{HMA}} + 1.78046 \log_{10} (PA_1/D_0^2) \quad \text{Equation 20}$$

$R^2 = 0.83$

For a <u>three-layer case</u>, equations were developed for both E_{HMA} and E_B as follows:

If both E_{HMA} and E_B unknown:

$$\log E_{HMA} = -4.13464 + 0.25726 (5.9/h_{HMA}) + 0.92874 \sqrt{5.9/h_B} - 0.69727 \sqrt{h_{HMA}/h_B} - 0.96687 \log_{10} E_{SG} + 1.88298 \log_{10} (PA_1/D_0^2) \quad \text{Equation 21}$$

$R^2 = 0.78$.

$$\log EB = 0.50634 + 0.03474 (5.9/h_{HMA}) + 0.12541 \sqrt{5.9/h_B} - 0.09416 \sqrt{h_{HMA}/h_B} + 0.51386 \log_{10} E_{SG} + 0.25424 \log_{10} (PA_1/D_0^2) \quad \text{Equation 22}$$

where $R^2 = 0.70$.

The following variables were used in the equations shown above:

P	=	applied load (lbs) on a 11.8 inch plate,
h_{HMA}	=	surface course thickness (inch),
h_B	=	base course thickness (inch),
E_{HMA}	=	surface course modulus (psi),
E_B	=	base course modulus (psi),
E_{SG}	=	subgrade modulus (psi),
D_0	=	deflection under center of applied load (inch),
$D_{0.67}$	=	deflection at 8 inches from center of applied load (inch),
D_1	=	deflection at 1 foot from center of applied load (inch),
D_2	=	deflection at 2 feet from center of applied load (inch),
D_3	=	deflection at 3 feet from center of applied load (inch),
D_4	=	deflection at 4 feet from center of applied load (inch), and
A_1	=	approximate area under deflection basin out to 3 feet
	=	$2 [2 (D_0 + D_{0.67}) + (D_{0.67} + D_1) + 3(D_1 + D_2) + 3(D_2 + D_3)]$
	=	4D0 + 6D0.67 + 8D1 + 12D2 + 6D3

2.5.2.7 Assumed Poisson's Ratio

Material Type		**Poisson's Ratio**
Hot mix asphalt		0.35
Portland Cement Concrete		0.15 - 0.20
Base or Subbase	Stabilized	0.25 - 0.35
	Unstabilized	0.35
Subgrade Soils	Cohesive (fine grain)	0.45
	Cohesion less (coarse grain)	0.35 - 0.40
Stiff Layer		0.35 or less

2.5.2.8 Convergence Errors

Root Mean Square Error (RMS)

One should attempt to obtain matches between the calculated and measured deflection basins, in terms of RMS, of about 1 to 2 percent. Often, this cannot be achieved and suggests that the basic input data be checked (such as layer thicknesses). The Area value (see Appendix **A**) might help in this regard.

General

"High" convergence errors suggest that there exists some fundamental problem with a specific backcalculation effort. The problem could be with the deflection data, layer types, and thicknesses, or lack of material homogeneity, which could include cracked and uncracked conditions. "High" convergence errors do not necessarily mean that the backcalculated layer moduli are "no good."

2.6 EVERCALC©

Evercalc© is a pavement analysis computer program that estimates the "elastic" moduli of pavement layers. Evercalc© estimates the elastic modulus for each pavement layer, determines the coefficients of stress sensitivity for unstabilized materials, stresses and strains at various depths, and optionally normalizes HMA modulus to a standard laboratory condition (temperature).

Evercalc© uses an iterative approach in changing the moduli in a layered elastic solution to match theoretical and measured deflections. A simplified flow diagram of this method is shown in Figure 17.

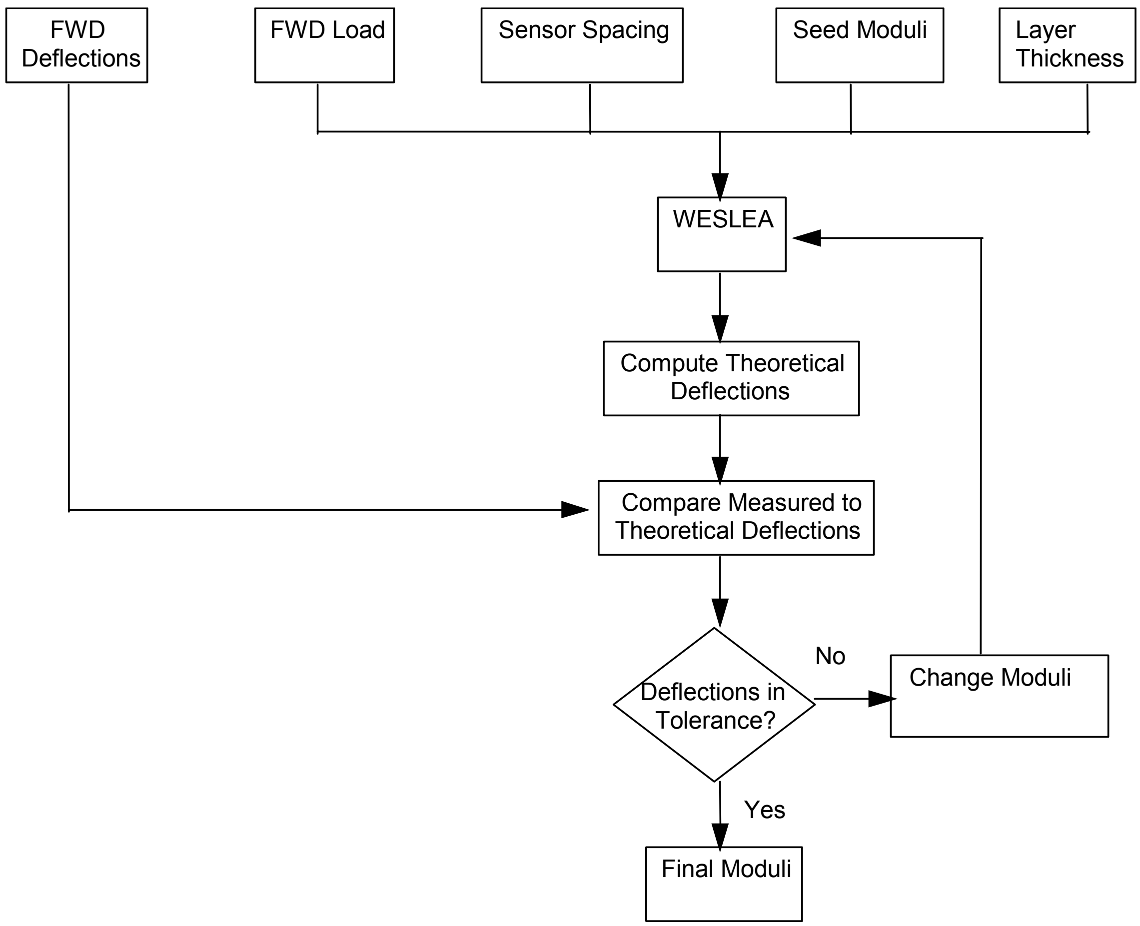


Figure 17. Simplified Flow Chart for Evercalc©

2.6.1 Characteristics of Evercalc©

The Evercalc© program uses WESLEA (provided by the Waterways Experiment Station, U. S. Army Corps of Engineers) as the layered elastic solution to compute the theoretical deflections and a modified Augmented Gauss-Newton algorithm for optimization. Basic assumptions of layered elastic theory include the following:

- Layers are infinitely long in the horizontal directions
- Layers have uniform thickness
- Bottom layer is semi infinite in the vertical direction
- Layers are composed of homogeneous, isotropic, linearly elastic materials, characterized by elastic modulus and Poisson's ratio.

An inverse solution technique is used to determine elastic moduli from FWD pavement surface deflection measurements. The program can handle up to ten sensors and twelve drops per station. The program is capable of evaluating a flexible pavement structure containing up to five layers. From an initial, rough estimate of layer moduli (seed moduli), the program iteratively searches for the “final” modulus for each pavement layer. The deflections calculated using WESLEA is compared with the measured ones at each iteration. When the discrepancies in the calculated and measured deflections as characterized by root mean square (RMS) error (Equation 23), or the changes in modulus (Equation 24) falls within the allowable tolerance, or the number of iterations has reached a limit the program terminates. Using the final set of moduli, the stresses and strains at the bottom of the HMA layer, middle of the other layers except the subgrade, and at the top of the subgrade is calculated. When deflection data for more than one load level is available at a given point, coefficients of stress sensitivity for unstabilized materials are also computed. Optionally, HMA layer modulus is normalized to a standard laboratory condition.

2.6.1.1 Seed Moduli

Two options for estimating the seed moduli are available. When a pavement structure containing up to three layers is being analyzed, a set of internal regression equations can be used [8]. These regression equations determine a set of seed moduli from the relationships between the layer modulus, surface deflections, applied load, and layer thickness. Alternatively, the user can provide these values. When more than one deflection data set at a given location is analyzed, the final moduli from the previous deflection data set is used as seed moduli for the next one in order to improve the performance of the program.

2.6.1.2 Termination

The program terminates when one or more of the following conditions are satisfied:

i) Deflection Tolerance:

$$RMS\,(\%) = \sqrt{\frac{1}{n_d}\sum_{i=1}^{n}\left(\frac{d_{ci} - d_{mi}}{d_{mi}}\right)^2}\,(100) \qquad \text{Equation 23}$$

where, d_{ei} and d_{mi} are the measured and calculated deflections at i-th sensor and n- is the number of sensors.

Normally a deflection tolerance of one percent is considered adequate.

ii) Moduli Tolerance:

$$\varepsilon_m = \frac{[E(k+1)i - Eki] \times (100)}{E_{ki}} \qquad \text{Equation 24}$$

where, E_{ki} and $E_{(k+1)i}$ are the i-th layer moduli at the k-th and (k+1)-th iteration, respectively, and m- is the number of layers with unknown moduli.

Again, a modulus tolerance of one percent is considered adequate.

iii) Number of iterations has reached the Maximum Number of Iterations. At every iteration a minimum of (m + 1) calls to WESLEA is made, where m- is the number of layers with unknown moduli. Normally, a maximum number of ten iterations is adequate.

2.6.1.3 Coefficients of Stress Sensitivity

The stress sensitivity characteristics of unstabilized material moduli are usually formulated as follows:

$E_b = k_1\theta^{k_2}$ for coarse grained soils Equation 25

$E_s = k_3\sigma_d^{k_4}$ for fine grained soils Equation 26

where,

E_b = resilient modulus of coarse grained soils,
E_s = resilient modulus of fine grained soils,
θ = bulk stress,
σ_d = deviator stress, and
k_1, k_2, k_3, and k_4 = regression coefficients

The program determines the stress sensitivity coefficients using a linear regression method when FWD deflection data for two or more load levels at a given point are available.

2.6.1.4 Temperature Correction

The stiffness of HMA is primarily affected by temperature and loading rate. While FWD loads occur over a 25 to 35 millisecond loading time (approximately) and at ambient temperature, the standard laboratory condition is taken to be a 77°F (25°C) temperature and a 100 millisecond loading time. Thus, the stiffness of HMA can be normalized to view the backcalculated modulus in terms of the "traditional" laboratory values (at least this is what is being attempted).

Temperature normalization of HMA is accomplished using the relationship between the modulus and temperature. The relationship for WSDOT Class B HMA was found as follows [9]:

$\log E_{ac} = 6.4721 - 1.47362 \times 10^{-4}(T_p)^2$ Equation 27

where,

E_{ac} = modulus of HMA (psi), and
T_p = pavement temperature (°F)

From the above modulus-temperature relationship, the backcalculated HMA modulus at the insitu field temperatures is multiplied by an adjustment factor in order to obtain a "standard" modulus at a temperature of 77° F:

$TAF = 100.000147362(Tp^2\text{-}77^2)$ Equation 28

where,

TAF = temperature adjustment factor, and
T_p = pavement temperature (°F)

Pavement temperature is determined either by direct measurement or Southgate's method, which uses pavement surface temperature, the previous five-day mean temperature, and pavement thickness. Both measurement methods are incorporated in the program.

It should be noted that the temperature correction is based on regression equations that were developed for the WSDOT Class B HMA and its validity to other classes of HMA are not known. However, Class B is a traditional, typical dense HMA mixture.

2.6.1.5 Depth to Stiff Layer

A depth to stiff layer (paragraph 2.3) is estimated using the scheme reported by Rhode and Scullion [3]. The basic assumption is that no surface deflection will occur beyond the offset (measured from the load plate), which corresponds, to the intercept of the applied stress zone and a stiff layer (the stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which zero deflection occurs.

This feature in Evercalc© is optional within the GENERAL DATA File (to be discussed in later SECTIONS). It is common to expect a stiff layer condition within a 30 foot depth. Accounting for a stiff layer condition generally reduces the subgrade modulus (layer above the stiff layer) and increases the base course modulus. If multiple deflection basins and associated loads exist at a specific station, the program calculates the depth to stiff layer for each basin adjusted to a 9000 lb (40 kN) load. The mean depth and associated standard deviation is calculated. Any depths outside of the limits of the mean $\pm$ the standard deviation are removed and the mean depth recalculated. This depth is then used in the subsequent layer moduli calculations at that station. If only one deflection basin and associated load is used, then the program linearly adjusts the required deflections to a 9000 lb (40 kN) load to estimate the depth to stiff layer.

2.6.2 Hardware Requirements

The Evercalc© program is coded in Microsoft Visual Basic and Microsoft FORTRAN Power Station 4.0 and designed to run on IBM or compatible personal computers with Microsoft Windows 95/NT 4.0 or higher.

2.6.3 Installation of the Program

To install the program, start Windows, click on the **Start** button, select Run and type a:\setup or select **Browse** and locate SETUP.EXE. Prior to installation of the program(s) the user will be shown the README.TXT. It is highly recommended that this file be reviewed prior to the installation of the program(s). Once README.TXT has been reviewed, the user is asked to select the source directory (default - a:\), the target directory (default = C:\EVERSERS), and which programs are to be installed. The user has the option of selecting Everstress©, Evercalc©, Everpave©, or any combination of the above. Once satisfied with the selection, select **Start Install**.

2.6.4 Program Contents

The following paragraphs describe each of the various menus and inputs of the program.

2.6.4.1 File

Open GENERAL DATA File – This menu option provides a form to create a new GENERAL DATA File or edit an existing one. GENERAL DATA File contains information that does not change from station to station, such as load plate radius, unit, sensor offsets, etc.

Open DEFLECTION DATA File – This menu option provides a form to create a new DEFLECTION DATA File or edit an existing one. This menu option requires an existing GENERAL DATA File. The DEFLECTION DATA File contains station specific data such as layer thickness, pavement temperature, number of drops, plate load and sensor deflection for each drop.

Perform Backcalculation – This menu option performs the backcalculation process. This menu option requires the GENERAL DATA File and DEFLECTION DATA File. Backcalculation is carried out in a DOS window and it is advised that you don't switch windows until the completion of backcalculation. If the Stiff Layer option is used, then depth to stiff layer is calculated first and then the actual backcalculation is performed. Backcalculation can be performed in either interactive or batch mode.

Interactive Mode: In interactive mode, the backcalculation is carried out in the foreground and the progress during each iteration and the calculated and measured deflection basins at the end of iteration are displayed on the screen.

Batch Mode: In batch mode, the backcalculation is carried out in the background. The iteration details are saved in a log file having the same name as the DEFLECTION DATA File with the extension .LOG.

If stiff layer option is used the user is presented with a histogram and a table of depth to apparent stiff layer and with the station identifier. The user can choose to accept the calculated depth to stiff layer values or modify it before performing the backcalculation.

Convert FWD DATA File – This menu option converts a raw FWD (Dynatest Model 8000) data file to an Evercalc© DEFLECTION DATA File. This menu option requires an existing GENERAL DATA File. If the deflection data is generated from any other NDT device, other than the Dynatest 8000, this option will not generate the appropriate file format.

Modify Standard Temperature – Since asphalt materials are temperature sensitive and FWD data collection temperature may vary within a specific location and from one location to the next, the establishment of a standard temperature is necessary. WSDOT default standard temperature for the determination of the asphalt moduli to be 77°F (25°C).

Exit – Exit the program and return to the Windows screen.

2.6.4.2 Print

Print/View Output

Displays formatted output data on the screen and provides the option to print on the default printer. The output data contains all calculations for all required iterations and can result in at least 2 pages per station.

Options – standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

Print/View Summary

Displays formatted summary data on the screen and provides the option to print on the default printer. This data contains the station, layer thickness, moduli for each specified layer, the RMS error.

Options – standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

Page Setup

Allows the user to modify the page margins. The default settings are shown.

Select Font

Allows the user to choose any available font for use in displaying and printing the output and summary information. This font is also saved as the default font for future output display.

2.6.4.3 Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

About EVERCALC© - lists program version information, responsible agency and personnel contacts, system memory and resources.

2.6.4.4 Open General File

Title - Any text that describes the GENERAL DATA File

No of Layers - Total number of layers (including the stiff layer, if a stiff layer option is selected). The minimum number of layers is two, and the maximum number of layers is five. Seed moduli will need to be provided if the number of layers is more than three.

No of Sensors - Total number of FWD sensors. Maximum number of sensors is limited to ten.

Units - Units of **measurement** and output, either Metric or US Customary.

Stiff Layer - Check this option to include a stiff layer. The depth to stiff layer is calculated prior to beginning the backcalculation process. The stiff layer moduli should be provided.

Temp. Correction - Check this option to adjust the moduli of the first layer to the standard temperature.

Temp. Measurement - Required only when temperature correction is required. Select the appropriate temperature measurement option. Choose the Direct Method option if using an HMA mid-depth temperature measurement. Use the Southgate Method option if pavement temperature is to be calculated from surface temperatures and five-day mean air temperatures (requires additional data).

Plate Radius - Radius of the FWD loading plate.

Seed Moduli - Seed moduli are the initial estimates of unknown layer moduli. Choose Internal if you want the program to estimate the seed moduli. The internal option cannot be used when the number of layers is more than three. The user can also specify seed moduli by selecting User Supplied.

Sensor Weigh Factor – This field allows the user to select amongst three options for calculating the error function that drives the backcalculation process. Evercalc© uses uniform as the default method. The three options are described as follows:

- Uniform: Each sensor deflection is weighed uniformly in constructing the error function. The error being minimized is:

$$100\sqrt{\frac{\sum_{i-1}^{N}\left(\frac{dm - dc}{dm}\right)^2}{N}} \qquad \text{Equation 29}$$

- Inverse First Sensor: Each sensor is weighed by the inverse of the first sensor deflection. The error being minimized is:

$$100\sqrt{\frac{\sum_{i-1}^{N}\left(\frac{dm}{d1}\left(\frac{dm - dc}{dm}\right)\right)^2}{N}} \quad \text{or} \quad 100\sqrt{\frac{\sum_{i-1}^{N}\left(\frac{dm - dc}{d1}\right)^2}{N}} \qquad \text{Equation 30}$$

- User Supplied: User specified weigh factors. User must provide weigh factors for each sensor. The error being minimized is:

$$100\sqrt{\frac{\sum_{i-1}^{N}\left(wm\left(\frac{dm - dc}{dm}\right)\right)^2}{N}} \qquad \text{Equation 31}$$

where,

d1	=	measured deflection at load cell
d2	=	measured deflection at 8 inches (20 cm) from load cell
dc	=	calculated deflections
dm	=	measured deflections
wm	=	user specified weighing factor
N	=	number of loads

Note: The RMS error reported in the output and summary output are always calculated with uniform weight -i.e.:

$$\text{RMS Error} = 100\sqrt{\frac{\sum_{i-1}^{N}\left(\frac{dm - dc}{dm}\right)^2}{N}} \qquad \text{Equation 32}$$

This is done so that the convergence can be compared regardless of the weighing factor used.

Radial Offsets - Radial offsets of the sensors from the center of the loading plate.

Layer Information

No - Layer number. The upper most layer is designated as number one and proceeds sequentially downward.

Layer ID - Enter 0 if the moduli of this layer is to be backcalculated (unknown moduli). Enter 1 if the moduli of this layer is fixed (known).

Poisson's Ratio - Enter the Poisson's ratio of this layer.

Initial Moduli - Enter seed moduli for this layer if the User Supplied option is selected for Seed Moduli or 0.0 if the Internal option is selected.

Min. Moduli - Enter the minimum value of the layer moduli for this layer (must be greater than or equal to 0.0). Can be set to 0.0 if no minimum limit is required.

Max. Moduli - Enter the maximum value of the layer moduli for this layer (must be greater than or equal to 0.0). Can be set to 0.0 if no minimum limit is required.

Max. Iteration - Maximum number of iterations allowed during the optimization. A value of ten is typically used.

RMS Tol. (%) - Root mean square error tolerance between the measured and calculated deflections (percentage). A value of 1.0 is typical.

Modulus Tol. (%) - Modulus percentage tolerance in successive iterations. A value of 1.0 is typical.

Stress and Strain Location – allows user to input up to 10 locations for stress and strain computation. The default locations are beneath the center load at the bottom of the asphalt layer, at the middle of the base layer, and at the top of the subgrade.

Save - Saves the current GENERAL DATA File under the same name. The user must save the file after the data is entered. The program will not save automatically or prompt user to save the data file.

Save As - Saves the current GENERAL DATA File under a different name.

Cancel - Discards any changes made without saving and returns the user to the Main Screen.

2.6.4.5 Open DEFLECTION DATA File

Route - Name of the Route or any other descriptive information.

Station Information

Station **-** Station identification, such as milepost. A maximum character limit of ten.

H(1) to H(4) - Thickness of each pavement layer, up to 5 layers. The last layer thickness is *e*xcluded (subgrade or stiff layer are considered to be infinite in depth).

No. of Drops - Total number of drops at this station. A maximum of twelve drops is allowed.

Pavement Temperature - Pavement temperature (if Direct Method) or five-day mean air temperature (if Southgate Method).

Deflection Information

Drop No – The drop number if more than one drop is input. The program allows up to eight drops per station.

Load - Plate load for each drop.

Sensor Deflection - Measured sensor deflection for each drop at each sensor starting from the closest sensor to the farthest sensor.

Add Station - Adds a station after the current station.

Plot – Allows user to view and print data plots of deflection basins (per station and all load levels), layer thickness, and normalized deflections (standard load of 9,000 lbs (80 kN)).

Delete Station - Deletes the current station.

Save - Saves the current DEFLECTION DATA File. The user must save the data file, the **program** will not automatically save or prompt the user to save the data file.

Save As - Saves the current DEFLECTION DATA File under a different name.

Cancel - Discards any changes made without saving and returns the user to the Main screen.

2.6.4.6 Perform Backcalculation

Interactive – this option requires user to initiate backcalculation process.

Batch – the option allows the user to backcalculate without requiring user intervention for completion. This option will turn off the iteration graphics so that multiple analysis can be started one after another. After starting one analysis the user can start additional analysis by selecting the batch mode menu item. However, all analyses are run in the background sharing the same computer resources and the CPU and memory limitation will dictate the number of analysis that can be started simultaneously.

2.6.4.7 FWD Conversion

GENERAL DATA File – Name of the GENERAL DATA File.

FWD DATA File - Name of the FWD raw data file including its path. Recall that this feature is only available with the Dynatest 8000 FWD’s (version 20).

DEFLECTION DATA File - Name of the DEFLECTION DATA File where the converted FWD data will be saved.

Project Data – this information (route name, number of layers, number of sensors, etc.) will automatically be displayed and is the contents of the GENERAL DATA File. The station locations will also be displayed based on the specified FWD DATA File.

Layer Thickness Information - FWD raw data file does not contain layer thickness information. When the user chooses an FWD file to be processed, a table is displayed with station identifiers in the first column (non-editable), selection option in the second column, and columns for thicknesses for each of the layers excluding the last layer and stiff layer, if any. The user can choose to include or exclude selected stations from the FWD file by clicking the “Selected” column to be checked on or off, respectively. If the stationing is alphanumeric then thicknesses should be provided for all stations selected for backcalculation. If the stationing is numeric then thicknesses need only be provided where it changes and the layer thicknesses for each station (mile post) in the FWD raw data file is chosen to be the same as that of the closest previous station from this list of thicknesses. A minimum of one set of data needs to be provided.

If layer thickness does not change through the project length, the user only needs to enter layer thickness at the first station. If various layer thickness depths exist, the user is only required to enter thicknesses where changes occur. For example, project limits are from station 0 to station 5, and the following layer thickness exist:

Station	Thickness of Asphalt H(1)	Thickness of Base H(2)
0	4.0 inches	6.0 inches
2.5	6.0 inches	8.0 inches

The user would then click on box adjacent to Station 0 and then type in 4.0 for H(1) and 6.0 for H(2). The same process would then be necessary next to station 2.5, click on the box adjacent to Station 2.5 and type in 6.0 for H(1) and 8.0 for H(2). The program will then use 4 inches for the asphalt layer and 6 inches for the base layer from Station 0 to Station 2.5, and 6 inches for the asphalt layer and 8 inches for the base layer from Station 2.5 to Station 5.0.

Select All – Selects all station locations for layer moduli determination.

Deselect All – Deselects all station locations. User selects specific locations for layer moduli determination.

Multiple Drops – Allows user various methods for analyzing data when multiple drops at the same load level are collected.

No – use all the load-deflection data in the backcalculation process. This option is recommended when only one drop per load level has been collected.

Average Normalized – FWD data was collected using multiple drops at each load level. The average load at each load level is determined and then the deflections are averaged and normalized at each load level. For this method the user must enter the number of drops per load. For example, the deflection data is collected using three drops at each load level. This option would then calculate the average load for all three drops (for each load level), then each of the three deflection readings are normalized to the average load and then the normalized deflections are averaged to obtain a single load-deflection data at that load level.

Average – FWD data was collected using multiple drops at each load level. This method averages the load and deflection data. For this method the user must enter the number of drops per load. If the deflection data was collected using multiple drops at each load level, this is the recommended procedure to minimize the random error that is associated with deflection and/or load measurements.

Convert - Converts the FWD raw data file to the necessary format. This process is extremely quick and the user is not prompted that the process is complete.

Exit – Exits the Convert screen and returns to the main screen.

2.6.4.8 Modify Standard Temperature

Allows user to modify the standard temperature for determining the asphalt layer moduli. WSDOT uses 77°F (25°C) as the standard temperature.

2.6.4.9 Exit

Exits the program and returns to Windows.

2.6.5 Execution of the Program

As a general note, any time you save a file in Evercalc©, use the same extension as designated by the program. The program calls the required files according to their extension. It will save the user time and keystrokes if the program extension protocols are followed. In addition, the program will not automatically save any data, the user must click on the "Save" or "Save As" buttons once data has been entered.

After the user has started Windows, the program can be initiated by double clicking on the Evercalc© icon. The screen as shown in Figure 18 will be displayed.

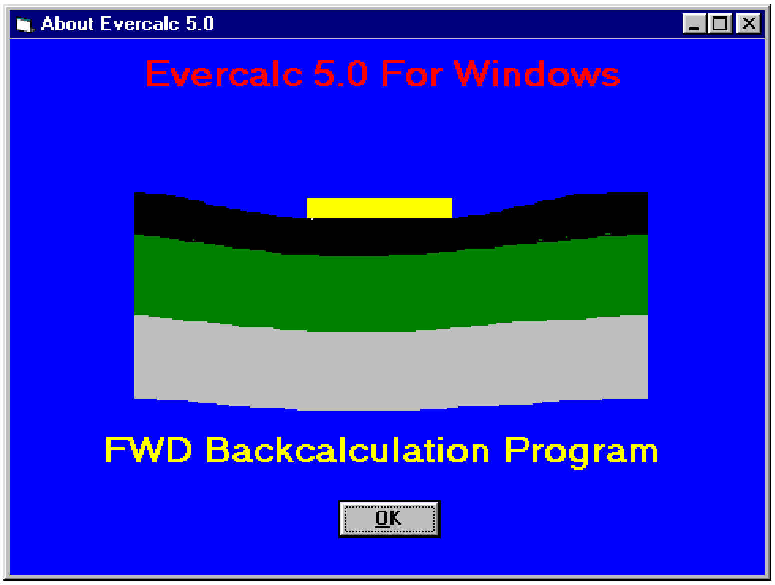


Figure 18. About Evercalc© Screen

Press the **OK** button and the screen as shown in Figure 19 will be displayed.

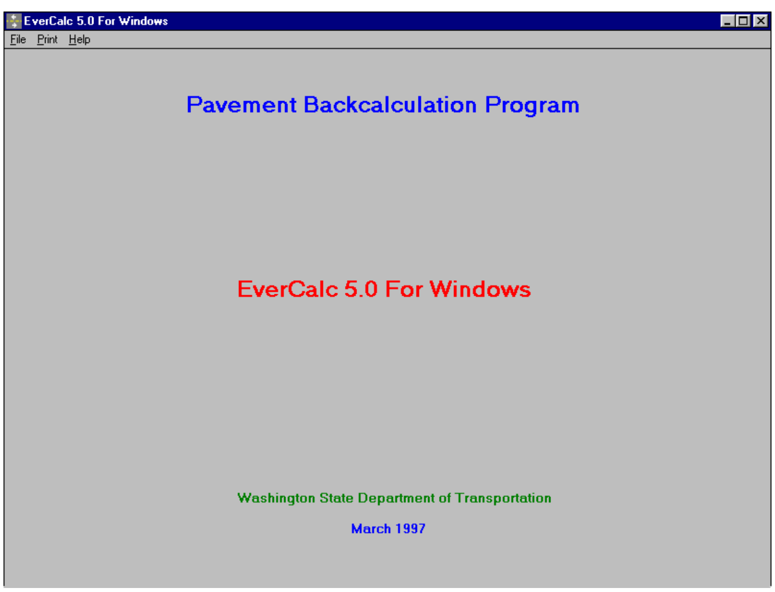


Figure 19. Evercalc© Main Screen

The first step for performing the backcalculation process is the development of the GENERAL DATA File. The GENERAL DATA File contains general pavement data and the general specifications of the nondestructive testing device. Select **File** and then select **Open General File** to create the GENERAL DATA File. The program will prompt the user for a filename, either select a file that is listed or enter a nonexistent filename to create a new GENERAL DATA File. Once the file has been generated the screen as shown in Figure 20 will be displayed.

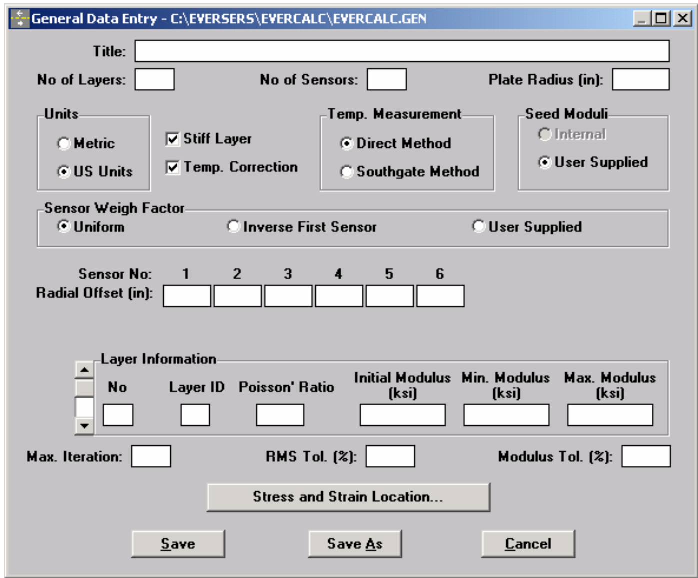


Figure 20. General Data Entry Screen

Begin by entering the following data:

- The title of the project
- The number of pavement layers. The number of layers is limited to five layers, including a stiff layer, if used
- The number of FWD sensors
- The radius of the FWD loading plate
- The units of measure
- Presence of a stiff layer?
- Is temperature correction desired for the HMA layer? Default value for temperature correction is 77°F (25°C) or can be established by the user by selecting **File** and **Modify Standard Temperature**.
- Pavement temperature measured using the Direct or Southgate Method?
- Are the seed moduli to be internal or user supplied? If a stiff layer is used, the user must supply the seed (initial) moduli.
- What sensor weigh factor will be used?
- The radial offset (inch or cm) of each sensor from the load plate. WSDOT uses the following sensor spacing: 0, 8 inches (20.3 cm), 12 inches (30.5 cm), 24 inches (61.0 cm), 36 inches (91.5 cm), and 48 inches (122.0 cm). Care must be taken to insure that the most distant sensor from the load is actually measuring a deflection. If this sensor is located too far from the loading plate, the sensor may pick up more “noise” than an actual deflection and may result in higher error than necessary.
- Layer information. Using the scroll bar, input the layer number, layer ID, Poisson’s ratio, initial modulus (ksi or MPa), and if supplied by the user, the minimum and maximum moduli (ksi or MPa) for each of the pavement layers.

- Enter the program termination values: maximum number of iterations, RMS tolerance (in percent) and the modulus tolerance (in percent).
- Modify stress and strain locations, if necessary.
- Prior to exiting this screen the data must be saved. Select the **Save** button and the data will be saved using the same filename. Selecting the **Save As** button will save the data as a different filename. Selecting the **Cancel** button will return the user to the Main Screen without saving any modifications to the file.

Following the creation of the GENERAL DATA File, the user must then create the DEFLECTION DATA File. The DEFLECTION DATA File contains the data collected from the nondestructive testing device. There are two methods of entering deflection data. The first method is by “hand” entering the load and deflection data. The second method is by converting a raw FWD (Dynatest 8000 version 20 only) data file. The latter of these two will be described later. To “hand” enter in the load and deflection data, select **File** and then select **Open DEFLECTION DATA File**. The user will be prompted to select the GENERAL DATA File to be used (the GENERAL DATA File must have already been created). Then the user will be prompted to open an existing DEFLECTION DATA File or to create a new DEFLECTION DATA File by entering a nonexistent filename. Once the file has been generated the following screen as shown in Figure 21 will be displayed.

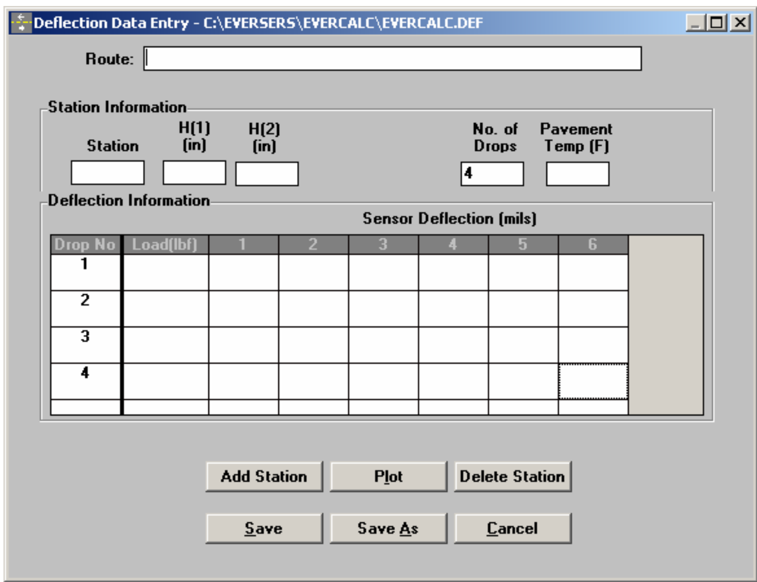


Figure 21. Deflection Data Entry Screen

At this screen, enter in the following data:

- Route, which can be any text that identifies the project.
- Station or milepost number, thickness of the HMA layer, thickness of the base layer, subbase layer(s) (if appropriate) number of drops, and the pavement temperature at the time of testing.
- For each station, enter the load(s) and the corresponding deflections.
- Additional stations may be added by selecting the **Add Station** button. Likewise, a station that is currently shown can be deleted by selecting the **Delete Station** button.
- Prior to exiting this screen the data must be saved. Select the **Save** button and the data will be saved using the same filename. Selecting the **Save As** button will save the data as a different filename. Selecting the **Cancel** button will return the user to the Main Screen without saving any modifications to the file.

To convert a raw FWD DATA File to a DEFLECTION DATA File, select file and then select **Convert FWD DATA File**. The user will be prompted to select the GENERAL DATA File and the FWD DATA File to be converted. The screen similar to what is shown in Figure 22 will be displayed.

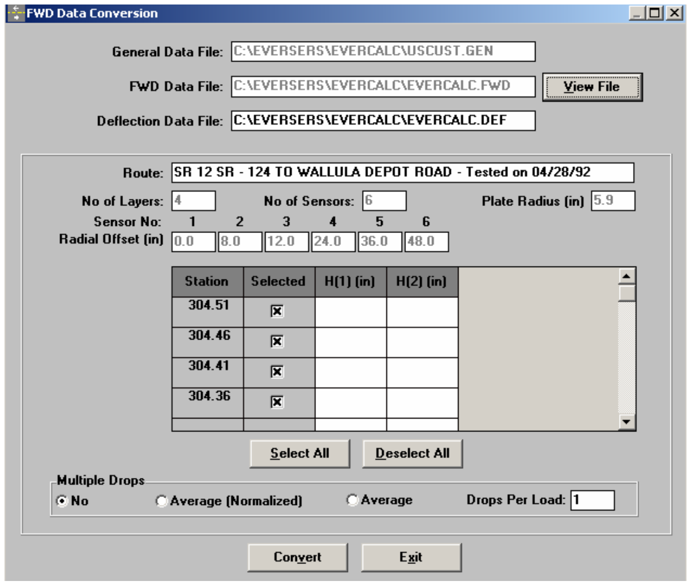


Figure 22. FWD Data Conversion Screen

The GENERAL DATA File and FWD DATA File that was selected by the user will be shown on the upper portion of this screen. The program will automatically name the DEFLECTION DATA File according to the name used for the FWD DATA File. The program will assign ".DEF" as the DEFLECTION DATA File extension. This screen will convert the raw FWD file into a format to be used in the backcalculation process. In addition, this screen will allow the user to input layer thickness for each of the layers as designated in the GENERAL DATA File. The stations to be included in the deflection data file are selected and the corresponding layer thicknesses are entered as explained earlier. Once all data has been entered, select **Convert** and the program will execute, and then select **Exit** to return to the Main screen.

The plot routines that are available in the **Deflection Data Entry** screen are deflection basin, layer thickness, and normalized deflection. Selecting the Plot button, the following screen will be displayed.

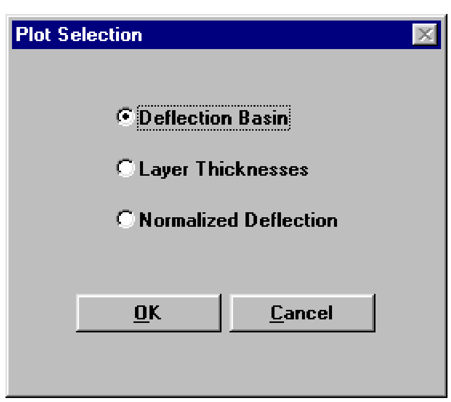


Figure 23. Deflection Data Plot Screen

Each one of these options will be briefly described.

Deflection Basin – the deflection basin (for all load levels) will be displayed **for** each individual station location. The buttons across the top of the screen will allow the user various options for presenting the data.

Figure 24. Plot Deflection Basin

Layer Thickness –the various layer thicknesses for the entire deflection data file will be displayed.

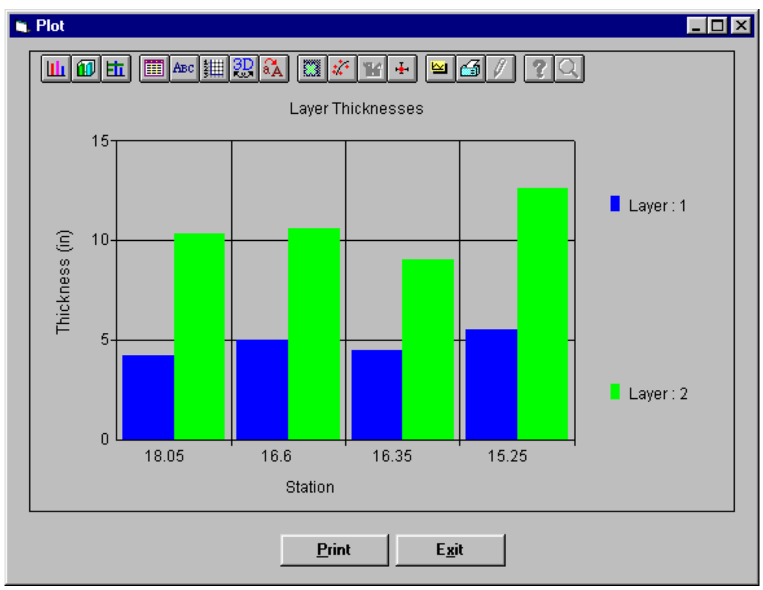


Figure 25. Plot Layer Thickness

Normalized Deflection – the normalized (to the standard temperature and 9000 lb (40 kN)) deflection will be displayed according to each sensor for the entire deflection data file.

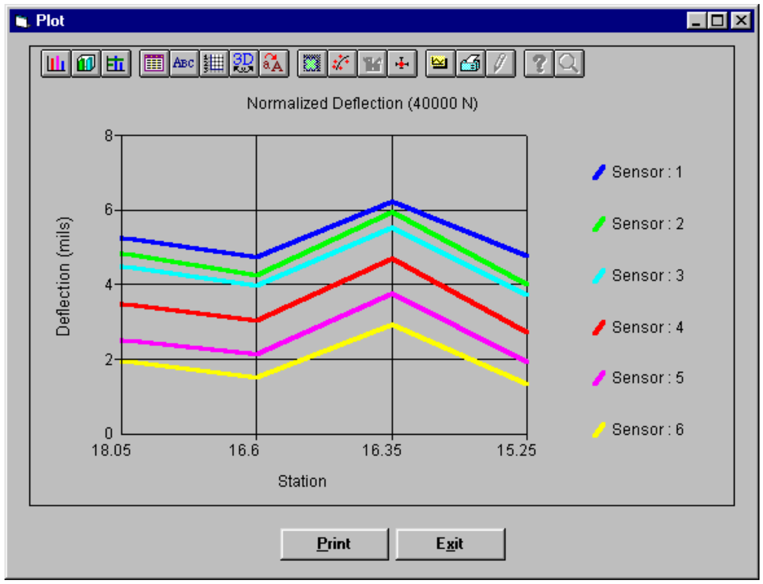


Figure 26. Plot Normalized Deflections

After creating the GENERAL DATA File and the DEFLECTION DATA File, the user is now able to begin the backcalculation process. Select **File** and then select **Perform Backcalculation**. The user will then have the choice to either run the backcalculation in the interactive or batch mode. If numerous deflection files are to be analyzed and the user does not want to be prompted to complete the analysis (run process over night for example) then the batch mode should be selected. In the interactive mode, the user will be prompted to select the GENERAL DATA File, the DEFLECTION DATA File, and to confirm the Output Filename. If the user selected to not use a stiff layer (GENERAL DATA File), the backcalculation process will begin. If the user selected a stiff layer, then the depth to stiff layer screen will be displayed and the user will be asked to modify the estimated depth to stiff layer or to accept the data as shown (see Figure 27).

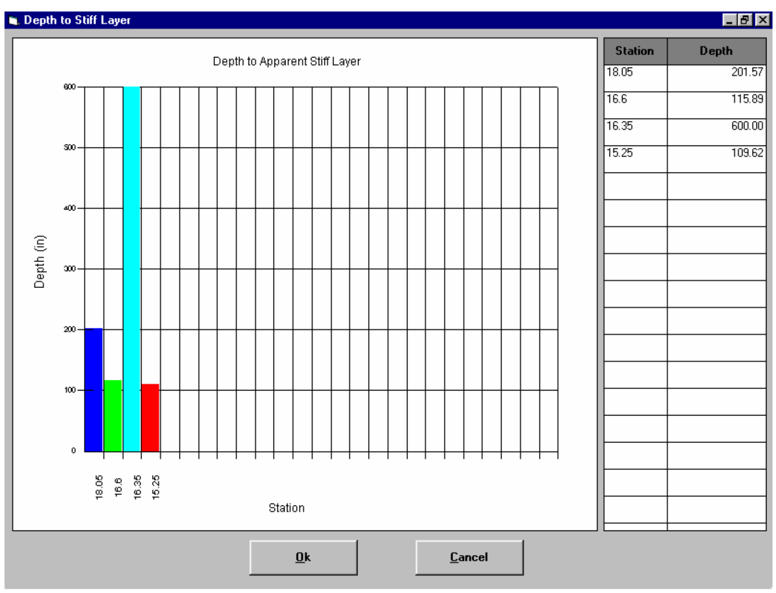


Figure 27. Depth to Apparent Stiff Layer Screen

If the user has actual borings to depth of stiff layer (or saturated layer) they can be entered directly onto this screen. Clicking on the depth to be modified will allow the user to enter the necessary values.

Click on the **OK** button and the backcalculation process will begin. The program will then display on the screen the measured and calculated deflections in the determination of the layer moduli. The computer will display this screen for each load level at each station. The process is completed when the word "Finished" is displayed in the lower left-hand corner as shown in Figure 28.

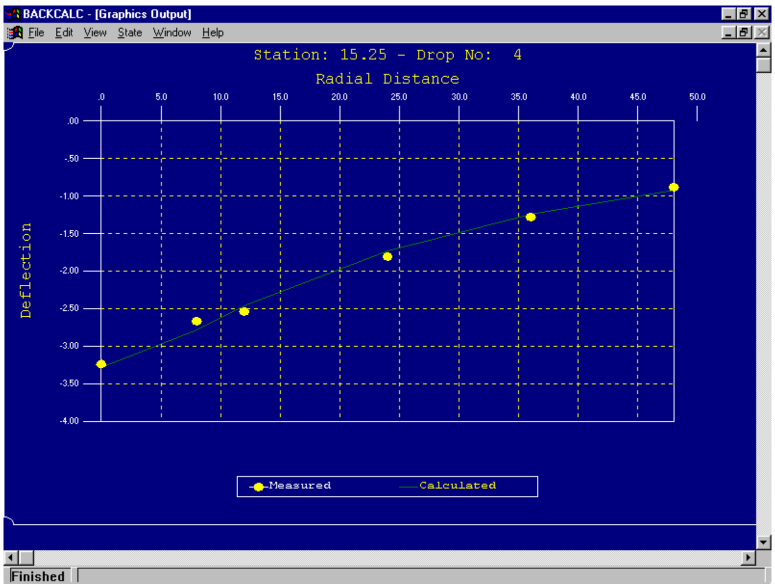


Figure 28. Backcalculation Screen

To return back to the main menu, select **File** and then **Exit** or close the screen using the X button in the upper right hand corner. The data can then be viewed or printed by selecting **Print** on the main menu tool bar. To exit the Evercalc© program, select **File** and then select **Exit**.

2.6.6 EVERCALC Deflection File Format

2.6.6.1 Sample of Evercalc© Deflection File

SR 14 6TH AVE. TO EVERGREEN BLVD. - Tested on 12/06/95 (description)
18.05 4 4.200 10.320 0.000 0.000 37.000 0.000 (test location 1/description)
17141.0 8.910 8.320 7.760 6.040 4.600 3.460 (load 1/deflection)
12946.0 7.150 6.720 6.220 4.830 3.650 2.720 (load 2/deflection)
9582.0 5.590 5.160 4.800 3.730 2.690 2.110 (load 3/deflection)
6201.0 3.590 3.390 3.100 2.420 1.800 1.290 (load 4/deflection)
16.6 4 5.000 10.560 0.000 0.000 37.000 0.000 (test location 2/description)
16240.0 8.280 7.400 6.970 5.320 3.800 2.690 (load 1/deflection)
12279.0 6.460 5.810 5.440 4.150 2.980 2.080 (load 2/deflection)
9077.0 4.770 4.280 4.020 3.050 2.160 1.520 (load 3/deflection)
5883.0 2.900 2.680 2.480 1.880 1.330 0.830 (load 4/deflection)
16.35 4 4.500 9.000 0.000 0.000 37.000 0.000 (test location 3/description)
15819.0 11.010 10.290 9.870 8.250 6.650 5.280 (load 1/deflection)
12180.0 8.620 8.240 7.690 6.540 5.260 4.120 (load 2/deflection)
9284.0 6.450 6.160 5.710 4.850 3.890 3.030 (load 3/deflection)
6062.0 3.980 3.930 3.690 3.060 2.430 1.940 (load 4/deflection)

2.6.6.2 File Description

The file is in free format – the values should be separated by a space, comma or hard TAB.

Line 1 – Route information (CHARACTER STRING, max length = 80)
Line 2
- Item 1 – station (CHARACTER STRING, max length = 10)
- Item 2 – number of drops at this station (Integer)
- Item 3 through Item 6 – four layer thickness (single precision). If there are less than four thickness (i.e. less than five layers), enter 0.0 for the rest. For example, for a three-layer case, enter the 1st and 2nd layer thickness first then enter 0.0 for the next two (inches or cm).
- Item 7 through Item 8 – temperature values (single precision). The temperature correction is defined in the GENERAL DATA File. If there is no temperature correction then enter 0.0 for both. If direct method then enter the temperature for Item 7 and enter 0.0 for Item 8. If Southgate method then enter surface temperature for Item 7 and mean temperature for Item 8 (°F or °C).

The following line is repeated for each drop at this station (defined in Line 2, Item 2)

Line 3
- Item 1 – Plate load (single precision) (lbf or N)
- Item 2 – Item x deflections (single precision). Enter as many deflection readings as the number of sensors defined in the GENERAL DATA File, starting from the sensor closest to the load plate (mils or microns)

The units should be consistent with that defined in the GENERAL DATA File. You can open this file in Evercalc© (Open Deflection Data) and check for its correctness.

2.6.7 Example No. 1 — No Stiff Layer

2.6.7.1 GENERAL DATA File

Number of layers = 3
No stiff layer
Temperature measurement = Direct Method
Seed Moduli = User Supplied
Plate Radius = 5.9 inches

Sensor Number	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information

No	Layer ID	Poisson's Ratio	Initial Modulus (ksi)	Minimum Modulus (ksi)	Maximum Modulus (ksi)
1	0	0.35	400	100	2000
2	0	0.40	25	5	500
3	0	0.45	15	5	500

Maximum Iteration = 10
RMS Tolerance (%) = 1.0
Modulus Tolerance (%) = 1.0

2.6.7.2 Deflection Data File

Station = 210.00
H(1) = 4 inches
H(2) = 16 inches
Number of drops = 4
Pavement Temperature = 50°F

Drop Number	Load (lb)	1	2	3	4	5	6
1	16717.69	35.98	29.21	25.16	16.77	11.22	7.56
2	12022.78	27.80	22.60	19.29	12.72	8.39	5.71
3	9421.52	22.32	17.99	15.28	9.84	6.38	4.37
4	6170.11	15.16	12.09	10.08	6.30	3.98	2.76

2.6.7.3 Backcalculation Results (No Stiff Layer)

BACKCALCULATION by Evercalc© 5.0 - Detail Output

Route: Example No. 1 - No Stiff Layer
Plate Radius (in): 5.9 — No. of Layers: 3
No of Sensors: 6 — Stiff Layer: No
Offsets (in) .0.0 8.0 12.0 24.0 36.0 48.0 — P-Ratio: .350 .400 .450

Station: 210 — No of Drops: 4 — Average RMS Error (%): 2.30
Thickness (in): 4.00 16.00 — Pavement Temperature (F): 50.0

Drop No: 1 — Load (N): 16717.7 — No of Iterations: 5
Convergence: Modulus Tolerance Satisfied — RMS Error (%): 2.73

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	35.980	29.210	25.160	16.770	11.220	7.560
Calculated Deflection (microns):	34.678	29.791	25.998	16.550	10.873	7.731
Difference (%):	3.62	-1.99	-3.33	1.31	3.10	-2.26

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	400.00	25.00	15.00	N/A
Calculated Moduli (MPa):	1666.63	14.76	12.36	520.638

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-22.91	-12.80	-7.86
Radial Stress (psi):	796.86	-1.41	-.98
Bulk Stress (psi):	1570.81	-15.62	-9.83
Deviator Stress (psi):	-819.77	-11.39	-6.88
Vertical Strain (10^{-6}):	-348.43	-790.78	-564.76
Radial Strain (10^{-6}):	315.59	289.57	242.65

Drop No: 2 — Load (N): 12022.8 — No of Iterations: 2
Convergence: Modulus Tolerance Satisfied — RMS Error (%): 2.46

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	27.800	22.600	19.290	12.720	8.390	5.710
Calculated Deflection (microns):	26.911	22.960	19.927	12.519	8.182	5.824
Difference (%):	3.20	-1.59	-3.30	1.58	2.47	-1.99

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	1666.63	14.76	12.36	N/A
Calculated Moduli (MPa):	1439.79	14.17	11.74	449.776

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-17.48	-9.61	-5.83
Radial Stress (psi):	555.45	-.99	-.69
Bulk Stress (psi):	1093.43	-11.60	-7.22
Deviator Stress (psi):	-572.93	-8.62	-5.13
Vertical Strain (10^{-6}):	-282.19	-622.18	-443.16
Radial Strain (10^{-6}):	255.01	220.25	190.85

Drop No: 3 Load (N): 9421.5 No of Iterations: 2
Convergence: Modulus Tolerance Satisfied RMS Error (%): 2.25

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	22.320	17.990	15.280	9.840	6.380	4.370
Calculated Deflection (microns):	21.659	18.284	15.733	9.669	6.254	4.448
Difference (%):	2.96	-1.63	-2.97	1.74	1.98	-1.78

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	1439.79	14.17	11.74	N/A
Calculated Moduli (MPa):	1271.06	14.21	11.95	397.067

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-14.73	-7.97	-4.78
Radial Stress (psi):	417.82	-.80	-.55
Bulk Stress (psi):	820.92	-9.57	-5.87
Deviator Stress (psi):	-432.55	-7.18	-4.23
Vertical Strain (10^{-6}):	-241.69	-516.41	-358.89
Radial Strain (10^{-6}):	217.72	190.83	154.89

Drop No: 4 Load (N): 6170.1 No of Iterations: 2
Convergence: Modulus Tolerance Satisfied RMS Error (%): 2.07

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	15.160	12.090	10.080	6.300	3.980	2.760
Calculated Deflection (microns):	14.771	12.242	10.382	6.160	3.931	2,801
Difference (%):	2.56	-1.26	-2.99	2.22	1.22	-1.49

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	1271.06	14.21	11.95	N/A
Calculated Moduli (MPa):	1039.24	14.40	12.29	324.646

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-10.87	-5.72	-3.36
Radial Stress (psi):	254.65	-.53	-.35
Bulk Stress (psi):	498.43	-6.78	-4.06
Deviator Stress (psi):	-265.52	-5.19	-3.00
Vertical Strain (10^{-6}):	-181.98	-367.81	-247.23
Radial Strain (10^{-6}):	162.93	136.82	107.09

Layer No:	1	2	3	1-(adj)
Mean Moduli (MPa)	1354.18	14.38	12.09	423.03
Normalized Moduli (MPa)	1241.01	14.23	12.00	387.678
K1 (MPa):	N/A	14.45	12.10	
K2:	N/A	.03	.00	
R-Squared:	N/A	49.97	3.93	
Soil Type:	N/A	Coarse	Coarse	

BACKCALCULATION by Evercalc© 5.0 - Summary Output

Route: Example No. 1 - No Stiff Layer
Plate Radius (in): 5.9 No of Layers: 3
No of Sensors: 6 Stiff Layer: No
Offsets (in) 0.0 8.0 12.0 24.0 36.0 48.0 P-Ratio: .350 .400 .450

Station	Load (lb)	Eadj(ksi)	E(1)(ksi)	E(2)(ksi)	E(3)(ksi)	RMS Error
210	Thickness (in)	-	4.00	16.00	-	-
210	16717.7	520.6	1666.6	14.8	12.4	2.73
210	12022.8	449.8	1439.8	14.2	11.7	2.46
210	9421.5	397.1	1271.1	14.2	12.0	2.25
210	6170.1	324.6	1039.2	14.4	12.3	2.07
210	Norm.	387.7	1241.0	14.2	12.0	2.38

2.6.8 Example No. 2 - Stiff Layer at 50 ksi

2.6.8.1 GENERAL DATA File

Number of layers = 4
Stiff layer
Temperature measurement = Direct Method
Seed Moduli = User Supplied
Plate Radius = 5.9 inches

Sensor Number	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information

No	Layer ID	Poisson's Ratio	Initial Modulus (ksi)	Minimum Modulus (ksi)	Maximum Modulus (ksi)
1	0	0.35	400	100	2000
2	0	0.40	25	5	500
3	0	0.45	15	5	500
4	1	0.20	50		

Maximum Iteration = 10
RMS Tolerance (%) = 1.0
Modulus Tolerance (%) = 1.0

2.6.8.2 DEFLECTION DATA FILE

Station = 210.00
H(1) = 4 inches
H(2) = 16 inches
Number of drops = 4
Pavement Temperature = 50°F

Drop Number	Load (lb)	1	2	3	4	5	6
1	16717.7	35.98	29.21	25.16	16.77	11.22	7.56
2	12022.78	27.80	22.60	19.29	12.72	8.39	5.71
3	9421.52	22.32	17.99	15.28	9.84	6.38	4.37
4	6170.11	15.16	12.09	10.08	6.30	3.98	2.76

2.6.8.3 BACKCALCULATION RESULTS

BACKCALCULATION by Evercalc© 5.0 - Detail Output

Route: Example No. 1 - Stiff Layer
Plate Radius (in): 6.9 — No. of Layers: 4
No of Sensors: 6 — Stiff Layer: Yes
Offsets (in) .0 8.0 12.0 24.0 36.0 48.0 — P-Ratio: .350 .400 .450 .200

Station: 210 — No of Drops: 4 — Average RMS Error (%): 1.85
Thickness (in): 4.00 16.00 284.83 — Pavement Temperature (F): 50.0

Drop No: 1 — Load (lbf): 16717.7 — No of Iterations: 5
Convergence: Modulus Tolerance Satisfied — RMS Error (%): 2.23

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	35.980	29.210	25.160	16.770	11.220	7.560
Calculated Deflection (microns):	35.031	29.744	25.806	16.474	10.955	7.719
Difference (%):	2.64	-1.83	-2.57	1.76	2.36	-2.10

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	400.00	25.00	15.00	50.00	N/A
Calculated Moduli (MPa):	1361.51	20.81	10.17	50.00	425.321

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-30.10	-14.29	-7.42
Radial Stress (psi):	691.08	.31	-.58
Bulk Stress (psi):	1352.06	-13.67	-8.58
Deviator Stress (psi):	-721.17	-14.60	-6.83
Vertical Strain (10^{-6}):	-377.41	-698.32	-677.40
Radial Strain (10^{-6}):	337.67	283.48	296.51

Drop No: 2 — Load (lbf): 12022.8 — No of Iterations: 3
Convergence: Modulus Tolerance Satisfied — RMS Error (%): 1.93

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	27.800	22.600	19.290	12.720	8.390	5.710
Calculated Deflection (microns):	27.188	22.914	19.770	12.470	8.253	5.808
Difference (%):	2.20	-1.39	-2.54	1.97	1.63	-1.72

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1361.51	20.81	10.17	50.00	N/A
Calculated Moduli (MPa):	1173.31	19.72	9.66	50.00	366.529

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-22.81	-10.69	-5.48
Radial Stress (psi):	479.81	.25	-.41
Bulk Stress (psi):	936.81	-10.19	-6.31
Deviator Stress (psi):	-502.63	-10.94	-5.07
Vertical Strain (10^{-6}):	-305.70	-552.22	-529.28
Radial Strain (10^{-6}):	272.62	224.42	232.00

Drop No: 3 — Load (lbf): 9421.5 — No of Iterations: 2
Convergence: Modulus Tolerance Satisfied — RMS Error (%): 1.70

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	22.320	17.990	15.280	9.840	6.380	4.370
Calculated Deflection (microns):	21.879	18.240	15.604	9.640	6.315	4.430
Difference (%):	1.97	-1.39	-2.12	2.03	1.02	-1.36

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1173.31	19.72	9.66	50.00	N/A
Calculated Moduli (MPa):	1041.23	19.28	9.89	50.00	325.270

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-18.89	-8.80	-4.51
Radial Stress (psi):	361.37	.13	.33
Bulk Stress (psi):	703.85	-8.54	-5.16
Deviator Stress (psi):	-380.27	-8.93	-4.18
Vertical Strain (10^{-6}):	-261.09	-462.02	-425.88
Radial Strain (10^{-6}):	231.94	186.73	186.85

Drop No: 4 Load (lbf): 6170.1 No of Iterations: 2
Convergence: Modulus Tolerance Satisfied RMS Error (%): 1.51

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	15.160	12.090	10.080	6.300	3.980	2.760
Calculated Deflection (microns):	14.927	12.204	10.287	6.151	3.977	2.783
Difference (%):	1.54	-.94	-2.06	2.36	0.7	-.84

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1041.23	19.28	9.89	50.00	N/A
Calculated Moduli (MPa):	851.63	18.93	10.25	50.00	266.039

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-13.68	-6.26	-3.17
Radial Stress (psi):	219.42	.05	-.21
Bulk Stress (psi):	425.15	-6.16	-3.60
Deviator Stress (psi):	-233.09	-6.31	-2.96
Vertical Strain (10^{-6}):	-196.41	-332.97	-290.69
Radial Strain (10^{-6}):	173.09	133.93	127.77

Layer No:	1	2	3	4	1-(adj)
Mean Moduli (MPa)	1106.92	19.68	9.99	50.00	345.79
Normalized Moduli (MPa)	1016.65	19.23	9.93	50.00	317.591
K1 (MPa):	N/A	20.36	9.80	N/A	
K2:	N/A	.15	-.02	N/A	
R-Squared:	N/A	96.79	21.17	N/A	
Soil Type:	N/A	Coarse	Fine	N/A	

BACKCALCULATION by Evercalc© 5.0 - Summary Output

Route: Example No. 1 - Stiff Layer
Plate Radius (in): 5.9 No of Layers: 4
No of Sensors: 6 Stiff Layer: Yes
Offsets (in) 0.0 8.0 12.0 24.0 36.0 48.0 P-Ratio: .350 .400 .450 .200

Station	Load (lbf)	Eadj(ksi)	E(1)(ksi)	E(2)(ksi)	E(3)(ksi)	E(4)(ksi)	RMS Error
210	Thickness (in)	-	4.00	16.00	284.83	-	-
210	16717.7	425.3	1361.5	20.8	10.2	50.0	2.23
210	12022.8	366.5	1173.3	19.7	9.7	50.0	1.93
210	9421.5	325.3	1041.2	19.3	9.9	50.0	1.70
210	6170.1	266.0	851.6	18.9	10.2	50.0	1.51
210	Norm.	317.6	1016.7	19.2	9.9	50.0	1.85

1.2.6 Interpretation of Example Results

From the summary outputs for the no stiff layer and stiff layer examples, the following normalized (9000 lb) results show:

Example	E_{adj}	E_1	E_2	E_3	RMSE
No stiff layer	387.7	1241.0	14.2	12.0	2.38
Stiff layer	317.6	1016.7	19.2	9.9	1.85

From this summary both the no stiff and stiff layer examples provide reasonable results with low RMSE. With the lower base moduli, it appears that the base material may have been compromised (infiltrated with fine material) due to the low stiffness (weak) subgrade (field evaluation could be used to verify this result). Use of either result would be appropriate. However, the results of the stiff layer provide a lower RMSE and more realistic moduli for the base and subgrade moduli.

3.1 INTRODUCTION

Everpave© is a flexible pavement overlay design program based on mechanistic analysis. Everpave© is based on the multilayered elastic analysis program, WESLEA (provided by the Waterways Experiment Station, U. S. Army Corps of Engineers), which produces the pavement response parameters such as stresses, strains, and deformations in the pavement system [1].

The determination of the overlay thickness is based on the required thickness to bring the damage levels to an acceptable level under a design traffic condition. The damage levels are based on two primary distress types, fatigue cracking and rutting, which are the most common criteria for mechanistic analysis based overlay design. The program is also capable of considering seasonal variations and stress sensitivity of the pavement materials.

3.2 CHARACTERISTICS OF EVERPAVE

A mechanistic-empirical overlay design procedure (Everpave) was developed by the Washington State Department of Transportation that is based on the backcalculation of material properties and fatigue and rutting failures. In this approach, layer moduli can be calculated for each deflection test point. The HMA modulus is corrected for temperature according to data for typical Washington mixtures (Figure 29). Next, an iterative process is used to determine an appropriate overlay thickness for each deflection test point as shown in Figure 30.

Both the unstabilized base course (subbase) and subgrade moduli can be non-linear with stress state, i.e., the base, subbase, and subgrade layer moduli can take the following form:

$$E = K_1 (\theta)^{K_2} \quad \text{or} \quad E = K_3 (\sigma_d)^{K_4} \qquad \text{Equation 33}$$

with the exponents being either positive or negative.

3.2.1 Failure Criteria

The failure criteria used in Everpave© are based on two basic criteria: rutting and HMA fatigue cracking (refer to Figure 31 for specific locations). The rutting criterion was adopted from the Asphalt Institute [10, 11]:

$$N_f = \left[\frac{1.05 \times 10^{-2}}{e_v}\right]^{4.4843} \qquad \text{Equation 34}$$

where N_f = allowable number of 18,000 lb (80 kN) single axles so that rutting at the pavement surface should not exceed 0.5 inch (12.7 mm), and

e_v = vertical compressive strain at the top of the subgrade layer.

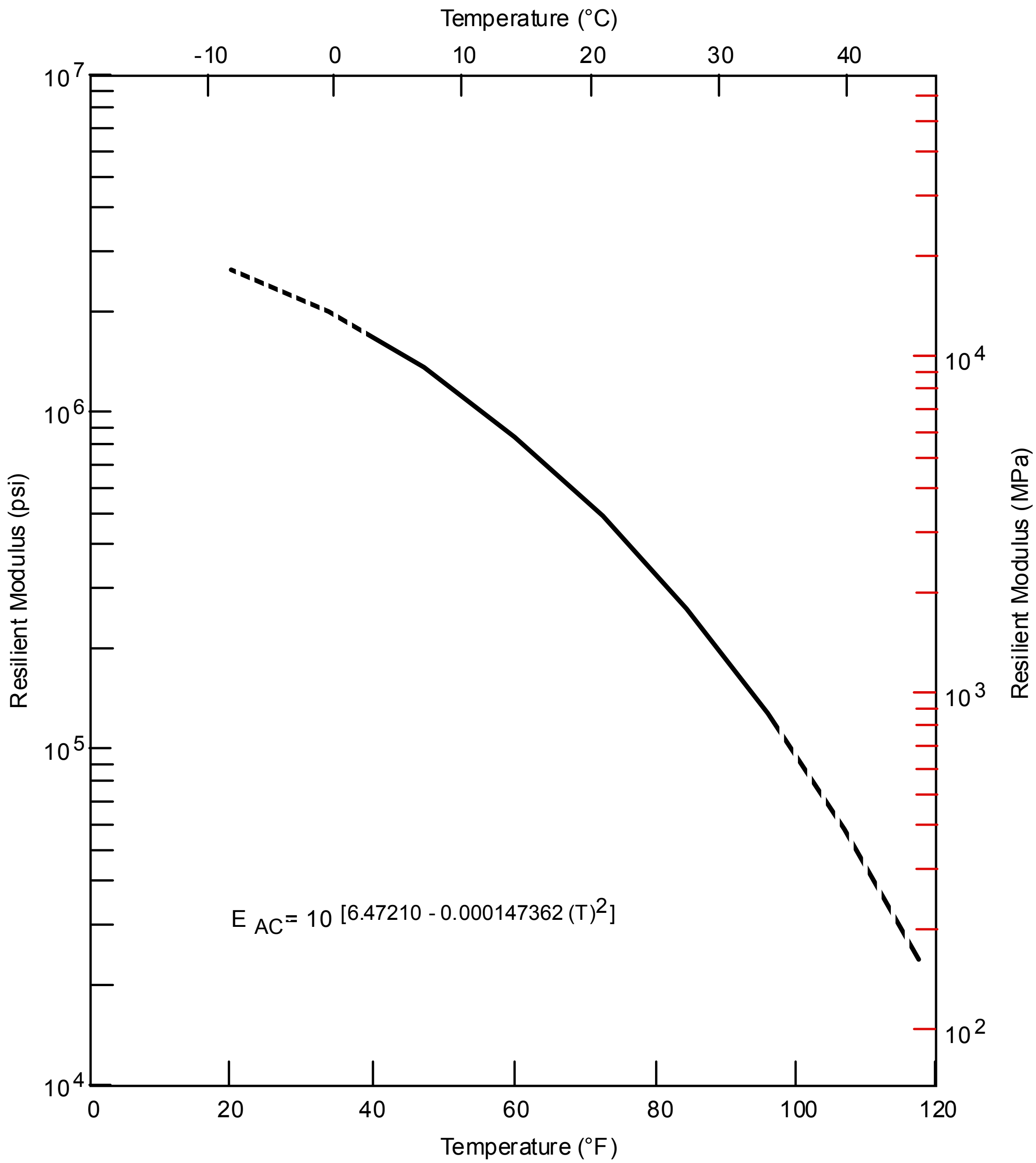
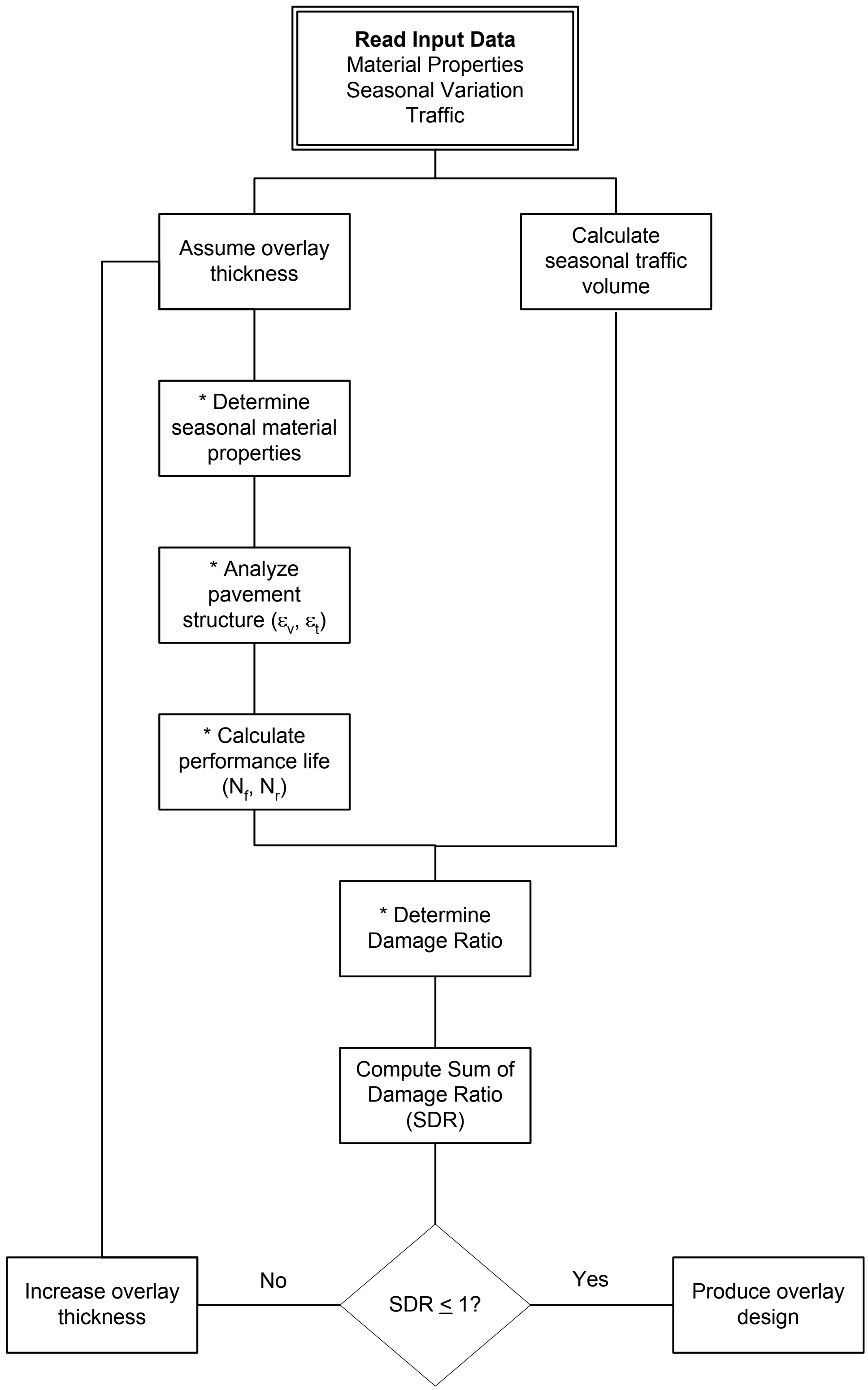
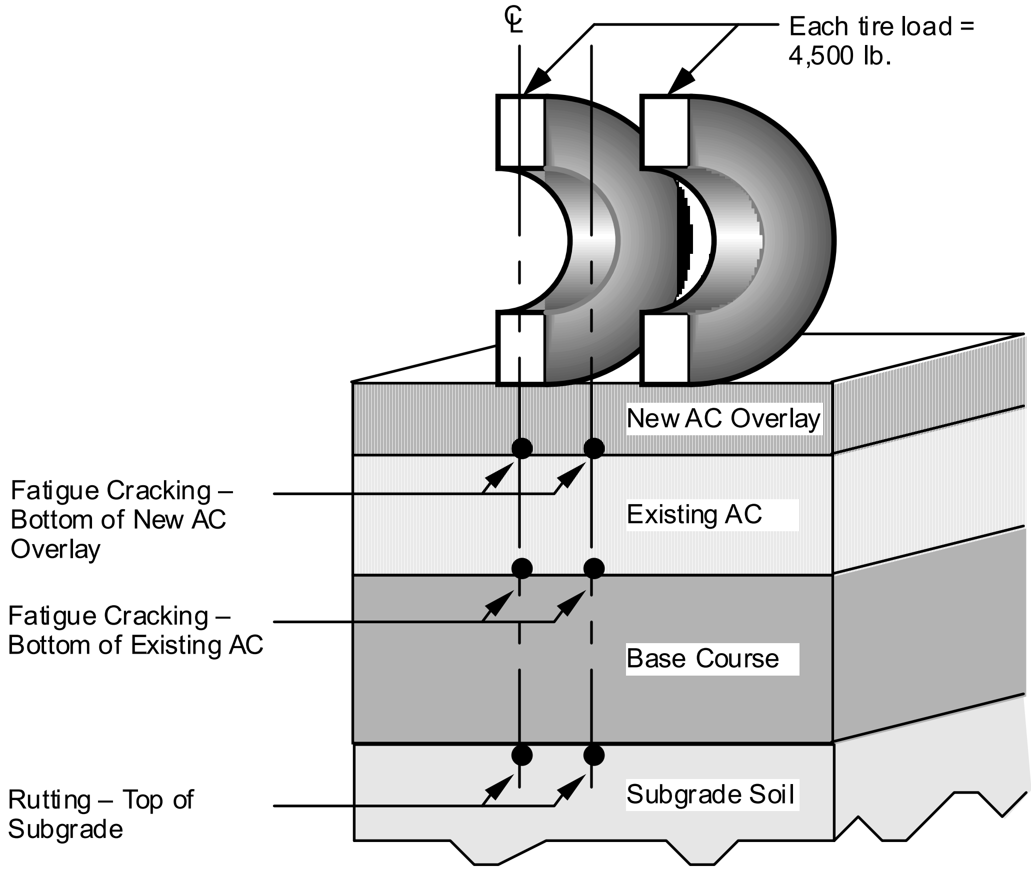


Figure 29. General Stiffness-Temperature Relationship for Class B (Dense Graded) HMA in Washington State



* Repeat for all seasons

Figure 30. WSDOT Overlay Design Flow Chart



Note: Failure criteria checked beneath one tire and between the two tires.

Figure 31. Failure Criteria Evaluation Points – Everpave Program

The fatigue cracking failure criterion is based on Monismith's laboratory based model [12] and the subsequent work by Finn, et al. [13] and Mahoney, et al. [14].

Fatigue cracking: $N_{field} = (N_{lab})\ (SF)$ Equation 35

where N_{field} = number of load applications of constant stress to cause fatigue cracking,

Nlab = relationship from laboratory data [9, 15],

$$= 10\left(14.82 - 3.291 \log\left(\frac{et}{10\text{-}6}\right) - 0.854 \log\left(\frac{Eac}{103}\right)\right)$$

SF = can range from about 4 to 10, depending on HMA thickness, ESAL level, climate.

The N_{field} applications are estimated to result in about 10 percent or less fatigue cracking in the wheelpath area. The original Finn, et al. [13] model based on the Monismith laboratory work [12] and the results of the AASHO Road Test is:

$$N_f = 10^{\left(15.947 - 3.291 \log\left(\frac{e_t}{10^{-6}}\right) - 0.854 \log\left(\frac{E_{ac}}{10^3}\right)\right)}$$ Equation 36

where N_f = number of axle applications to result in 10 percent or less fatigue cracking in the wheelpath area,

e_t = horizontal tensile strain at the bottom of the HMA layer

Eac = modulus of the HMA layer (psi).

The difference between the Finn equation above and the Monismith laboratory based relationship is about 13.4. Thus, the laboratory fatigue relationship was "shifted" by a factor of 13.4 to more realistically represent a field fatigue prediction for the accelerated loading conditions at the AASHO Road Test. WSDOT studies [14] have shown, as stated above, that realistic shift factors for in-service WSDOT pavements are less than 13.4 (more like 4 to 10). Generally, the shift factor is increased for high traffic conditions on say 4 to 6 inch (100 to 150 mm) HMA. The shift factor is lower for flexible pavements with HMA thicknesses of about 7 to 8 inch (175 to 200 mm) or thicker. WSDOT personnel have often observed for these thick HMA pavements that the cracking starts at the pavement surface, not the bottom of the HMA. It is appropriate to note that Finn, et al. [13] only analyzed the 4, 5, and 6 inch (100, 125, 150 mm) thick HMA flexible pavement sections from Loop 4 (7 sections) and Loop 6 (10 sections) from the AASHO Road Test data.

3.2.2 Reliability

Reliability can be incorporated into the design procedure in a very appropriate and similar manner as used in the AASHTO Guide. Basically, reliability is simply a multiplier to the estimated design period ESALs, as follows:

Design ESALs = (Estimated ESALs) (F_R) Equation 37

where F_R = Reliability design factor (≥ 1) = $10^{(-z_R)(s_o)}$

z_R = z-statistic associated with normal distributions

So = overall standard deviation of normal distribution of errors associated with traffic prediction and pavement performance.

An S_o value of 0.5 will be assumed to be applicable for the design of WSDOT overlays (i.e., a greater uncertainty than experienced at the AASHO Road Test for new design). Thus, F_R for various reliability levels are:

Reliability Level (%)	z_R	Reliability Design Factor (F_R)
50	0.00	1.00
60	-0.25	1.33
70	-0.52	1.82
75	-0.67	2.16
80	-0.84	2.63
85	-1.04	3.31
90	-1.28	4.37
95	-1.65	6.68
99	-2.33	14.62
99.9	-3.10	35.48

For example, if the estimated design period ESALs = 1,000,000, then the following design ESALs would be used as the ESAL input into the Everpave program (for various reliability levels):

Reliability Level (%)	Design ESALs
50	1,000,000
60	1,330,000
70	1,820,000
75	2,160,000
80	2,630,000
85	3,310,000
90	4,370,000
95	6,680,000
99	14,620,000
99.9	35,480,000

The above illustrates how the reliability process works. In very general terms, doubling the design ESALs will increase the HMA overlay thickness about 1 inch (for example, going from R = 50% to R = 75 % would add about one inch of HMA to the overlay). WSDOT currently uses a reliability level of 50 percent for the design of all HMA overlays.

Note that the use of reliability can never be a substitute for proper mix design, construction, maintenance, etc. Further, WSDOT does not currently use this reliability procedure for overlay design, in effect, using an F_R = 1.0 (or reliability level of 50 percent). This is due to at least two reasons. First, using this reliability approach is not entirely appropriate in a non-AASHTO design process. Second, with HMA overlays, environmental as well as traffic considerations limit overlay life.

3.2.3 Required Inputs — Everpave

The required input data are:

- **(a) Design ESALs** — Estimated ESALs for the design period adjusted for reliability.
- **(b) Design Load** — Normally a dual tire load of 4500 lb on each tire at 100 psi inflation pressure speed 15 inch c-c; however, this can be varied to suit the design conditions.
- **(c) Seasonal Variation of Layer Moduli** — The unstabilized base, subbase, and subgrade layers can be adjusted for seasonal effects. If no adjustment is necessary, use 1.0.
- **(d) Seasonal Temperatures** — Used to adjust the HMA moduli for seasonal temperature changes. Refer to Appendix B for specific recommendations.
- **(e) Shift Factor for Fatigue Criterion** — Ranges from about 4 to 10 (typically). Discussed in Paragraph 3.2.1.
- **(f) Minimum Overlay Thickness** — Generally start with a 0.5 to 1.0 inch thickness.
- **(g) Overlay Incremental Thickness** — Generally use 0.25 to 0.5 inch
- **(h) Unstabilized Layer Moduli** — These can be fixed as linear, elastic (e.g., E_{BS} = 30,000 psi) or non-linear as described in Paragraph 3.2.3.3.

3.2.3.1 Seasonal Variation of Unstabilized Moduli

Based on FWD deflections obtained over a three-year period (1985 to 1987), the ratio of the moduli for the different seasons were estimated. These initial estimates are shown in Table 5.

Table 5. Design Moduli Ratios for Western and Eastern Washington Base Course and Subgrade Materials[1]

	Seasonal Period			
Region	**Spring**	**Summer**	**Fall**	**Winter**
Western Washington	Cool/Wet	Warm/Dry	Cool/Damp	Cool/Wet
	March April May	June July August September	October November	December January February
	0.85	1.00	0.90	0.75
	0.85	1.00	0.90	0.85
Eastern Washington	Thaw	Hot/Dry	Cool/Dry	Freeze
	February March April May	June July August September	October November December	January
	0.65	1.00	0.90	1.10
	0.90	1.00	0.90	1.10

[1]Design moduli ratios are appropriate for use if stress sensitive moduli relationships are not used. If stress sensitive moduli relationships are used (e.g., $E = k_1\theta^{k2}$), then use of these ratios may overestimate seasonal effects.

The data in Table 5 suggest a greater variation in the base course (seasonally) than the subgrade. Clearly, this phenomenon can be quite site-specific. As such, the ratios are only, at best, "rules of thumb."

For dense graded base materials, numerous sources have suggested that moisture levels exceeding 85 percent of saturation can result in significant moduli reductions.

3.2.3.2 Seasonal Temperatures

Seasonal air temperatures are required inputs. These temperatures are used to adjust the HMA moduli seasonally. These mean monthly air temperatures (MMAT) are converted to mean monthly pavement temperatures (MMPT) by use of the following equation:

$$MMPT = MMAT \left(1 + \left(\frac{1}{z+4}\right)\right) - \left(\frac{34}{z+4}\right) + 6$$

where MMPT = mean monthly pavement temperature (°F),
MMAT = mean monthly air temperature (°F), and
z = depth below pavement surface (inch).

For example, if the MMAT = 65 °F and z = 3 inch, then

$$\begin{aligned} MMPT &= (65)\left(1 + \left(\frac{1}{3+4}\right)\right) - \left(\frac{34}{3+4}\right) + 6 \\ &= 75.4\ °F \end{aligned}$$

3.2.3.3 Unstabilized Layer Moduli

Based on extensive laboratory testing, a general model for WSDOT crushed surfacing top course (CSTC) is:

$$E_{BS} = 8500\ (\theta)^{0.375} \qquad \text{Equation 38}$$

where E_{BS} = Modulus of base course (psi),
θ = Bulk Stress = sum of principal stresses under the design load.

If no other data is available, the above model can be used as a default.

3.2.4 Hardware Requirements

The Evercalc© program is coded in Microsoft Visual Basic and Microsoft FORTRAN Power Station 4.0 and designed to run on IBM or compatible personal computers with Microsoft Windows 95/NT 4.0 or higher.

3.2.5 Installation of the Program

To install the program, start Windows and at the Program File Manager select Run and type a:\setup. Prior to installation of the program(s) the user will be shown the README.TXT. It is highly recommended that this file be reviewed prior to the installation of the program(s). Once README.TXT has been reviewed, the user is asked to select the source directory (default - a:\), the target directory (default = C:\EVERSERS), and which programs are to be installed. The user has the option of selecting Everstress©, Evercalc©, Everpave©, or any combination of the above. Once satisfied with the selection, select **Start Install**.

3.2.6 Program Contents

The following paragraphs describe each of the various menus and inputs of the program:

3.2.6.1 File Menu

Prepare General Data - creates the GENERAL DATA File or edit an existing one. GENERAL DATA File contains truck and pavement data, such as, the design tire load and pressure, spacing of dual tires, fatigue shift factor for old and new HMA, and the seasonal variation parameters.

Prepare Traffic Data - creates the TRAFFIC DATA File or edit an existing one. TRAFFIC DATA File contains information to determine the number of 18,000 lb (80 kN) equivalent single axle loads (ESAL's) for the design period. Traffic data can be entered according to the total traffic volume, annual traffic, or average daily traffic.

Prepare Pavement Data – creates the PAVEMENT DATA File or edit an existing one. The pavement data includes parameters related to the pavement structure, such as, pavement section location, material type, stress sensitivity coefficients, Poisson's ratio, layer thickness, etc.

Analyze Pavement - This menu option performs the overlay design. The GENERAL DATA File, TRAFFIC DATA File, and PAVEMENT DATA File must be created before this option is selected. **Print/View Results** - This menu item allows the user to view the output on the screen and print the output on the Windows default printer.

Modify Standard Values – This menu item is used to change the standard temperature and the fatigue and rutting equation coefficients.

Exit – This command closes the program and returns the user to the Windows screen.

3.2.6.2 Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

About Everpave© - lists program version information, responsible agency and personnel contacts, system memory and resources.

3.2.6.3 Prepare General Data

File

Open - Open an existing GENERAL DATA File.

Save - Save the current GENERAL DATA File under the same name.

Save As - Save the current GENERAL DATA File under a different name.

Exit - Exit general data entry. Does not prompt for saving.

Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

General Data

Title - Any descriptive text for identification purposes.

Units - Units of measurement and output, either metric or US Customary.

Design Tire Load - Design load per tire.

Design Tire Pressure - Design tire contact pressure.

Dual Spacing - Center to center distance between dual tires.

Fatigue Shift Factor for New HMA - Shift factor for the new HMA that modifies the laboratory fatigue equation to field fatigue conditions.

Fatigue Shift Factor for Old HMA - Shift factor for the old HMA that modifies the laboratory fatigue equation to field fatigue conditions.

Seasonal Variation Coarse Grained - Reduction factor for moduli values for coarse-grained material. Unity means no reduction. Material types 1 or 3 (in Pavement Data) uses these values.

Seasonal Variation Fine Grained - Reduction factor for moduli values for fine-grained material. Unity means no reduction. Material types 2 or 4 (in Pavement Data) uses these values.

Seasonal Variation Traffic - Reduction factor for traffic values. Total traffic volume is distributed according to the above fractions for each season.

Seasonal Mean Temperature - Seasonal mean air temperature used in adjusting the old HMA and the new HMA (overlay) moduli for the temperature change. The moduli values specified in the pavement data corresponds to standard temperature.

Seasonal Period - Number of months in each period.

3.2.6.4 Prepare Traffic Data

File

Open - Open an existing TRAFFIC DATA File.

Save - Save the current TRAFFIC DATA File under the same name.

Save As - Save the current TRAFFIC DATA File under a different name.

Exit - Exit general data entry. Does not prompt for saving.

Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User’s Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

Traffic Data

Title - Any descriptive text for identification purposes.

Units - Units of measurement and output, either Metric or US Customary.

Traffic Data Option - Select one of three options for entering traffic data.

18 KESALs for Design Period

Traffic data is to be specified with the total number of 18,000 lb (80 kN) equivalent single axle loads for the design period.

18 KESALs (80 kN ESALs) for Design Period - 18,000 lb (80 kN) equivalent single axle loads for the design period.

Lane Distribution Factor (decimal) - Decimal of the total one-way ESALs in the design lane. This is a function of the number of lanes in each direction and can range from a high of 1.0 to a low of about 0.5. AASHTO recommends the following:

Number of Lanes (one way)	**Lane Distribution Factor**
1	1.00
2	0.80 - 1.00
3	0.60 - 0.80
4 or more	0.50 - 0.75

18 KESALs per Year

Traffic data is to be specified with the total number of 18,000 lb (80 kN) equivalent single axle loads per year.

18 KESALs (80 kN ESALs) for Design Period - 18,000 lb (80 kN) equivalent single axle loads for the design period.

Design Period (years) - Design period in number of years.

Annual Growth (%) - Annual traffic growth rate in percentage.

Lane Distribution Factor (decimal) - Decimal of the total one-way ESALs in the design lane. This is a function of the number of lanes in each direction and can range from a high of 1.0 to a low of about 0.5. AASHTO recommends the following:

Number of Lanes (one-way)	**Lane Distribution Factor**
1	1.00
2	0.80 - 1.00
3	0.60 - 0.80
4 or more	0.50 - 0.75

Average Daily Traffic

Traffic data is to be specified by the average daily traffic.

Average Daily Traffic (one-way) - Average daily traffic (one-way)

Truck Percentage - Truck traffic as a percentage of the average daily traffic.

Truck Factor - Truck factor for converting truck traffic into 18 KESALs (80 kN ESALs).

Design Period (years) - Design period in number of years.

Annual Growth (%) - Annual growth rate of traffic (percentage).

Lane Distribution Factor (decimal) - Decimal of the total one-way ESALs in the design lane. This is a function of the number of lanes in each direction and can range from a high of 1.0 to a low of about 0.5. AASHTO recommends the following:

Number of Lanes (one-way)	Lane Distribution Factor
1	1.00
2	0.80 - 1.00
3	0.60 - 0.80
4 or more	0.50 - 0.75

3.2.6.5 Prepare Pavement Data

File

Open - Open an existing PAVEMENT DATA File.

Save - Save the current PAVEMENT DATA File under the same name.

Save As - Save the current PAVEMENT DATA File under a different name.

Exit - Exit general data entry. Does not prompt for saving.

Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on… - Typical Windows format for searching for key program descriptions.

Pavement Data

Route - Route name for identification purposes.

Units - Units of measurement and output, either in Metric or US Customary.

Overlay Data

Station/Milepost - Station or milepost, a maximum of ten characters.

Overlay HMA Modulus - Modulus of the HMA overlay material taken at the standard temperature

Poisson's Ratio - Poisson's ration of the HMA overlay material.

Initial Overlay Thickness - Beginning overlay thickness. The program increases the initial overlay thickness by multiples of the Overlay Thickness Increment until the fatigue or rutting damage levels are less than one for the design traffic. The initial overlay thickness must be greater than 0 inches (0 cm).

Overlay Thickness Increment - Thickness by which the program increases the overlay depth until the fatigue and rutting damage levels are less than one for the design traffic.

Station/Milepost - Station or milepost, a maximum of ten characters.

Existing Pavement Data

No of Layers - Total number of layers, excluding the overlay layer. The maximum number of layers is limited to five, including the stiff layer.

Layer Information

Layer ID - Identifies whether the moduli of this layer is stress sensitive.

- 0 Is an HMA Material (Moduli is stress insensitive)
- 1 Coarse Grained Material (Moduli varies with bulk stress)
  E = Multiplier x (Bulk Stress/Atmospheric Pressure)^{Power}
- 2 Fine Grained Material (Moduli varies with deviator stress)
  E = Multiplier x (Deviator Stress/Atmospheric Pressure)Power
- 3 Coarse Grained Material (Moduli stress insensitive), but coarse-grained seasonal variation applies
- 4 Fine Grained Material (Moduli stress sensitive), but fine grained seasonal variation applies
- 5 The specified layer modulus is used for all seasons without any corrections for Temperature, Stress Sensitivity, or Seasonal Variation.

Where Atmospheric Pressure is in the same unit as the stresses (14.696 psi or 101.4 kPa). Bulk Stress and Deviator Stress include static (overburden) stresses. The stresses used are calculated at the center of the Dual Tire location and at the bottom of the first layer, at the top of last layer, and at the middle of intermediate layers.

Note: It was customary to use the following form of the equation to describe stress sensitive moduli:

E = Multiplier x (Bulk Stress) ^{Power} (for Coarse Grained)

E = Multiplier x (Deviator Stress) ^{Power} (for Fine Grained)

The new coefficients are related to these coefficients by the following relationship:

Power New = Power Old

Multiplier New = Multiplier Old x (Atmospheric Pressure) $^{\text{Power Old}}$

Example: The following equation:

E = 8500 x (Bulk Stress)$^{0.375}$ would be equivalent to:

E = 8500 x (14.696)$^{0.375}$ x (Bulk Stress/Atmospheric Pressure)$^{0.375}$

= 23287 x (Bulk Stress/Atmospheric Pressure)$^{0.375}$

Poisson's Ratio - Enter the Poisson's ratio of this layer.

Thickness - Enter the thickness of this layer (inches or cm).

Modulus - Modulus of this layer. If this layer is stress sensitive, this will be used as the initial modulus and the program will compute a stress compatible modulus iteratively. If the material is HMA (or asphalt stabilized), the required input modulus must be taken at the standard temperature.

Multiplier - If this layer is stress sensitive, use K1 or K3 regression coefficients.

Power - If this layer is stress sensitive, use K2 or K4 regression coefficients.

Max. Iteration - If any of the layers are stress sensitive, the maximum number of iterations allowed in obtaining the stress compatible moduli. A value of five is typical.

Modulus Tol. (%) - If any of the layers are stress sensitive, the modulus percentage tolerance in successive iterations. A value of 1.0 is typical.

Add Station - Add another station to be analyzed.

Delete Station - Delete the current station.

Unit Weight - Unit weight of the materials of the pavement layers.

Open - Open an existing PAVEMENT DATA File.

Save - Save the current PAVEMENT DATA File under the same name.

Save As - Save the current PAVEMENT DATA File under a different name.

Exit - Exit the Pavement Data Entry screen. Does not prompt for saving.

3.2.6.6 Print/View Results

This menu item allows the user to select the Output File Name to be either reviewed on the screen or printed to the default Windows printer.

Options – standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

3.2.6.7 Modify Standard Values

The Standard Temperature and Fatigue and Rutting Equation coefficients can be changed using this menu item. These values are saved in a file called Everpave.STD in the same directory as the Everpave© Programs files. These values need not be modified for each run but only when there is a need to change the old values. Please take extra care in reviewing the form of the equations listed below while determining the coefficients. The form of the equations might be slightly different from what you might have been using.

Standard Temperature – temperature correction is applied to the HMA moduli according to the following equation:

$$E_T = 10^{0.000147362(T_s^2 - T^2)} E_{T_s}$$ Equation 39

where,

T_s = Standard Temperature (°F)
T = Pavement Temperature (°F)
E_{Ts} = Hot mix asphalt Moduli at the Standard Temperature
E_T = Hot mix asphalt Moduli at the Pavement Temperature

The above regression equation is based on the results of various research projects, which determined the HMA moduli at various laboratory-testing temperatures.

Fatigue Equation Constants – the fatigue equation used in this program has the following format:

$$N_{fv} = SF\left[a\,\varepsilon_t^b\left(\frac{E_{AC}}{AtmosphericPressure}\right)^c\right]$$ Equation 40

or

$$\log N_f = \log SF + \log a + b \log \varepsilon_t + c \log\left(\frac{E_{AC}}{AtmosphericPrssure}\right)$$ Equation 41

where,

Nf = Loads to failure in fatigue, number of loads for pavement to reach 10 percent alligator cracking
SF = Shift Factor
ε_t = Tangential tensile strain at the bottom of the HMA layer (microns, 10^{-6})
E_{HMA} = Hot mix asphalt moduli
a = Constant
b = Exponent for strain
c = Exponent for moduli

The b and c coefficients are negative and the sign should be included in entering their values. Atmospheric pressure is in the same unit as the stresses (14.696 psi or 101.4 kPa).

The default values for a, b, and c are 2.428E+16, -3.291, and -0.854, respectively [12] from the original equation:

$$\log N_f \quad = \quad 14.82 - 3.291 \log \varepsilon_t - 0.854 \log\left(\frac{E_{AC}}{1000}\right)$$

Suggested values for the shift factor are as follows:

Shift Factor	Comment
4	HMA thickness is greater than 8 inches (200 mm)
7	HMA thickness ranges from 4 and 8 inches (100 and 200 mm)
10	HMA thickness is less than 4 inches (100 mm)

Rutting Equation Constants – the rutting equation used in the program has the following format:

$$Nr = a\ \varepsilon_v^{\ b} \qquad \text{Equation 42}$$

or

$$\log Nr = \log a + b \log \varepsilon v \qquad \text{Equation 43}$$

where,

Nr	=	Loads to failure in rutting, number of loads for subgrade rutting to reach 0.5 inches (13 mm)
ε_v	=	Vertical compressive strain at the top of the subgrade (in microns, 10^{-6})
a	=	Constant
b	=	Exponent for Strain

The coefficients a and b are negative and the sign should be included when entering their values into the equation.

The default values for a and b and are 1.077E+18 and -4.4843, respectively [11].

3.2.6.8 Exit

Exits the program and returns to Windows.

3.2.7 Execution of the Program

As a general note, any time you save a file in Everpave©, use the same extension as designated by the program. The program calls the required files according to their extension. It will save the user time and keystrokes if the program extension protocols are followed.

After the user has started Windows, the program can be initiated by double clicking onto the Everpave© icon. The screen as shown in Figure 32 will be displayed.

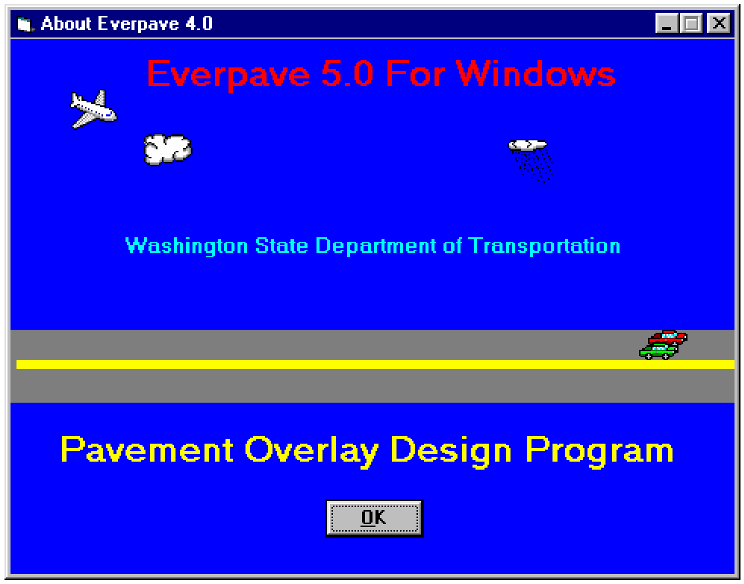


Figure 32. About EVERPAVE© Screen

Press the **OK** button and the screen as shown in Figure 33 will be displayed.

Figure 33. Everpave© Main Screen

To begin the pavement overlay process, the GENERAL DATA File, the PAVEMENT DATA File, and the TRAFFIC DATA File must first be created. To create the GENERAL DATA File, select **File** and then select **Prepare General Data**. The screen as shown in Figure 34 will be displayed.

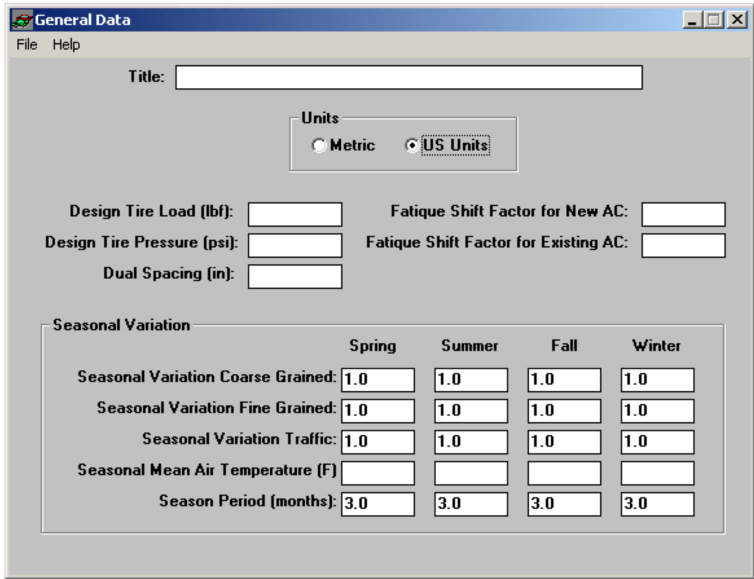


Figure 34. General Data Screen

At this screen the user must enter the following information:

- Title of the project,
- Units of measurement
- Design tire load (lbf or kN) and design tire pressure (psi or kPa)
- Center to center spacing of the dual tires (inches or cm). If the pavement is being analyzed using single tires enter a spacing of 0 inches (0 cm),
- Fatigue shift factor of the new and old HMA,
- Seasonal variation of the coarse and fine grained soils and traffic,
- Seasonal mean air temperature (°F or °C) and the number of months in each seasonal period.

After all the data has been entered, the data must be saved as a file. Select **File,** select **Save** and the program will prompt the user for the filename. After the GENERAL DATA File has been saved, select **File** and then select **Exit** to return to the Main Screen.

To enter the traffic data, select File and then select Prepare Traffic Data. The screen as shown in Figure 35 will be displayed.

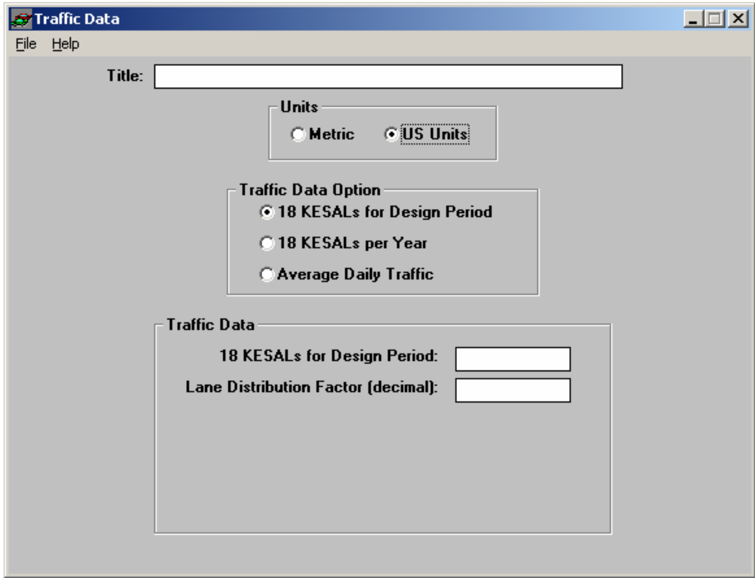


Figure 35. Traffic Data Screen (18 KESAL's for Design Period)

At this screen the user must enter the title description of the project, the units of measure, the traffic data option and the necessary traffic data. Three options are available for determining the traffic data: 18 KESAL's for Design Period (as shown in Figure 35), 18 KESAL's per year (as shown in Figure 36) and Average Daily Traffic (as shown in Figure 37).

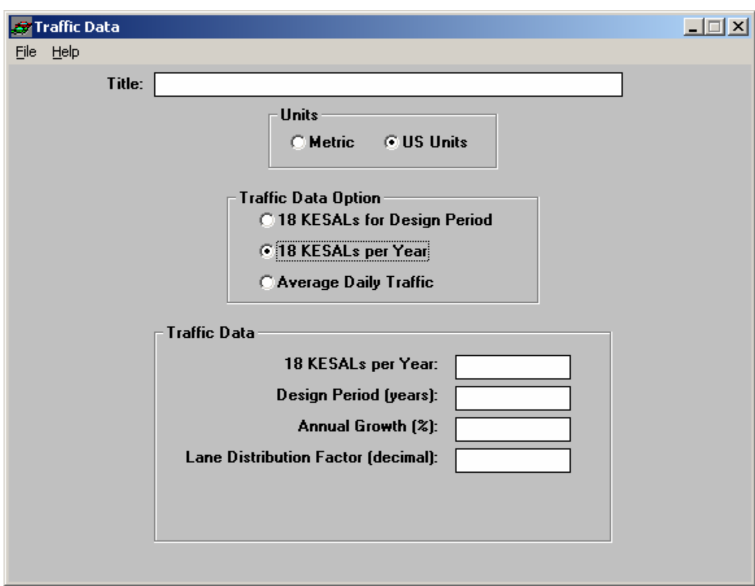


Figure 36. Traffic Data Screen (18 KESAL's for Design Period)

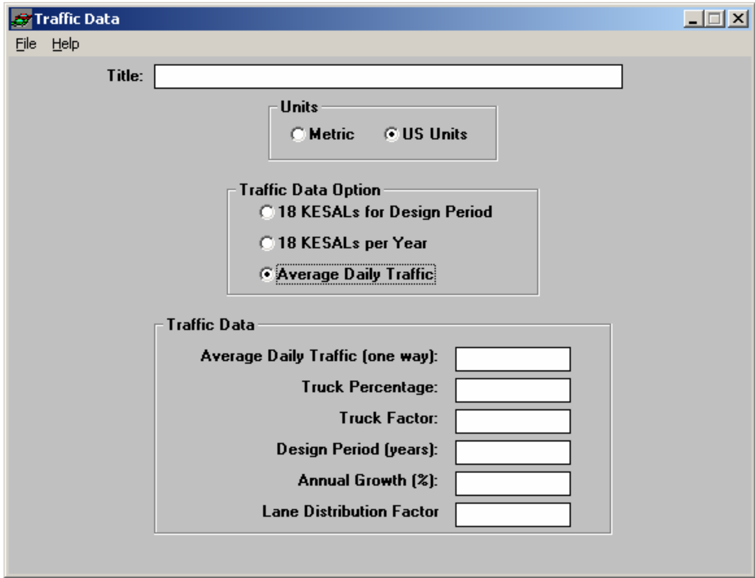


Figure 37. Traffic Data Screen (Average Daily Traffic)

Upon completion of data entry, the user must save the data as a file. Select **File**, select **Save** and the user will be prompted for the filename. To return to the Main screen select **File** and then select **Exit**.

To enter the pavement data, select **File** and then select **Prepare Pavement Data**. The screen as shown in Figure 38 will be displayed.

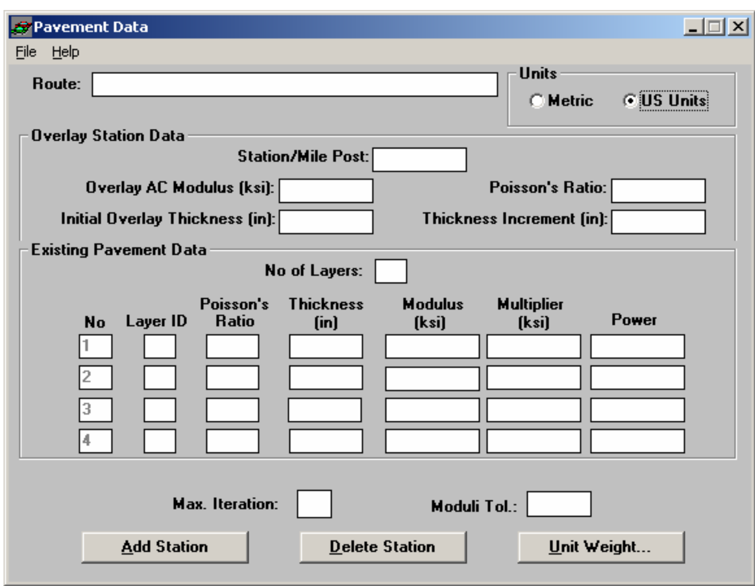


Figure 38. Pavement Data Screen

At this screen the user must enter the following:

- Description of the Route,
- Units of measure (US Customary or metric),

- Station/milepost location
- Modulus of the HMA overlay (ksi or MPa)
- Poisson's ratio of the HMA overly
- Initial overlay thickness (inches or cm)
- Thickness increment (inches or cm)
- Number of pavement layers
- For the existing pavement structure - layer number, layer identification number (identifies stress sensitivity), Poisson's ratio, thickness (inches or cm), and layer modulus (ksi or MPa)

The user is also capable of modifying the unit weight for each of the layers entered. To modify the unit weights, select **Unit Weight** and make the necessary changes. Once modifications have been made, select **Exit** to return to the Pavement Data Screen.

Once all data has been entered, the data must be saved to a file. Select **File**, select **Save** and the user will be promoted for the filename. To return to the Main screen, select **File** and then select **Exit**.

To analyze the data, select **Analyze Pavement**. The program will prompt the user for the name of the GENERAL DATA File, the TRAFFIC DATA File, and the PAVEMENT DATA File to be used. The program will then ask the user if the filename of the Output File is OK, select **OK** or modify the output filename.

To view the results select **File** and then select **Print/View Results**. The up and down arrows or the page up and page down keys can be used to view the data. To print the data on the Windows default printer, select **Options** and then select **Print**. To exit this screen, select **Options** and then select **Exit**.

To exit the EVERPAVE© program, select **File** and then select **Exit**.

3.2.8 Example

General Data:
Design Tire Load = 9,000 lb
Tire Pressure = 100 psi
Dual Spacing = 14 inches
Fatigue Shift Factor (new and old HMA) = 10
Season Variation:

	Spring	Summer	Fall	Winter
Coarse Grained	.650	1.000	.900	1.100
Fine Grained	.950	1.000	.900	1.100
Traffic Volume	1.000	1.000	1.000	1.000
Mean Air Temp (F)	45.5	64.4	45.5	27.0
Period (month)	4	4	3	1

Traffic Data
18 KESALs for Design Period = 1 700 000
Lane Distribution Factor (decimal) = 1.00

Pavement Data

Overlay HMA modulus = 400 ksi
Poisson's Ratio for HMA overlay = 0.35
Initial Overlay Thickness = 1 inches

Thickness Increment = 0.5 in
Existing Pavement Data:
Number of layers = 3

Number	Layer ID	Poisson's Ratio	Thickness (in)	Modulus (MPa)
1	0	0.35	4	300
2	3	0.40	16	20
3	4	0.45		10

3.2.8.1 Overlay Thickness Design Results

Layered Elastic Analysis by Everpave© 5.0

General Data: Example
Design Tire Load (lbf): 9000.0 Tire Pressure (psi): 100.00 Dual Tire Spacing (in): 14.0
Fatigue Shift Factor: New HMA: 10.00 Old HMA: 10.00

Seasonal Variation:	Spring	Summer	Fall	Winter
Coarse Grained:	.650	1.000	.900	1.100
Fine Grained:	.950	1.000	.900	1.100
Traffic Volume:	1.000	1.000	1.000	1.000
Mean Air Temp (F):	45.5	64.4	45.5	27.0
Period (month):	4.0	4.0	3.0	1.0

Traffic Data: Example
18 KESALs for Design Period: 1700000.
Lane Distribution Factor (decimal): 1.00
Total Design Traffic (18 KESALs): 1700000.

Route: Test
Station: 210

Layer	Poisson's Ratio	Thickness (in)	Moduli (1) (ksi)
1	.35	1.000	400.00
2	.35	4.000	300.00
3	.40	16.000	20.00
4	.45		10.00

Pavement Moduli Used (ksi)

Layer	Material	Spring	Summer	Fall	Winter
1	A.C.	1180.03	498.83	1180.03	2090.72
2	A.C.	885.02	374.12	885.02	1568.04
3	C.G.	59.00	24.94	59.00	104.54
4	F.G.	29.50	12.47	29.50	52.27

Critical Values

Season:	Spring	Summer	Fall	Winter
Tensile Strain in New HMA:	31.35	74.15	31.35	17.69
Tensile Strain in Old HMA:	91.66	216.82	91.66	51.73
Compressive Strain in Subgrade;	137.74	325.85	137.74	77.74
Max. Surface Deflection (microns):	9.20	21.76	9.20	5.19

Damage Levels

Fatigue Damage on New A.C.: .000
Fatigue Damage on Old A.C.: .805
Rutting Damage on Subgrade: .101
Overlay Thickness (in): 5.50

SR 395 MP 207.80 to MP 212.67
Chewelah to Iron Mountain Road

4.1 INTRODUCTION

This case study comes from a section of State Route (SR) 395, which begins at the community of Chewelah, Washington (MP 207.81) and proceeds north to Iron Mountain Road (MP 212.67). The 1994 pavement condition survey for this project indicated 5 to 15 percent of low to medium severity alligator cracking and 30 percent medium to high severity longitudinal cracking. According to the WSPMS, the current PSC on this project is 58 and is projected to reach a program level PSC of 50 in 1995; however, the PSC ranges from 0 to 80 for specific locations (refer to photos shown in Appendix D). In addition to a structural overlay, this project also proposes to widen the roadway by 2 feet to provide for a 12 foot lane and 8 foot shoulder in each direction. This project is scheduled for construction in 1995.

The Stevens County Soils Survey shows the project site is composed of varying morphology. The predominate soil type is a Hodgson Silt Loam (ML). This soil is very deep, moderately well drained and is located in undulating terraces. From February to April there is typically a perched water table at depths of 24 to 35 inches. Related engineering properties are: moderately slow permeability, low to moderate shrink swell potential, and moderate susceptibility to frost action. Typical base material, retrieved by augering, is silty sandy gravel or sandy gravel and varies from 12 to 18 inches in depth.

This project was originally constructed in 1945 with a 0.80 inches bituminous surface treatment placed over 3 inches of crushed surfacing top course (crushed stone base) and from 9 to 18 inches of select roadway borrow. Construction during 1948 placed an additional 0.80 inches of bituminous surface treatment. Projects after 1948 rehabilitated different sections within the current project limits. A summary of HMA core depths, base thickness and core description are listed in Table 6. The base thickness was taken from the WSPMS.

Table 6. Summary of Roadway Surfacing Depths

Core Location	Depth		Comments
	HMA (in)	Base (in)	
207.85	5.3	18.0	Core taken at a crack, crack is full depth
208.00	6.0	18.0	Core taken at a crack, core not intact
208.50	4.7	12.0	Core taken at a crack, crack is full depth
209.00	4.6	12.0	Very fatigued, core broke into several pieces
209.05	4.2	12.0	Fatigued area, crack is full depth
209.40	5.9	13.2	Core taken at a crack, crack is full depth
209.80	6.5	15.6	HMA core intact
210.00	4.4	14.4	Fatigue in both wheel paths, crack is full depth
210.50	98	14.4	Core taken at a crack, crack is full depth
211.00	9.0	14.4	Core broke into several pieces
211.50	11.1	14.4	HMA core intact
212.00	11.8	14.4	HMA core intact
212.50	9.0	14.4	Top 183 mm in good condition

Current traffic volumes are around 5,500 vehicles per day (two way) with 13 percent trucks. The design period is 15 years and the associated estimated ESALs are 2,896,000.

Table 7 summarizes the deflection data that was collected on this project on April 14, 1993. Though the project was over 4.85 mile long and FWD testing was performed every 250 feet, only the FWD data that corresponds to a core location is being evaluated as part of this case study. Knowing the HMA layer thickness to within ¼ inch is essential in assuring a more accurate prediction of layer moduli in the backcalculation procedure. The average pavement temperature at the time the FWD data was collected was 46°F to 50°F. The timing of the survey was about 1.5 to 2 months after the spring thaw in this area.

Table 7. FWD Deflections, Area Value and Subgrade Modulus

Core Location	Load (lbf)	Deflections (mils) D0	D8	D12	D24	D36	D48	Area Value (in)	M_R (psi)
207.85	16,940	31.30	26.18	23.19	13.78	9.09	6.65		
	12,086	24.21	20.31	18.11	10.35	6.81	4.96		
	9,421	19.45	16.38	14.57	8.11	5.28	3.98		
	6,218	13.19	11.26	9.92	5.12	3.39	2.83		
Normalized Values		18.39	15.51	13.78	7.60	5.00	3.82	21	14,358
208.00	16,987	27.04	21.53	18.58	11.26	7.32	5.28		
	12,070	21.26	16.97	14.61	8.66	5.55	3.98		
	9.405	17.52	13.94	11.97	7.01	4.45	3.23		
	6,186	12.32	9.76	8.31	4.65	2.87	2.05		
Normalized Values		16.57	13.23	11.34	6.57	4.17	2.99	20	16,534
208.50	16,829	14.92	11.89	10.23	5.91	3.19	2.28		
	12,245	11.65	9.29	7.95	4.49	2.13	1.73		
	9,533	9.61	7.63	6.53	3.62	1.81	1.30		
	6,297	6.73	5.35	4.49	2.40	1.26	0.87		
Normalized Values		9.01	7.17	6.10	3.39	1.69	1.26	19	32,198
209.00	16,305	59.25	48.58	42.52	21.30	9.53	5.12		
	11,737	46.14	37.52	32.56	15.59	6.69	3.58		
	9,247	36.93	29.80	25.63	11.77	4.96	2.68		
	6,154	25.00	19.88	16.77	7.28	3.03	1.73		
Normalized Values		35.51	28.66	24.61	11.42	4.84	2.64	19	9,572
209.05	15,972	56.14	44.88	38.15	21.89	13.54	9.29		
	11,531	44.02	35.20	29.57	16.34	10.00	6.85		
	9,088	35.63	28.27	23.50	12.64	7.52	5.04		
	5,995	25.35	19.21	15.43	7.48	4.65	2.80		
Normalized Values		35.16	27.64	22.87	12.24	7.44	4.92	19	8,847
209.40	16,004	62.87	51.81	43.54	24.84	14.84	9.61		
	11,610	49.92	41.10	34.29	19.33	11.54	7.44		
	9,104	40.16	33.31	27.40	15.04	8.94	5.71		
	6,733	28.54	22.87	18.35	9.49	5.71	3.70		
Normalized Values		39.45	32.32	26.57	14.53	8.66	5.59	20	7,397
209.80	17,257	26.65	21.57	18.70	11.26	7.17	4.96		
	12,229	20.79	16.89	14.61	8.66	5.39	3.70		
	9,533	16.77	13.66	11.73	6.73	4.21	2.83		
	6,265	11.73	9.45	7.99	4.37	2.72	1.73		
Normalized Values		15.83	12.83	11.02	6.30	3.94	2.64	20	17,259
210.00	16,718	35.98	29.21	25.16	16.77	11.22	7.76		
	12,023	27.80	25.60	19.29	12.72	8.39	5.71		
	9,422	22.32	17.99	15.28	9.84	6.38	4.37		
	6,170	15.16	12.09	10.08	6.30	3.98	2.76		
Normalized Values		21.18	17.09	14.45	9.29	6.06	4.13	21	11,603

Table 7. FWD Deflections, Area Value and Subgrade Modulus, continued…

Core Location	Load (lbf)	Deflections (mils) D0	D8	D12	D24	D36	D48	Area Value (in)	M_R (psi)
210.50	17,162	22.36	19.21	16.65	10.43	6.89	4.72		
	12,213	17.36	14.96	12.95	7.91	5.04	3.50		
	9,437	13.98	12.05	10.39	6.26	3.94	2.68		
	6,170	9.61	8.27	7.05	4.09	2.48	1.65		
Normalized Values		13.22	11.38	9.80	5.87	3.66	2.52	21	18,565
211.00	17,178	13.54	11.81	10.94	8.03	6.06	4.57		
	12,324	10.39	8.90	8.23	6.10	4.57	3.35		
	9,628	7.99	7.13	6.54	4.80	3.54	2.60		
	6,392	5.67	4.76	4.29	3.15	2.28	1.69		
Normalized Values		7.64	6.61	6.02	4.45	3.27	2.40	25	24,366
211.50	17,463	12.60	10.47	9.41	6.65	4.69	3.23		
	12,626	9.21	7.68	6.89	4.84	3.42	2.32		
	9,881	7.05	5.91	5.28	3.66	2.56	1.73		
	6,487	4.45	3.70	3.27	2.24	1.57	1.06		
Normalized Values		6.38	5.31	4.76	3.31	2.32	1.57	23	32,779
212.00	17,717	22.44	20.43	19.01	14.25	10.59	7.83		
	12,626	16.97	15.43	14.33	10.71	7.91	5.87		
	10,024	13.39	12.20	7.36	8.46	6.22	4.65		
	6,582	8.59	8.03	7.40	5.47	4.06	2.99		
Normalized Values		12.04	10.94	10.11	7.56	5.59	4.13	26	14,359
212.50	18,193	19.49	17.36	16.02	12.44	9.53	6.97		
	12,927	15.04	13.27	12.20	9.49	7.20	5.31		
	10,294	11.65	10.51	9.61	7.52	5.67	4.02		
	6,789	8.11	7.01	6.34	4.92	3.66	2.52		
Normalized Values		10.47	9.26	8.42	6.57	4.92	3.50	26	16,534

As shown in Table 7, the normalized D0 deflection ranges from 6 to 39 mils and average 18.5 mils with a standard deviation of 11.2 mils. Deflections less than about 30 mils are considered normal.

The Area values shown in Table 7 do not suggest extremely weak HMA, such as a loss of stiffness due to stripping. Table 8 illustrates typical theoretical Area values for various uncracked HMA thicknesses are:

Table 8. Typical Theoretical Area Values for Uncracked HMA

HMA Thickness (in)	Approximate Area Parameter (in) Normal Stiffness	Low Stiffness
2	17	16
3	19	18
4	21	19
5	23	21
6	24	22
7	26	22
8	26	23
9	27	24
10	28	24

A quick, approximate check of the pavement structure is to compare the actual Area value to see if it falls within the range (normal to low stiffness), above this range (above normal stiffness) or below this range (below normal stiffness). This comparison is shown in Table 9:

Table 9. Comparison of Area Value and Acceptable Area Value Range

Core Location	HMA Thickness (in)	Actual Area (in)	Above, Below or Within Range
207.85	5.3	21	Within
208.00	6.0	20	Below
208.50	4.7	19	Below
209.00	4.6	19	Below
209.05	4.2	19	Below
209.40	5.9	20	Below
209.80	6.5	20	Below
210.00	4.7	21	Below
210.50	3.9	22	Above
211.00	9.0	25	Within
211.50	11.1	23	Below
212.00	11.8	26	Within
212.50	9.0	26	Within

The above suggests MP's 207.85 to 210.00 will likely need a structural overlay. MP's 210.50 to MP 212.50 are in better structural condition suggesting the overlay requirement will be minimal.

The elastic modulus values of the subgrade range from 7,400 to 32,800 psi with an average of 15,809 psi and a standard deviation of 8,122 psi. On the average, a subgrade modulus of 15,000 psi is typical for Washington State. This fairly large variation in stiffness is most likely due to variation in soil moisture and the proximity of underlying rock, more than actual soil or deposition changes along the roadway.

There are two fairly distinct sections occurring within the project limits. The roadway from MP 207.80 to MP 210.55 is in fair to poor condition with low to medium severity longitudinal and alligator cracking. From MP 210.55 to MP 212.67 the roadway is generally in good condition with only a few locations of low severity longitudinal and alligator cracking. Figure 39 graphically shows how the normalized center deflection, normalized Area value and subgrade modulus varies throughout the projects length. Figure 39 was created from an in-house computer program and this program has yet to be converted to metric units. Therefore, Figure 39 shows the center deflection in mils, the Area value in inches and the subgrade modulus in ksi.

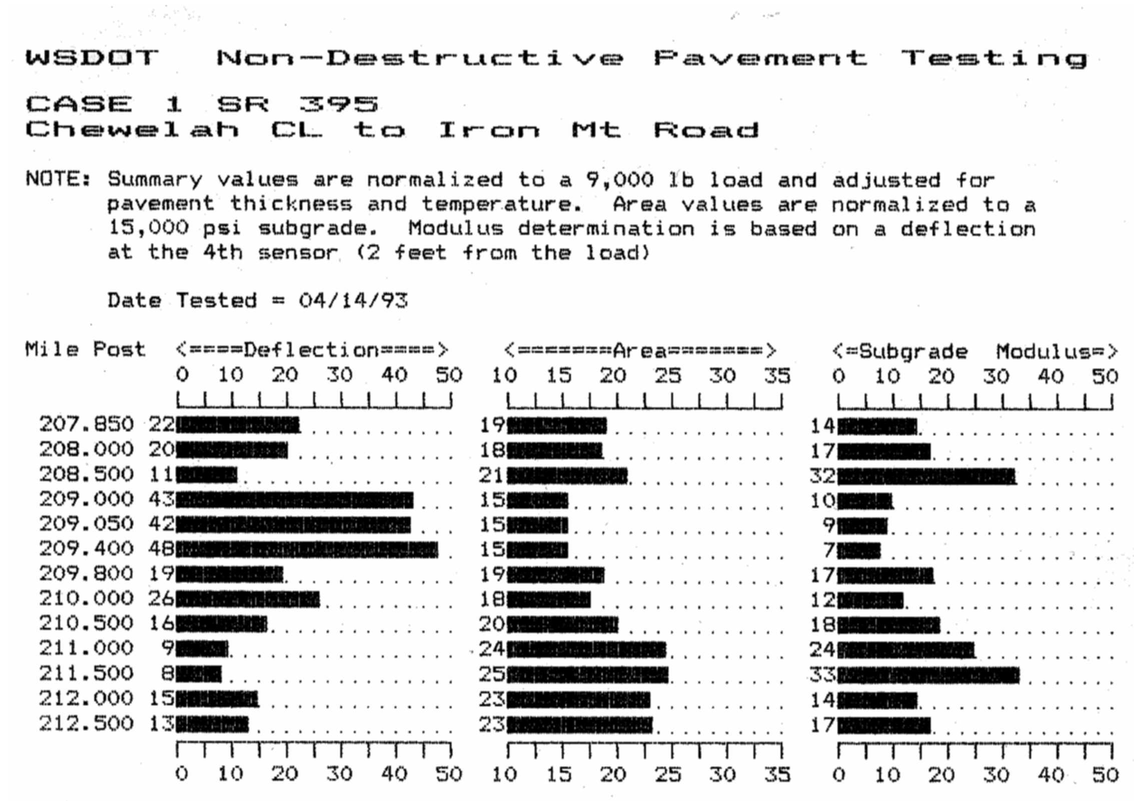


Figure 39. Normalized Center Deflection, Area Value, and Subgrade Modulus

4.2 OVERLAY DESIGN PROCEDURES

This section describes three overlay design procedures that are currently used by WSDOT: 1) WSPMS SCOPER, 2) WSDOT Empirical-Mechanistic Overlay Design, and 3) AASHTO Overlay Design Procedure. The three procedures can be used as design checks as will be more fully described later.

4.2.1 WSPMS SCOPER Overlay Design Procedures

WSPMS SCOPER is partially based on the Asphalt Institutes Component Analysis procedure (see Appendix E). Specific modifications made by WSDOT can be found in "Washington State Pavement Management - A 1993 Update", Research Report WA-RD 274.1, Washington State Department of Transportation, Olympia, Washington, 1993.

The WSPMS SCOPER uses a component analysis approach that essentially requires the total pavement structure to be developed as a new design for the specified service conditions and then compared to the existing pavement structure (taking into account both pavement condition, type, and thickness of the pavement layers). The component design process requires substantial engineering judgment. This judgment is mainly associated with the selection of "weighting factors" or "conversion factors" to use in evaluating the structural adequacy of the existing pavement layers. The SCOPER design approach uses relationships between subgrade strength, pavement structure, and traffic to determine the overlay thickness.

Example of Calculations

Layer coefficients and ESAL's were determined using the WSPMS. The subgrade modulus as determined from the FWD analysis as shown in Table 7 was used in this analysis. Refer to Table 10 for SCOPER overlay design results. To illustrate this process, MP 207.85 will be used as an example.

MP 207.85

(5.28 in HMA)(0.30)	=	1.6 in
<u>(18.0 in Base)(0.30)</u>	=	<u>5.4 in</u>
Effective Thickness	=	7.0 in

M_R = 14,359 psi

ESAL = 2,896,000

Refer to Design Thickness charts in Asphalt Institutes MS-1 Manual and Appendix E.

Design Thickness	=	9.3 in
<u>Effective Thickness</u>	=	<u>7.0 in</u>
Overlay Thickness	=	2.3 in

Table 10. WSPMS SCOPER Overlay Design Procedure

Core Locations	Depths HMA (in)	Depths Base (in)	Layer Coefficients HMA	Layer Coefficients Base	Subgrade Modulus (psi)	Thickness (in) Design	Thickness (in) Effective	Thickness (in) Overlay
207.85	5.3	18.0	0.30[1]	0.30	14,359	9.3	7.0	2.3
208.00	6.0	18.0	0.30	0.30	16,534	9.1	7.2	1.9
208.50	4.7	12.0	0.30	0.30	32,198	7.2	5.0	2.2
209.00	4.6	12.0	0.30	0.30	9,572	10.2	5.0	5.2
209.05	4.2	12.0	0.30	0.30	8,847	10.6	4.9	5.7
209.40	5.9	13.2	0.30	0.30	7,400	11.0	5.7	5.3
209.80	6.5	15.6	0.30	0.30	17,259	9.0	6.6	2.4
210.00	4.5	14.4	0.30	0.30	11,603	9.7	5.7	4.0
210.50	3.9	14.4	0.30	0.30	18,565	9.0	5.5	3.5
211.00	9.0	14.4	0.82[2]	0.30	24,366	8.2	11.7	0
211.50	11.2	14.4	0.82	0.30	32,779	7.2	13.5	0
212.00	11.8	14.4	0.82	0.30	14,359	9.3	14.0	0
212.50	9.0	14.4	0.82	0.30	16,534	9.1	11.7	0

[1] HMA "C" value based on a PSC = 0
[2] HMA "C" value based on a PSC = 74

4.2.2 WSDOT Mechanistic-Empirical Overlay Design

4.2.2.1. Evercalc©

Currently, when a pavement structure is analyzed using FWD data and a backcalculation procedure, it is recommended to vary the use and stiffness of the stiff layer. A stiff layer should be used when the underlying material is known to be saturated or if underlying rock or other very stiff deposits are known to exist (refer to Paragraph 2.3). In most instances, the presence, the stiffness, and depth to stiff layer is not known. Therefore, it is advisable to use three backcalculation approaches with regard to a potential stiff layer: 1) no stiff layer, 2) a stiff layer at 50,000 psi, which indicates a moist or saturated layer, and 3) a stiff layer at 1,000,000 psi, which indicates a rock layer or stiff deposit.

Input Values

General Data

Number of layers = 3 (no stiff layer)
4 (stiff layer)
Units = US Customary
Indicate whether or not a stiff layer option is to be used
Temperature correction to be applied
Temperature Measurement = Direct Method
Plate radius = 5.9 inches
Seed Moduli = User supplied

Sensor No.	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information is shown in Table 11.

Table 11. Layer Characteristics Input Values

Layer	Description	Poisson's Ratio	Modulus (ksi) Initial	Min.	Max.
1	HMA	0.35	400	100	2,000
2	Base	0.40	25	5	500
3	Subgrade	0.45	15	5	500
4*	Stiff layer (water)	0.35	50		
4*	Stiff layer (rock)	0.30	1,000		

* Denotes the use of a stiff layer.

Deflection Data

Refer to Paragraph 2.6.4.5 for the necessary procedures for entering deflection data or for converting the raw FWD deflection file into Evercalc©.

Backcalculation Results

The backcalculated layer moduli, for all three cases (no stiff layer and stiff layers at 50 and 1,000 ksi) are shown in Table 12.

Table 12. Summary of EVERCALC© Results

	No Stiff Layer					Depth to Stiff Layer	*Stiff Layer @ 50 ksi*					*Stiff Layer @ 1,000 ksi*				
Core Location	E_{adj}[1] (ksi)	E_{hma}[2] (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS	(in)	E_{adj} (ksi)	E_{hma} (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS	E_{adj} (ksi)	E_{hma} (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS
207.85	165	528	17	12	3.09	195	**142**[3]	455	**22**	**10**	4.12	135	431	24	9	4.53
208.00	131	418	18	15	0.70	159	**107**	341	**24**	**12**	1.80	98	314	28	10	2.52
208.50	530	247	17	36	3.39	61	**368**	1177	**43**	**22**	5.37	203	650	110	9	10.73
209.00	88	283	5	13	13.40	47	**251**[4]	805	**17**	**5**	24.56	367	1221	5	5	41.88
209.05	169	542	6	9	2.04	98	**90**	287	**19**	**5**	5.29	185	592	12	5	10.12
209.40	60	193	5	8	2.00	85	**94**	300	**5**	**5**	14.39	95	303	5	5	21.76
209.80	142	453	12	17	0.96	142	**113**	363	**21**	**13**	1.60	100	321	26	11	2.41
210.00	297	951	14	10	2.29	127	**165**	528	**29**	**7**	0.83	145	464	33	6	0.99
210.50	706	2471	17	17	0.64	340	**639**	2236	**21**	**17**	0.76	602	2108	24	16	0.85
211.00	273	954	21	20	0.76	224	**276**	966	**28**	**18**	0.63	260	912	38	15	0.68
211.50	191	668	12	37	0.66	120	184	645	18	30	0.67	**168**	588	**39**	**16**	1.13
212.00	120	419	5	14	2.08	314	127	444	5	13	1.88	**130**	454	**5**	**12**	1.86
212.50	285	999	5	18	1.23	202	279	279	10	13	0.97	**266**	932	**15**	**11**	0.86

[1] E_{adj} is E_{hma} adjusted to a standard temperature of 77°F (25°C).
[2] E_{hma} is the actual backcalculated modulus for the HMA at the insitu field temperatures.
[3] Bold number indicate the moduli that were selected for input into EVERPAVE. Moduli are selected based on engineering judgment and low RMS.
[4] Due to the severity of distress at the location (refer to the Appendix), the HMA modulus was "fixed" at 100 ksi and the base and subgrade moduli were reevaluated in EVERCALC. The corresponding base and subgrade moduli are 17 and 5 ksi, respectively

4.2.2.2. *Everpave©*

Everpave© is a mechanistic-empirical overlay design procedure that was developed by WSDOT. The pavement analysis is accomplished by use of Everstress© (used as a subroutine, see SECTION 1.0), which can account for the stress sensitive characteristics of the unbound materials. Everpave© uses the material properties (modulus) of each pavement layer (e.g. HMA, base and subgrade), traffic load repetitions and the environment (seasonal temperatures and moduli) to determine the appropriate overlay design thickness. The determination of the appropriate thickness is based on the two primary distresses found in flexible pavements in Washington State; rutting and fatigue cracking. The Everpave© program calculates the overlay thickness by comparing the pavement performance lives for fatigue and rutting with the projected design traffic volume (ESALs). When the minimum repetitions of the two failure criteria is greater than the traffic volume, the final overlay thickness is produced. Otherwise, the overlay thickness is increased by an incremental thickness and the analysis is repeated.

Input Values

General Input Data (see Paragraph 3.2.3)

Tire Load	8,000 lb
Tire Pressure	100 psi
Shift factor for New HMA	10
Shift factor for Existing HMA	10
Dual Tire Spacing	14 in

	Spring	Summer	Fall	Winter
Seasonal Variation				
Base Course	1.00	1.54	1.38	1.69
Subgrade	1.00	1.11	1.00	1.22
Traffic	1.00	1.00	1.00	1.00
Mean Air Temperature °F	46	65	45	27
Season Period (months)	4	4	3	1

For mean air temperature refer to Appendix B, Table B-1 and for seasonal periods (months) refer to Table C-1 in Appendix C. The moduli ratios assume that the FWD deflection testing was performed during the critical spring period. Thus, the spring moduli ratios shown above were set to 1.0 (base and subgrade). The other seasonal moduli ratios were then adjusted accordingly.

Pavement Data

Overlay HMA Moduli	=	400 ksi
Poisson's ratio	=	0.35
Initial Overlay Thickness	=	0.2 in
Thickness Increment	=	0.2 in

Traffic Data

18 KESAL's for Design Period (15 years)	=	2,896,000
Lane Distribution Factor	=	1.00
Total Design ESAL's	=	2,896,000

The results of the Everpave© overlay analysis are presented in Table 13. As a reminder, the initial overlay thickness was established at 0.2 inches for this case study. Therefore, those locations that indicate a 0.2 inch overlay, are more likely based on the initial overlay thickness set by the user.

Table 13. Everpave© Overlay Thickness Results

Core Location	HMA (in)	Base (in)	Selected Layer Moduli Eac (ksi)	Ebase (ksi)	Esub (ksi)	EVERPAVE© Overlay (in)
207.85	0.53	1.80	143.0	21.6	10.2	2.2
208.00	0.60	1.80	108.9	24.1	11.8	1.6
208.50	0.47	1.20	414.2	34.5	25.4	0.6
209.00	0.46	1.20	100.0	17.8	5.0	3.9
209.05	0.42	1.20	74.8	20.2	5.0	3.9
209.40	0.59	1.32	95.9	5.0	5.0	4.7
209.80	0.65	1.56	112.5	20.7	13.1	1.6
210.00	0.44	1.44	161.3	30.3	7.4	2.2
210.50	0.39	1.44	571.6	23.3	17.1	1.6
211.00	0.90	1.44	278.2	28.6	18.6	0.2
211.50	1.11	1.44	163.9	45.0	15.4	0.2
212.00	1.18	1.44	128.4	5.0	12.3	0.2
212.50	0.90	1.44	267.7	14.5	10.9	0.2

4.2.3 AASHTO DARWin® Pavement Design System

AASHTO DARWin® is the computerized version of the pavement design models presented in AASHTO's "Guide for Design of Pavement Structures 1993". From the AASHTO DARWin® User's Guide, "In the AASHTO overlay design procedure, the structural capacity for future traffic (SC_f) and the effective structural capacity (SC_{eff}) of the existing pavement are calculated using one of up to four available methods. These structural capacities are then used to determine the required overlay structural capacity." For this case study, the non-destructive testing method will be used for overlay determination. AASHTO DARWin® uses the deflection data to backcalculate the subgrade modulus (M_R) and the effective pavement modulus (E_p). These values are then used to determine the structural numbers for the existing pavement and for future traffic volumes. The required overlay structural number is the difference between SC_f and SC_{eff}.

Input Values

18 KESAL's	2,896,000
Initial Serviceability	4.5
Terminal Serviceability	3.0
Reliability Level (%)	50
Overall Standard Deviation	0.50
Overlay Layer Coefficient (a_{ol})	0.44

Calculated Overlay Structural Number (SN_{ol}) = Non-Destructive Method

Point-by-Point	Backcalculation
FWD Load	9000 lbs
Resilient Modulus Correction Factor	0.5
Base Type	Granular

Mid-depth Pavement Temperature 50°F (MP 207.85 - MP 210.05)
47°F (MP 210.05 - MP 212.67)

The normalized load (9000 lbs) and corresponding deflections are shown in Table 14. WSDOT uses a FWD sensor spacing of 0, 8, 12, 24, 36, and 48 inches. AASHTO DARWin® will accommodate deflection data collected at any deflection spacing and at any load level. The FWD sensor spacing was selected such that the deflection basin would be adequately identified. Typically, the pavement structural design is based on a legally loaded axle of 18,000 lbs (9,000 lbs per one-half of the axle). Therefore, the normalized deflections at 9,000 lbs are used in this procedure. Results of this analysis are shown in Table 15.

Table 14. Normalized Deflection Data

MP	Load (lbs)	$D_{at\ 0"}$ (mils)	$D_{at\ 8"}$ (mils)	$D_{at\ 12"}$ (mils)	$D_{at\ 24"}$ (mils)	$D_{at\ 36"}$ (mils)	$D_{at\ 48"}$ (mils)
207.85	9,000	18.37	15.51	13.77	7.59	4.99	3.83
208.00	9,000	16.59	13.21	11.32	6.56	4.16	2.98
208.50	9,000	9.01	7.16	6.10	3.37	1.68	1.24
209.00	9,000	35.51	28.65	24.62	11.40	4.84	2.65
209.05	9,000	35.14	27.62	22.88	12.24	7.43	4.90
209.40	9,000	39.46	32.33	26.59	14.54	8.68	5.58
209.80	9,000	15.83	12.83	11.00	6.30	3.93	2.62
210.00	9,000	21.18	17.07	14.45	9.31	6.05	4.15
210.50	9,000	13.21	11.39	9.79	5.86	3.68	2.52
211.00	9,000	7.63	6.61	6.02	4.45	3.28	2.41
211.50	9,000	6.36	5.31	4.75	3.31	2.31	1.57
212.00	9,000	12.05	10.95	10.13	7.55	5.58	4.14
212.50	9,000	10.49	9.27	8.44	6.57	4.94	3.50

Table 15. AASHTO DARWin® Overlay Thickness Results

Core Location	Pavement Depths HMA (in)	Base (in)	Total (in)	SN for Future Traffic	Effective Existing Pavement SN	Calculated Overlay SN (SN_{ol})	Overlay Thickness (in)
207.85	5.3	18.0	23.3	3.72	3.80	0.00	0
208.00	6.0	18.0	24.0	3.46	3.98	0.00	0
208.50	4.7	12.0	16.7	2.70	3.58	0.00	0
209.00	4.6	12.0	16.6	4.37	2.19	2.18	5.0
209.05	4.2	12.0	16.2	4.48	2.20	2.28	5.2
209.40	5.9	13.2	19.1	4.77	2.44	2.33	5.3
209.80	6.5	15.6	22.1	3.38	3.75	0.00	0
210.00	4.4	14.4	18.8	4.05	3.07	0.98	2.2
210.50	3.9	14.4	18.3	3.37	3.50	0.00	0
211.00	9.0	14.4	23.4	3.14	5.40	0.00	0
211.50	11.1	14.4	25.5	2.73	5.95	0.00	0
212.00	11.8	14.4	26.2	3.87	5.12	0.00	0
212.50	9.0	14.4	23.4	3.70	4.96	0.00	0

4.3. OVERLAY THICKNESS DESIGN SUMMARY

Table 16. Summary of Overlay Thickness

Core Location	EVERPAVE© (in)	AASHTO DARWin (in)	WSPMS SCOPER (in)
207.85	2.2	0	2.8
208.00	1.6	0	2.2
208.50	0.6	0	2.2
209.00	3.9	5.0	5.6
209.05	3.9	5.2	6.1
209.40	5.1	5.3	5.6
209.80	1.6	0	2.6
210.00	2.2	2.2	4.6
210.50	1.6	0	3.5
211.00	0.2	0	0
211.50	0.2	0	0
212.00	0.2	0	0
212.50	0.2	0	0

As shown in Table 16, the three overlay design procedures indicate various required overlay thickness at any given location. The variations between the three overlay design procedures are due in part by the various characteristics and design criteria used by each design method. However, using multiple design procedures allows for a check and balance of the necessary overlay thickness and requires the use of engineering judgment for the final decision.

Due to the difficulty in constructing many changes in overlay thickness, the project should be constructed with logical overlay thickness breaks. For this case study, MP 207.85 to MP 208.50 would require a 1.8 inch overlay, MP 208.50 to MP 209.40 would require a 3.9 inch overlay, MP 209.40 to MP 210.50 would require a 1.8 inch overlay and finally, no structural overlay would be required from MP 211.00 to MP 212.50.

Even though the three overlay design procedures indicate that no overlay is required on the last 1.5 mile, it is important to consult the WSPMS to verify that there is no need for rehabilitation on the last section of this project. The WSPMS and core data indicates that rehabilitation would be needed on this section of roadway in 1997 albeit to correct surface cracking. The adjacent project (12.4 miles) to the north was overlaid with 1.6 inch HMA Class B in 1994. Therefore, for timing purposes, the last 1.5 mile should be overlaid with this project. The recommended overlay thickness for that portion of the project would be 1.8 inch.

The actual rehabilitation of this project consists of two options:

1. Cold in-place recycling from MP 207.80 to MP 210.55, to a maximum thickness of 4 inch and then overlaying with HMA Class F at the following depths:

Milepost	Depth
207.81 to 209.00	1.8 inch
209.00 to 209.65	2.4 inch
209.65 to 212.67	1.8 inch

2. Grind a maximum depth of 3.5 inch and replace with 3.5 inch HMA Class F. Then overlay the roadway as indicated by the overlay depths in Option 1.

SR 7 MP 0.00 to MP 16.82
Morton to Nisqually

5.1. INTRODUCTION

This case study comes from a section of State Route (SR) 7, which begins at the community of Morton, Washington (MP 0.00) and proceeds north for 16.82 miles to the Nisqually River Bridge (MP 16.82). The 1993 pavement condition survey for this project indicated numerous areas where the pavement is distressed with alligator, transverse and longitudinal cracking. At several locations, Maintenance has placed either an HMA patch or a chip seal on the more heavily distressed pavement. According to the WSPMS, this project was projected to reach a program level PSC of 50 in 1994. This overlay project was constructed in 1994.

This area of Lewis County has a terrain that consists of level flood plains to rolling terraces along East Creek and the Tilton River. Elevations range from approximately 800 to 1,800 feet above sea level. Annual precipitation is 7.9 feet per year. The mean temperature is 52°F, with a record low and high temperatures of 9°F and 106°F, respectively. The mean number of days (annually) with temperatures above 90°F is 6 days and below 32°F is 156 days. Frost penetration near Morton, measured about 9 inches in the record cold winter of 1949-1950.

This section of SR-7 was originally constructed in 1937 with 0.7 inches of a bituminous surface treatment placed over 8 to 9 inches of select roadway borrow. Construction during 1956 and 1967 placed and additional 0.8 inches of HMA Class B. A project in 1974 added an additional 2.4 inches of HMA Class B. A summary of HMA core depths, base thickness and core description are listed Table 17. The base thickness was taken from the WSPMS.

Table 17. Summary of Roadway Surfacing Depths

Core Location	Depth HMA (in)	Depth Base (in)	Comments
0.23	3.7	9.0	Core taken at a crack, crack is full depth
0.43	5.7	9.0	Core taken at a crack, crack is full depth
0.98	3.6	9.0	Core taken at a crack, top 60 mm is cracked
1.83	7.8	9.0	Core taken intact
2.38	6.6	9.0	Core taken intact
3.68	6.1	9.0	Core taken intact
4.08	5.0	9.0	Core taken intact
4.48	6.6	9.0	Core taken intact
5.03	5.0	9.0	Core taken at a crack, top 46 mm is cracked
5.63	7.4	9.0	Core taken at a crack, top 85 mm is cracked
6.13	4.6	9.0	Core taken at a crack, crack is full depth
6.48	6.7	9.0	Core taken intact
7.18	6.7	9.0	Core taken intact
7.73	6.7	9.0	Core taken intact
8.23	5.0	9.0	Core taken intact
8.78	6.5	9.0	Core taken intact
9.48	5.7	9.0	Core taken intact
9.98	3.3	9.0	Core taken intact
10.58	5.5	9.0	Core taken intact
10.98	5.5	9.0	Core taken intact

Table 17. Summary of Roadway Surfacing Depths, continued…

Core Location	Depth HMA (in)	Base (in)	Comments
13.03	8.0	5.0	Core taken intact
13.53	6.0	5.0	Core taken intact
14.53	8.4	8.0	Core taken intact
15.08	6.0	9.0	Core taken intact
15.68	6.6	8.0	Core taken intact
16.03	11.3	8.0	Core taken intact
16.55	8.1	9.0	Core taken intact

Current traffic volumes range from 3,600 to 5,000 vehicles per day (two way) with 14 percent trucks. The design period is 15 years and the associated estimated ESALs are 1,200,000.

Table 18 summarizes the deflection data that was collected on this project on June 9, 1992. Though the project was over 16.8 miles in length and FWD testing was performed every 250 feet, only the FWD data that corresponds to a core location is being evaluated as part of this case study. Knowing the HMA layer thickness to within ¼ inch is essential in assuring a more accurate prediction of layer moduli in the backcalculation procedure. The average pavement temperature at the time the FWD data was collected was 79°F. The normalized (9,000 lb) deflections, Area value (see Appendix **A**) and the subgrade modulus using the normalized deflections are shown in Table 18.

Table 18. FWD Deflections, Area Value and Subgrade Modulus

Core Location	Load (lbf)	Deflections D0	D8	D12	D24	D36	D48	Area (in)	M_R (psi)
0.23	13,847	21.73	18.82	16.38	10.98	7.87	5.94		
	10,722	20.47	14.69	12.68	8.31	5.91	4.49		
	9,263	17.87	12.76	10.98	7.09	5.00	3.82		
	5,171	9.96	7.09	5.91	3.62	2.52	1.93		
Normalized Values		16.46	12.28	10.55	6.85	4.84	3.66	20	15,809
0.43	13,609	16.97	15.71	15.35	13.66	11.61	9.49		
	10,421	12.87	11.85	11.57	10.28	8.78	7.12		
	8,977	7.09	10.16	9.92	8.86	7.52	6.10		
	5,076	5.83	5.28	5.08	4.49	3.78	3.03		
Normalized Values		10.98	10.08	9.84	8.74	7.40	6.02	30	12,328
0.98	13,054	41.69	31.14	25.23	14.45	9.02	5.91		
	10,119	33.11	24.61	19.72	10.87	6.57	4.25		
	8,692	28.90	21.30	16.97	9.13	5.47	3.54		
	4,790	17.09	11.97	9.21	4.49	2.56	1.61		
Normalized Values		29.65	21.81	17.44	9.53	5.75	3.74	18	11,458
1.83	14,608	20.08	15.12	12.36	6.97	4.13	2.60		
	11,150	15.87	12.13	9.84	5.39	3.11	1.93		
	9,691	14.01	10.67	8.66	4.69	2.68	1.61		
	5,742	8.82	6.65	5.31	2.72	1.50	0.91		
Normalized Values		13.03	9.88	7.99	4.29	2.44	1.50	18	25,092
2.38	13,990	25.04	16.65	12.76	6.73	4.61	3.39		
	10,770	19.17	12.99	9.88	5.04	3.39	2.48		
	9,406	16.54	11.26	8.52	4.69	2.87	2.13		
	5,329	9.88	6.50	4.80	2.28	1.57	1.22		
Normalized Values		16.10	10.83	8.19	4.09	2.80	2.09	16	26,107

Table 18. FWD Deflections, Area Value and Subgrade Modulus, continued…

Core Location	Load (lbf)	Deflections D0	D8	D12	D24	D36	D48	Area (in)	M_R (psi)
3.68	13,796	46.14	37.36	32.16	19.92	12.72	8.19		
	10,500	34.88	28.27	24.21	14.88	9.37	6.06		
	9,009	29.17	23.94	20.39	12.44	7.87	5.08		
	4,901	14.33	12.17	10.47	6.65	4.06	2.68		
Normalized Values		29.13	23.86	20.47	12.52	7.95	5.16	21	8,702
4.08	13,830	37.13	30.39	25.98	16.26	10.98	7.99		
	10,548	28.78	23.58	20.08	12.44	8.31	5.98		
	9,088	24.88	20.35	17.28	10.67	7.13	5.16		
	4,917	13.35	11.14	9.41	5.75	3.90	2.83		
Normalized Values		24.41	20.04	17.05	10.55	7.09	5.12	21	10,298
4.48	13,736	30.08	25.51	22.52	14.92	9.96	6.81		
	10,500	22.48	19.25	16.97	11.06	7.32	5.00		
	9,009	19.09	16.42	14.37	9.29	6.18	4.17		
	4,821	9.65	8.46	7.24	4.69	3.15	2.17		
Normalized Values		19.09	16.38	14.37	9.37	6.22	4.25	23	11,603
5.03	13,942	36.50	31.18	27.44	18.46	12.80	9.29		
	10,580	28.27	23.86	20.91	13.90	9.65	7.05		
	9,120	23.98	20.35	17.76	11.77	8.19	5.98		
	4,901	12.44	10.39	8.94	5.91	4.17	3.11		
Normalized Values		23.58	19.96	17.44	11.61	8.07	5.91	22	9,282
5.63	13,308	47.52	39.88	34.80	21.69	13.46	8.46		
	10,125	36.26	30.59	26.46	16.02	9.84	6.18		
	8,771	31.06	26.14	22.40	13.35	8.15	5.08		
	4,711	15.71	13.11	11.18	6.26	3.82	2.48		
Normalized Values		31.69	26.65	23.03	13.90	8.54	5.35	21	7,832
6.13	13,990	25.63	22.36	20.20	15.28	11.54	8.54		
	10,662	19.53	16.77	15.16	11.42	8.58	6.34		
	9,088	16.38	14.25	12.91	9.69	7.25	5.39		
	4,848	9.17	7.13	6.46	4.80	3.59	2.68		
Normalized Values		16.50	17.95	12.72	9.53	7.17	5.28	24	11,313
6.48	13,212	67.20	55.98	48.66	31.06	18.82	12.17		
	10,056	54.13	44.80	38.62	24.06	14.33	9.09		
	8,644	46.97	38.82	33.11	20.39	12.05	7.60		
	4,584	25.87	21.34	17.87	10.24	6.02	3.98		
Normalized Values		47.83	39.65	34.06	21.10	12.60	8.07	21	5,076
7.18	13,736	48.35	41.30	36.57	23.19	14.65	9.33		
	10,500	37.28	31.57	27.80	17.32	10.75	6.85		
	9,009	31.65	26.85	23.54	14.57	8.98	5.71		
	4,774	16.81	13.82	11.97	7.24	4.49	2.91		
Normalized Values		31.69	26.77	23.54	14.65	9.13	5.83	22	7,397
7.73	13,530	37.09	31.54	25.98	14.29	8.98	6.69		
	10,310	29.29	24,45	20.12	10.91	6.77	5.12		
	8,930	26.81	21.06	17.24	9.29	5.75	4.33		
	4,758	14.76	11.10	9.29	4.76	3.11	2.36		
Normalized Values		25.98	21.10	17.40	9.41	5.87	4.41	19	11,603
8.23	13,816	29.76	24.25	20.83	13.03	9.09	7.01		
	10,611	22.95	18.50	15.71	9.69	6.81	5.28		
	9,025	19.76	15.67	13.23	8.03	5.67	4.45		
	4,711	9.17	7.95	6.57	3.98	2.87	2.32		
Normalized Values		19.13	15.59	13.22	8.15	5.75	4.49	21	13,343

Table 18. FWD Deflections, Area Value and Subgrade Modulus, continued…

Core Location	Load (lbf)	Deflections						Area (in)	M_R (psi)
		D0	D203	D305	D610	D915	D1220		
8.78	13,561	51.50	44.53	38.43	23.07	14.76	10.08		
	10,326	42.09	36.30	30.94	18.03	11.34	7.76		
	8.835	37.13	31.85	27.01	15.51	9.61	6.57		
	4,727	21.22	18.07	14.92	8.23	5.08	3.50		
Normalized Values		36.69	31.57	26.81	15.59	9.80	6.69	21	6,962
9.48	13,165	68.42	56.46	44.41	21.54	11.06	6.85		
	10,389	54.76	44.49	34.68	15.79	8.11	5.00		
	8.835	46.69	31.15	29.53	13.03	6.77	4.13		
	4,806	26.54	21.02	15.28	6.06	3.15	2.17		
Normalized Values		47.56	38.70	29.88	13.54	6.97	4.37	18	7,977
9.98	13,022	67.13	53.43	43.74	21.06	12.56	8.74		
	10,151	55.24	42.87	34.57	15.94	9.25	6.46		
	8,708	49.29	37.60	29.88	13.54	7.76	5.35		
	4,679	28.53	20.75	19.33	6.57	3.78	2.60		
Normalized Values		49.25	38.03	30.43	14.01	8.15	5.67	18	7,687
10.58	13,038	74.53	61.65	50.98	24.49	12.52	8.46		
	10,008	61.30	49.72	40.35	18.50	9.33	6.30		
	8,581	53.82	43.19	34.76	15.55	7.83	5.28		
	4,536	30.84	23.70	18.35	7.64	4.02	2.80		
Normalized Values		54.84	44.29	35.91	16.46	8.39	5.67	18	6,527
10.98	13,292	56.65	46.06	39.57	23.15	12.60	6.57		
	10,215	45.24	36.14	30.79	17.32	9.21	4.84		
	8,866	39.17	31.30	26.26	14.53	7.76	4.02		
	4,885	21.38	16.85	13.74	7.13	3.78	2.09		
Normalized Values		39.21	31.42	26.57	14.88	7.99	4.21	20	7,252
11.63	13,149	59.72	49.88	42.32	24.01	13.11	7.32		
	10,072	47.44	38.78	32.32	17.72	9.45	5.35		
	8,692	40.87	33.23	27.28	14.49	7.56	4.45		
	4,695	21.77	17.52	14.09	6.06	4.06	2.32		
Normalized Values		41.69	34.17	28.43	15.20	8.43	4.76	19	7,107
12.18	12,673	94.05	77.44	66.65	37.20	20.71	12.56		
	9,691	71.65	59.65	50.83	27.60	15.24	9.17		
	8,438	66.02	52.05	44.17	23.66	13.07	7.91		
	4,632	36.69	27.40	22.83	12.01	6.93	4.49		
Normalized Values		67.99	54.92	46.81	25.51	14.21	8.66	20	4,206
12.53	13,101	68.23	56.42	47.95	29.33	18.82	12.99		
	10,072	54.65	44.53	37.23	22.20	14.25	9.88		
	8,660	47.20	38.43	31.89	18.78	12.01	8.39		
	4,663	25.75	20.28	16.18	9.17	5.94	4.13		
Normalized Values		48.27	39.33	32.80	19.53	12.56	8.70	20	5,511
13.03	13,355	50.00	38.27	31.65	21.26	15.35	12.64		
	10,373	39.21	30.24	24.76	16.46	11.97	9.84		
	8,946	35.24	26.46	21.61	14.21	10.28	8.50		
	4,806	20.03	15.00	11.73	7.13	5.55	4.57		
Normalized Values		34.76	26.46	21.54	14.25	10.35	8.54	20	7,687
13.53	13,815	37.52	27.36	22.76	13.27	8.07	5.55		
	10,738	29.61	21.57	17.80	10.24	6.10	4.25		
	9,342	25.71	18.66	15.43	8.78	5.08	3.58		
	5,345	15.59	10.71	8.70	4.80	2.80	2.01		
Normalized Values		24.96	17.95	14.80	8.43	5.00	3.50	18	12,763

Table 18. FWD Deflections, Area Value and Subgrade Modulus, continued…

Core Location	Load (lbf)	Deflections D0	D203	D305	D610	D915	D1220	Area (in)	Mr (psi)
14.53	13,387	38.39	33.46	30.51	22.99	17.09	12.36		
	10,611	30.35	26.14	23.74	17.64	13.15	9.69		
	9,120	26.02	22.36	20.51	15.08	11.42	8.43		
	4,996	14.41	12.09	10.71	8.23	5.16	3.54		
Normalized Values		25.75	22.13	20.08	15.00	10.91	7.91	24	7,252
15.08	13,355	43.62	36.46	31.89	20.67	13.78	9.21		
	10,404	34.21	28.50	24.68	15.67	10.31	6.93		
	8,930	29.57	24.49	21.10	12.27	9.02	5.83		
	4,869	16.46	13.15	11.06	6.73	4.41	3.07		
Normalized Values		29.65	24.53	21.18	13.43	8.86	5.98	21	8,122
15.68	13,403	63.07	52.52	46.54	30.51	19.25	12.72		
	10,246	50.67	42.28	37.13	23.50	14.49	9.53		
	8,930	44.80	37.24	32.56	20.16	12.32	7.91		
	4,822	26.42	21.14	17.99	10.43	6.26	4.02		
Normalized Values		44.68	36.97	32.36	20.31	12.56	8.11	21	5,366
16.03	13,720	40.20	33.62	29.61	19.49	12.76	8.27		
	10,627	32.05	26.61	23.35	15.00	9.61	6.18		
	9,041	27.87	23.07	20.16	12.83	8.15	5.20		
	4,854	15.51	12.48	10.75	6.57	4.06	2.60		
Normalized Values		27.32	22.60	19.72	12.64	8.07	5.20	22	8,557
16.55	14,053	29.92	25.24	22.60	15.98	11.57	8.39		
	10,659	23.58	19.84	17.76	12.36	8.82	6.38		
	9,168	20.39	17.20	15.28	10.59	7.52	5.43		
	4,933	12.13	9.72	8.54	5.79	4.02	2.91		
Normalized Values		20.08	16.77	14.92	10.39	7.40	5.35	23	10,443

As shown in Table 18, the average normalized D0 deflection ranges from 10.98 to 67.99 mils and has an average center deflection of 31.61 mils with a standard deviation of 13.78 mils. Deflections less than about 29 mils are considered normal.

The Area values shown in Table 18 do not suggest an extremely weak HMA, such as a loss of stiffness due to stripping. But the Area values indicate that some weakening of the pavement structure does exist. A quick, approximate check of the pavement structure is to compare the actual Area value to see if it falls within the range (normal to low stiffness), above this range (above normal stiffness) or below this range (below low stiffness). This comparison follows (refer to Case Study No. 1 for typical Area Values):

Table 19. Comparison of Area Value and Acceptable Area Value Range

Core Location	HMA Thickness (in)	Actual Area (in)	Above, Below or Within Range
0.23	3.7	20.1	Within
0.43	5.7	29.9	Above
0.98	3.6	17.8	Below
1.83	7.8	18.1	Below
2.38	6.6	16.0	Below
3.68	6.1	20.9	Below
4.08	5.0	21.0	Within
4.48	6.6	22.5	Within
5.03	5.0	22.5	Within
5.63	7.4	21.3	Below
6.13	4.6	24.4	Above
6.48	6.7	21.1	Below
7.18	6.7	21.9	Below
7.73	6.7	19.4	Below
8.23	5.0	20.9	Within
8.78	6.5	21.1	Below
9.48	5.7	17.6	Below
9.98	3.3	17.6	Below
10.58	5.5	18.1	Below
10.98	5.5	19.6	Below
11.63	5.2	19.4	Below
12.18	7.2	19.7	Below
12.53	6.7	20.2	Below
13.03	8.0	19.8	Below
13.53	6.0	18.1	Below
14.53	8.4	24.5	Within
15.08	6.0	21.5	Below
15.68	6.6	21.5	Below
16.03	11.3	21.7	-
16.55	8.1	23.0	Below

The above analysis suggests minimal structural weakness at MP's such as 0.23, 0.43, 4.08, 4.48, 5.03, 6.13, 8.23, 14.53, and 16.03; however, since the actual HMA thickness varies, this does not necessarily imply no requirement for a structural overlay.

The elastic modulus values of the subgrade range from 4,206 to 26,107 psi with an average of 10,008 psi and a standard deviation of 5,221 psi. On average, a subgrade modulus of 15,000 psi is typical for Washington State. This large variation in stiffness is most likely due to variation in soil moisture and the proximity of underlying rock, more than actual soil or deposition changes along the roadway.

Though there is substantial variation in the pavement deflections, Area values, and subgrade modulus, there doesn't appear to be a consistent pattern to isolate separate sections for this project. Figure 40 graphically shows how the normalized center deflection, normalized Area value and subgrade modulus varies throughout the projects length. Figure 40 was created from an in-house computer program and this program has yet to be converted to metric units. Therefore, Figure 40 shows the center deflection in mils, the Area value in inches and the subgrade modulus in ksi.

5.2. OVERLAY DESIGN PROCEDURES

This SECTION describes three overlay design procedures that are currently used by WSDOT: 1) WSPMS SCOPER, 2) WSDOT Empirical-Mechanistic Overlay Design, and 3) AASHTO Overlay Design Procedure. The three procedures can be used as design checks as will be more fully described later.

5.2.1 WSPMS SCOPER Overlay Design Procedure

WSPMS SCOPER is partially based on the Asphalt Institutes Component Analysis procedure (see Appendix E). Specific modifications made by WSDOT can be found in “Washington State Pavement Management - A 1993 Update,” Research Report WA-RD 274.1, Washington State Department of Transportation, Olympia, Washington, 1993.

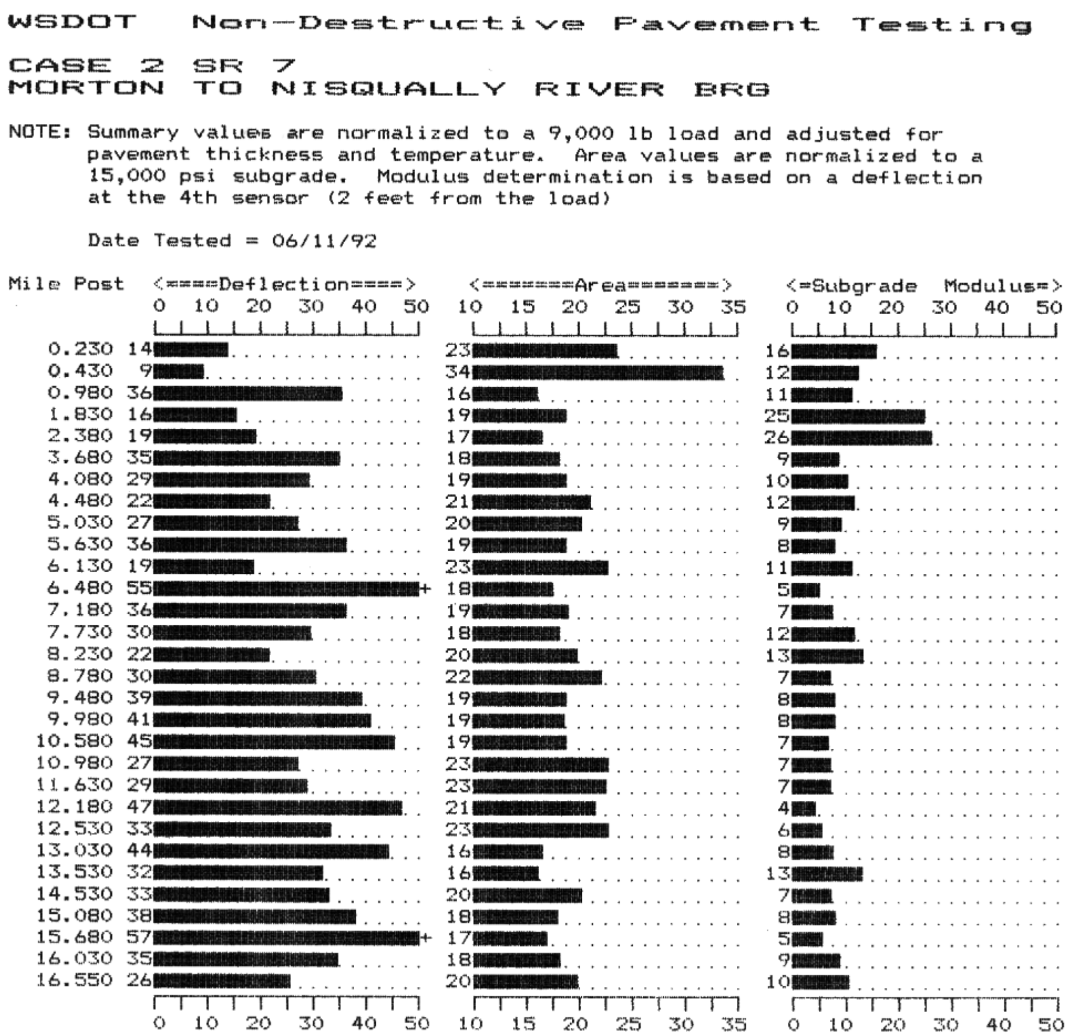


Figure 40. Normalized Center Deflection, Area Value, and Subgrade Modulus

The WSPMS SCOPER uses a component analysis approach that essentially requires the total pavement structure to be developed as a new design for the specified service conditions and then compared to the existing pavement structure (taking into account both pavement condition, type, and thickness of the pavement layers). The component design process requires substantial engineering judgment. This judgment is mainly associated with the selection of "weighting factors" or "conversion factors" to use in evaluating the structural adequacy of the existing pavement layers. The SCOPER design approach uses relationships between subgrade strength, pavement structure, and traffic to determine the overlay thickness.

5.2.1.1. Example of Calculations

Layer coefficients and ESAL's were determined using the WSPMS. The subgrade modulus as determined from the FWD analysis as shown in Table 18 was used in this analysis. Refer to Table 20 for SCOPER overlay design results. To illustrate this process, MP 0.23 will be used as an example:

MP 0.23

(3.7 inches HMA)(0.82)	=	3.0 inches
(9.02 inches Base)(0.30)	=	2.7 inches
Effective Thickness	=	5.7 inches

M_R = 15,809 psi
ESAL = 1 200 000

Refer to Design Thickness charts in Asphalt Institutes MS-1 Manual or Appendix E.

Design Thickness	=	7.7 inches
Effective Thickness	=	5.7 inches
Overlay Thickness	=	2.0 inches

Table 20. WSPMS SCOPER Overlay Design Procedure

Core Locations	Depths HMA (in)	Depths Base (in)	Layer Coefficients HMA	Layer Coefficients Base	Subgrade Modulus (psi)	Thickness (in) Design	Thickness (in) Effective	Thickness (in) Overlay
0.23	3.7	9.0	0.82	0.30	15,809	7.7	5.7	2.0
0.43	5.7	9.0	0.82	0.30	12,328	8.4	7.4	1.0
0.98	3.6	8.0	0.82	0.30	11,458	8.6	5.2	3.4
1.83	7.8	8.0	0.64	0.30	25,092	6.4	7.4	0
2.38	6.6	8.0	0.64	0.30	26,107	6.2	6.7	0
3.68	6.1	8.0	0.78	0.30	8,702	9.3	7.2	2.1
4.08	5.0	8.0	0.75	0.30	10,298	8.9	6.2	2.7
4.48	6.6	8.0	0.75	0.30	11,603	8.5	7.4	1.1
5.03	5.0	8.0	0.66	0.30	9,282	9.1	5.7	3.4
5.63	7.4	8.0	0.66	0.30	7,832	9.5	7.3	2.2
6.13	4.6	8..0	0.62	0.30	11,313	8.6	5.2	3.4
6.48	6.7	8.0	0.62	0.30	5,076	10.0	6.6	3.4
7.18	6.7	8.0	0.62	0.30	7,387	9.6	6.6	3.0
7.73	6.7	8.0	0.62	0.30	11,603	8.5	6.6	1.9
8.23	5.0	8.0	0.51	0.30	13,343	8.1	5.0	3.1
8.78	6.5	8.0	0.51	0.30	6,962	9.7	5.7	4.0
9.48	5.7	8.0	0.51	0.30	7,977	9.5	5.4	4.1
9.98	3.3	8.0	0.51	0.30	7,687	9.5	4.1	5.4
10.58	5.5	8.0	0.55	0.30	6,527	9.8	5.4	4.4
10.98	5.5	8.0	0.55	0.30	7,252	9.6	5.4	4.2
11.63	5.2	8.0	0.62	0.30	7,107	9.7	5.6	4.1
12.18	7.1	8.0	0.62	0.30	4,206	10.7	6.9	3.8
12.53	6.7	8.0	0.62	0.30	5,511	10.0	6.6	3.4
13.03	8.0	5.0	0.51	0.30	7,687	9.5	6.6	3.9
13.53	6.0	5.0	0.51	0.30	12,763	8.3	4.6	3.7

Table 20. WSPMS SCOPER Overlay Design Procedure, continued…

Core Locations	Depths HMA (in)	Depths Base (in)	Layer Coefficients HMA	Layer Coefficients Base	Subgrade Modulus (psi)	Thickness (in) Design	Thickness (in) Effective	Thickness (in) Overlay
14.53	8.4	8.0	0.51	0.30	7,252	9.6	6.7	2.9
15.08	6.0	9.0	0.61	0.30	8,122	9.4	6.3	3.1
15.68	6.6	8.0	0.69	0.30	5,366	10.0	7.0	3.0
16.03	11.3	8.0	0.69	0.30	8,557	9.3	10.2	0
16.55	8.1	9.0	0.82	0.30	10,442	8.8	9.4	0

5.2.2 WSDOT Mechanistic-Empirical Overlay Design

5.2.2.1. Evercalc©

Currently, when a pavement structure is analyzed using FWD data and a backcalculation procedure, it is recommended to vary the use and stiffness of the stiff layer. A stiff layer should be used when the underlying material is known to be saturated or if underlying rock or other very stiff deposits are known to exist (refer to Paragraph 2.3). In most instances, the presence, the stiffness, and depth to stiff layer is not known. Therefore, by evaluating the data using no stiff layer, a stiff layer at 50,000 psi (345 MPa), which indicates a saturated layer, and a stiff layer at 1,000,000 psi (6,895 MPa), which indicates a rock layer or stiff deposit, would help in identifying the modulus characteristic of the pavement layers.

Input Values

General Data

Number of layer = 3 (no stiff layer)
4 (stiff layer)
Units = Metric
Indicate whether or not a stiff layer option is to be used
Temperature correction to be applied
Temperature Measurement = Direct Method
Plate radius = 15 cm
Seed Moduli = User supplied

Sensor No.	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information is shown in Table 21.

Table 21. Layer Characteristics Input Values

Layer	Description	Poisson's Ratio	Modulus (ksi) Initial	Modulus (ksi) Min.	Modulus (ksi) Max.
1	HMA	0.35	400	10	2,000
2	Base	0.40	25	5	500
3	Subgrade	0.45	15	5	500
4*	Stiff layer (water)	0.35	50		
4*	Stiff layer (rock)	0.30	1,000		

* Denotes the use of a stiff layer.

Deflection Data

Refer to Paragraph 2.6.4.5 for the necessary procedures for entering deflection data or for converting the raw FWD deflection file into EVERCALC©.

Backcalculation Results

The backcalculation layer moduli, for all three cases (no stiff layer and stiff layers at 345 and 6 895 MPa) are shown in Table 22.

5.2.2.2. Everpave©

Everpave© is a mechanistic-empirical overlay design procedure that was developed by WSDOT. The pavement analysis is accomplished by use of Everstress© (see SECTION 1.0), which can account for the stress sensitive characteristics of the unbound materials. Everpave© uses the material properties (modulus) of each pavement layer (e.g. HMA, base and subgrade). traffic load repetitions and the environment (weather) to determine the appropriate overlay design thickness. The determination of the appropriate thickness is based on the two primary distresses found in flexible pavements in Washington State; rutting and fatigue cracking (see SECTION 3.0). The Everpave© program calculates the overlay thickness by comparing the pavement performance lives for fatigue and rutting with the projected design traffic volume (ESALs). When the minimum repetitions of the two failure criteria are greater than the traffic volume, the final overlay thickness is produced. Otherwise, the overlay thickness is increased by an incremental thickness and the analysis is repeated.

Input Values

General Input Data

Tire Load	4,500 lbs
Tire Pressure	100 psi
Shift factor for New HMA	10
Shift factor for Existing HMA	10
Dual Tire Spacing	14 inches

	Spring	Summer	Fall	Winter
Seasonal Variation				
Base Course	0.85	1.00	0.90	0.75
Subgrade	0.85	1.00	0.90	0.85
Traffic	1.00	1.00	1.00	1.00
Mean Air Temperature °F	48.6	62.1	50.7	38.5
Season Period (months)	3	4	2	3

For mean air temperature refer to Appendix B, Table B-1 and for seasonal periods (months) refer to Table C-1, Appendix C.

Table 22 Summary of EVERCALC© Results

Core Location	*No Stiff Layer* E_{adj}[1] (ksi)	E_{hma}[2] (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS	Depth to Stiff Layer (in)	*Stiff Layer @ 50 ksi* E_{adj} (ksi)	E_{hma} (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS	*Stiff Layer @ 1,000 ksi* E_{adj} (ksi)	E_{hma} (ksi)	E_{base} (ksi)	E_{sub} (ksi)	RMS
0.23	415	172	95	13	0.78	600	379	**1570**[3]	**112**	**14**	2.05	252	105	145	14	2.46
0.43	4817	2000	266	7	2.19	600	4817	2000	301	7	1.92	4817	2000	306	7	1.89
0.98	2324	965	6	12	4.57	200	795	**330**	**26**	**10**	0.83	707	294	31	9	0.77
1.83	218	354	6	32	1.94	81	**152**	246	**26**	**18**	1.71	109	177	77	11	6.65
2.38	103	167	25	23	1.52	200	**78**	126	**42**	**22**	4.43	73	118	58	18	7.60
3.68	193	313	5	9	2.35	111	**108**	176	**33**	**5**	2.41	110	178	34	5	5.27
4.08	297	483	16	9	0.69	195	**156**	254	**47**	**8**	2.84	145	235	54	7	3.49
4.48	347	563	5	12	0.88	152	**238**	386	**32**	**8**	1.46	212	344	43	7	2.05
5.03	449	615	21	8	0.52	235	**268**	368	**54**	**7**	1.81	248	341	59	7	2.18
5.63	110	150	5	8	5.03	100	**176**	242	**6**	**5**	5.25	183	250	5	5	10.44
6.13	1058	1450	69	9	1.21	314	**535**	734	**139**	**8**	0.67	512	703	147	8	0.76
6.48	78	107	5	5	6.41	107	**88**	120	**5**	**5**	25.63	86	118	5	5	30.30
7.18	159	218	5	8	4.13	107	**262**	3600[4]	**5**	**5**	4.94	252	346	5	5	10.12
7.73	129	177	8	11	2.24	170	**93**	127	**23**	**9**	5.92	87	119	28	8	6.88
8.23	223	306	45	11	2.05	600	**179**	245	**60**	**12**	3.56	174	239	63	11	3.83
8.78	125	172	5	7	2.88	150	**124**	170	**12**	**5**	4.16	197	270	5	5	6.49
9.48	255	100	5	9	13.77	56	**623**	244	**5**	**5**	34.28	807	317	5	5	46.16
9.98	991	389	5	7	4.63	180	**774**	304	**10**	**6**	3.64	710	2874	12	6	4.63
10.58	255	100	5	7	13.48	52	**470**	184	**5**	**5**	47.07	607	238	5	5	57.33
10.98	423	166	5	9	13.98	63	**955**	3751[5]	**5**	**5**	23.99	1075	422	5	5	25.60
11.63	881	179	5	8	11.25	66	1959	**3981**	**5**	**5**	26.25	2172	441	5	5	36.36
12.18	493	100	5	5	22.43	74	493	**100**	**5**	**5**	49.19	493	100	5	5	54.38
12.53	554	112	5	5	1.81	161	649	**132**	**5**	**5**	13.84	639	130	5	5	16.87
13.03	493	100	24	6	4.34	600	493	**100**	**40**	**6**	6.35	493	100	41	6	6.51
13.53	137	281	5	14	3.06	100	49	**1000**[6]	**110**	**8**	6.89	49	100	167	7	9.53
14.53	152	312	8	6	1.88	367	119	**245**	**25**	**6**	1.25	1	236	30	5	1.33
15.08	185	381	5	8	1.41	111	147	**301**	**20**	**5**	5.11	303	623	5	5	8.91
15.68	67	138	5	5	4.92	116	77	**158**	**5**	**5**	21.56	75	1547	5	5	25.96
16.03	49	100	5	9	7.49	111	57	**117**	**5**	**5**	2.39	60	123	5	5	3.66
16.55	162	333	10	9	0.75	266	129	**266**	**28**	**8**	0.68	122	250	31	8	0.86

1 E_{hma} is the actual backcalculated modulus for the HMA at the insitu field temperatures.
2 E_{adj} is E_{hma} adjusted to a standard temperature of 77°F (25°C).
3 Bold numbers indicate the moduli that were selected for input into EVERPAVE. Moduli are selected based on engineering judgment and low RMS.
4 Base moduli “fixed” at 20 ksi in EVERCALC. This resulted in a HMA modulus of 165 ksi and a subgrade modulus of 5 ksi. These re-calculated moduli values were entered into EVERPAVE
5 Base moduli “fixed” at 20 ksi in EVERCALC. This resulted in a HMA modulus of 100 ksi and a subgrade modulus of 5 ksi. These re-calculated moduli values were entered into EVERPAVE.
6 Base moduli “fixed at 20 ksi in EVERCALC. This resulted in a HMA modulus of 378 ksi and a subgrade modulus of 5 ksi. These re-calculated moduli values were entered into EVERPAVE.

At several MP locations the Eadj moduli values appear to be unrealistically high, therefore the unadjusted Eac moduli were selected for input for EVERPAVE

Pavement Data

Overlay HMA Moduli	=	400 ksi
Poisson's ratio	=	0.35
Initial Overlay Thickness	=	0.2 inches
Thickness Increment	=	0.2 inches

Traffic Data

18 KESAL's for Design Period (15 years)	=	1,200,000
Lane Distribution Factor	=	1.00
Total Design ESAL's	=	1,200,000

The results of the Everpave© overlay analysis are presented in Table 23. As a reminder, the initial overlay thickness was established at 0.2 inch for this case study. Therefore, those locations that indicate a 0.2 inch overlay, are due to the minimum initial overlay thickness set by the user.

Table 23. EVERPAVE© Overlay Thickness Results

			Selected Layer Moduli			EVERPAVE©
Core Location	HMA (in)	Base (in)	Eac (ksi)	Ebase (ksi)	Esub (ksi)	Overlay (in)
0.23	9.4	22.9	186	107	14	0.2
0.98	9.1	20.4	352	25	10	2.2
1.83	19.8	20.4	158	23	19	0.2
2.38	16.8	20.4	80	42	22	0.2
3.68	15.5	20.4	110	33	5	2.2
4.08	12.8	20.4	158	47	8	1.2
4.48	16.8	20.4	239	31	8	0.2
5.03	12.8	20.4	257	56	7	0.8
5.63	18.9	20.4	150	9	5	1.4
6.13	11.6	20.4	533	137	9	0.2
6.48	17.1	20.4	90	5	5	3.3
7.18	17.1	20.4	124	20	5	2.0
7.73	17.1	20.4	91	24	9	1.4
8.23	12.8	20.4	181	60	12	0.2
8.78	16.5	20.4	116	13	5	2.4
9.48	14.6	20.4	248	5	5	2.2
9.98	8.5	20.4	293	10	6	3.7
10.58	14.0	20.4	188	5	5	3.0
10.98	14.0	20.4	100	20	5	3.3
11.63	13.1	20.4	100	20	5	3.7
12.18	18.3	20.4	100	5	5	3.0
12.53	17.1	20.4	135	5	5	2.6
13.03	20.4	12.8	100	39	6	1.2
13.53	15.2	12.8	382	20	9	0.2
14.53	21.3	20.4	249	25	6	0.2
15.08	15.2	22.9	228	27	5	1.2
15.68	16.8	20.4	161	5	5	2.4
16.03	28.7	20.4	117	5	6	0.2
16.55	20.7	22.9	265	28	8	0.2

5.2.3 AASHTO DARWin® Pavement Design System

AASHTO DARWin® is the computerized version of the pavement design models presented in AASHTO's "Guide for Design of Pavement Structures 1993." As stated in the AASHTO DARWin® User's Guide, "In the AASHTO overlay design procedure, the structural capacity for future traffic (SC_f) and the effective structural capacity (SC_{eff}) of the existing pavement are calculated using one of up to four available methods. These structural capacities are then used to determine the required overlay structural capacity". For this case study, the non-destructive testing method will be used for overlay determination. AASHTO DARWin® uses the deflection data to backcalculate the subgrade modulus (M_R) and the effective pavement modulus (E_p). These values are then used to determine the structural numbers for the existing pavement and for future traffic volumes. The required overlay structural number is the difference between SC_f and SC_{eff}.

5.2.3.1. Input Values

18 KESAL's	1,200,000
Initial Serviceability	4.5
Terminal Serviceability	3.0
Reliability Level (%)	50
Overall Standard Deviation	0.50
Overlay Layer Coefficient (a_{ol})	0.44

Calculated Overlay Structural Number (SN_{ol}) = Non-Destructive Method

Point-by-Point Backcalculation	
FWD Load	9000 lbs
Resilient Modulus Correction Factor	0.5
Base Type	Granular

Mid-depth Pavement Temperature	92°F MP 0.00 to MP 1.23
	67°F MP 1.28 to MP 4.23
	71°F MP 4.53 to MP 8.93
	93°F MP 8.98 to MP 11.33
	103°F MP 11.38 to MP 13.33
	62°F MP 13.38 to MP 16.81

The normalized load (9000 lbs) and corresponding deflections are shown in Table 24. WSDOT uses a FWD sensor spacing of 0, 8, 12, 24, 36, and 48 inches. AASHTO DARWin® will accommodate deflection data collected at any deflection spacing and at any load level. The FWD sensor spacing was selected such that the deflection basin would be adequately defined. Typically, the pavement structural design is based on a legally loaded axle of 18,000 lbs (9000 lbs per one-half of the axle). Therefore, the normalized deflections at 9000 lbs are used in this procedure. Results of this analysis are shown in Table 25.

Table 24. Normalized Deflection Data

MP	Load (lbs)	$D_{at\ 0"}$ (mils)	$D_{at\ 8"}$ (mils)	$D_{at\ 12"}$ (mils)	$D_{at\ 24"}$ (mils)	$D_{at\ 36"}$ (mils)	$D_{at\ 48"}$ (mils)
0.23	9000	16.44	12.30	10.56	6.84	4.85	3.68
0.43	9000	10.97	10.09	9.84	8.75	7.42	6.03
0.98	9000	29.65	21.83	17.43	9.51	5.76	3.74
1.83	9000	13.02	9.89	8.00	4.31	2.46	1.51
2.38	9000	16.11	10.82	8.17	4.14	2.80	2.08
3.68	9000	29.14	23.87	20.47	12.52	7.97	5.16
4.08	9000	24.39	20.05	17.05	10.56	7.09	5.13
4.48	9000	19.09	16.39	14.36	9.38	6.24	4.25
5.03	9000	23.57	19.96	17.43	11.60	8.07	5.90
5.63	9000	31.71	26.65	23.02	13.88	8.54	5.37
6.13	9000	16.50	14.03	12.70	9.53	7.17	5.33
6.48	9000	47.85	39.65	34.05	21.09	12.59	8.07
7.18	9000	31.69	26.79	23.53	14.65	9.14	5.83
7.73	9000	25.97	21.11	17.41	9.39	5.88	4.42
8.23	9000	19.15	15.60	13.21	8.13	5.74	4.47
8.78	9000	36.70	31.56	26.83	15.58	9.79	6.71
9.48	9000	47.54	38.69	29.89	13.54	6.97	4.37
9.98	9000	49.27	38.03	30.45	14.01	8.16	5.66
10.58	9000	54.85	44.31	35.89	16.44	8.37	5.66
10.98	9000	39.21	31.43	26.56	14.90	7.98	4.20
11.63	9000	41.69	34.19	28.44	15.21	8.41	4.76
12.18	9000	67.99	54.92	46.81	25.50	14.20	8.66
12.53	9000	48.27	39.32	32.79	19.54	12.54	8.71
13.03	9000	34.77	26.45	21.55	14.24	10.34	8.53
13.53	9000	24.97	17.94	14.81	8.44	5.01	3.50
14.53	9000	25.75	22.13	20.09	15.01	10.92	7.93
15.08	9000	29.66	24.53	21.19	13.42	8.85	5.97
15.68	9000	44.69	36.96	32.35	20.31	12.54	8.18
16.03	9000	27.31	22.59	19.74	12.64	8.07	5.19
16.55	9000	20.09	16.77	14.93	10.38	7.39	5.35

Table 25. AASHTO DARWin® Overlay Thickness Results

Core Location	Pavement Depths HMA (in)	Base (in)	Total (in)	SN for Future Traffic	Effective Existing Pavement SN	Calculated Overlay SN (SN_{ol})	Overlay Thickness (in)
0.23	3.72	9.00	12.72	3.08	3.03	0.05	0.1
0.43	5.76	9.00	14.76	-	-	-	-
0.98	3.60	8.04	11.64	3.52	2.14	1.38	3.1
1.83	7.80	8.04	16.08	2.56	3.21	0.00	0.0
2.38	6.60	8.04	14.64	2.52	2.62	0.00	0.0
3.68	6.12	8.04	14.16	3.92	2.40	1.52	3.5
4.08	5.04	8.04	13.08	3.67	2.42	1.25	2.8
4.48	6.60	8.04	14.64	3.50	3.02	0.48	1.1
5.03	5.04	8.04	13.08	3.80	2.64	1.16	2.6
5.63	7.44	8.04	15.48	4.08	2.55	1.53	3.5
6.13	4.56	8.04	12.60	3.52	3.11	0.41	0.9
6.48	6.72	8.04	14.76	4.75	2.16	2.59	5.9
7.18	6.72	8.04	14.76	4.16	2.51	1.65	3.8
7.73	6.72	8.04	14.76	3.50	2.50	1.00	2.3
8.23	5.04	8.04	13.08	3.30	2.67	0.63	1.4
8.78	6.48	8.04	14.52	4.26	2.31	1.95	4.4
9.48	5.76	8.04	13.80	4.04	2.05	1.99	4.5
9.98	3.36	8.04	11.40	4.09	1.71	2.38	5.4
10.58	5.52	8.04	13.56	4.34	1.96	2.38	5.4
10.98	5.52	8.04	13.56	4.19	2.37	1.82	4.1
11.63	5.16	8.04	13.20	4.22	2.40	1.82	4.1
12.18	7.20	8.04	15.24	4.77	2.22	2.55	5.5
12.53	6.72	8.04	14.76	4.56	2.59	1.97	4.5
13.03	8.04	5.04	13.08	4.25	2.98	1.27	2.9
13.53	6.00	5.04	11.04	3.35	1.93	1.42	3.2
14.53	8.40	8.04	16.44	4.34	3.03	1.31	3.0
15.08	6.00	9.00	15.00	4.03	2.45	1.58	3.6
15.68	6.60	8.04	14.64	4.69	2.11	2.58	5.9
16.03	11.28	8.04	19.32	3.87	3.02	0.85	1.9
16.55	8.16	9.00	17.16	3.74	3.24	0.50	1.1

5.2.4 Overlay Thickness Design Summary

Table 26. Summary of Overlay Thickness

Core Location	EVERPAVE© (in)	AASHTO DARWin (in)	WSPMS SCOPER (in)
0.23	0.2	0.08	1.9
0.43	-	-	1.0
0.98	2.2	3.1	3.3
1.83	0.2	0	0
2.38	0.2	0	0
3.68	2.2	3.5	2.1
4.08	1.2	2.8	2.7
4.48	0.2	1.1	1.1
5.03	0.8	2.6	3.4
5.63	1.4	3.5	2.2
6.13	0.2	0.9	3.4
6.48	3.3	5.9	3.5
7.18	2.0	3.8	3.0

Table 26. Summary of Overlay Thickness, continued…

Core Location	EVERPAVE© (in)	AASHTO DARWin (in)	WSPMS SCOPER (in)
7.73	1.4	2.3	1.9
8.23	0.2	1.4	3.2
8.78	2.4	4.4	4.0
9.48	2.2	4.5	4.1
9.98	3.7	5.4	5.4
10.58	3.0	5.4	4.4
10.98	3.3	4.1	4.2
11.63	3.7	4.1	4.1
12.18	3.0	5.8	3.8
12.53	2.6	4.5	3.4
13.03	1.2	2.9	3.9
13.53	0.2	3.2	3.7
14.53	0.2	3.0	2.9
15.08	1.2	3.6	3.0
15.68	2.4	5.9	3.0
16.03	0.2	1.9	0
16.55	0.2	1.1	0

As discussed in the previous case study, the project should be constructed with logical breaks in the overlay thickness. The variations between the three overlay design procedures are due in part by the various characteristics and design criteria used by each design method. However, using multiple design procedures allows for a check and balance of the necessary overlay thickness and requires the use of engineering judgment for the final decision.

The actual limits of the overlay may vary due to actual field conditions and limitations. As a note, this roadway was last overlaid in 1974 with 60 mm HMA, the project from MP 6.42 to MP 16.55 received an additional chip seal in 1987. It can be assumed that the majority of the severely distressed pavement will be removed and reconstructed. With this assumption, the required overlay thickness for this project would be as follows:

MP Limits	Overlay Thickness
0.00 to 8.78	1.8 inches
8.78 to 12.53	2.4 inches
12.53 to 16.55	1.8 inches

The actual rehabilitation of this project included sealing of all cracks, preleveling as necessary with HMA Class G to correct rutted and settled pavement, dig outs as necessary to correct the severely distressed pavement and overlaying the entire project with the following HMA thickness:

MP Limits	Overlay Thickness
0.00 to 1.00	2.4 inches
1.00 to 6.00	1.8 inches
6.00 to 13.00	2.4 inches
13.00 to 16.82	1.8 inches

Case Study No. 3

I 90 MP 275.50 to MP 280.16
Spokane West UAB to Spokane Viaduct

6.1. INTRODUCTION

This case study comes from a section of Interstate 90, which begins at the west UAB for Spokane, Washington (MP 275.50) and proceeds east to the Spokane Viaduct (MP 280.16). This project addresses the need to rehabilitate the distressed concrete pavement, replace the existing drainage system and reconstruct the roadway shoulders and slopes. This project was reconstructed in 1994 and 1995.

The predominant soil type in this area is loam, of the Marble, Hesseltine, and Cheney Groups. There are some rock outcroppings and Hesseltine Very Rock Complex areas from MP 277.20 to MP 279.20. From MP 275.50 to MP 277.50 the roadway traverses a generally flat plateau. Between MP 277.50 to MP 279.50, the roadway drops at a five percent grade to a structure over Latah Creek. From the structure to the end of the project, the roadway rises at a more gradual slope.

This section of I-90 was originally constructed from 1964 to 1966 with 8 inches of plain jointed (15 foot joint spacing) portland cement concrete, over 2.4 inches of crushed surfacing top course, over 3.0 inches of special gravel base, over a sandy subgrade with some silt.

Current traffic volumes are around 30,000 (two way) vehicles per day with 12 percent trucks. The design period is 40 years and the associated estimated ESALs are 65,000,000.

Prior to rehabilitation, this roadway section was distressed with severe transverse cracking, joint spalling and faulting. In addition, the original drainage system was undersized for an area with poor soil drainage characteristics and the potential for underground springs.

6.2. NEW/RECONSTRUCTION DESIGN PROCEDURES

The design process to be used for new or reconstructed pavements will be according to the AASHTO Guide for Design of Pavement Structures (1986 or later version).

6.2.1 Flexible Structural Design

WSDOT input values can be found in the WSDOT Pavement Guide Volume 1[1]. The AASHTO DARWin® pavement design system will be used in the determination of pavement depths for this case study.

6.2.1.1 Input Values

18 KESALs Over Initial Performance Period	=	65,000,000
Initial Serviceability	=	4.5
Terminal Serviceability	=	3.0
Reliability (percent)	=	95

[1] http://www.wsdot.wa.gov/biz/mats/pavement/Volume%201.pdf

Overall Standard Deviation	=	0.50
Roadbed Soil Resilient Modulus (psi)[1]	=	17,000
Stage Construction	=	1
Design Structural Number	=	5.55

[1]Note: Assumes subgrade modulus @ 15,000 psi for 5 months per year and @ 20,000 psi for 7 months of the year.

6.2.1.2 Specified Thickness Design

A number of material types (HMA Class A, E, CSTC, crushed surfacing base course (CSBC), crushed surfacing (CS), etc..) can be used in the determination of the pavement section. The materials and thickness shown below were chosen as an example. Typical roadway section could be as follows:

4.0 inches HMA Class A
6.9 inches HMA Class E
5.3 inches CS
16.2 inches Total

The layer coefficients used were:

$a_{HMA\ A,\ E}$ = 0.44
$a_{HMA\ CS}$ = 0.13

The HMA Class A was fixed at 4.0 inches and the CS at 5.3 inches (minimums noted in WSDOT Pavement Policy). The remaining pavement thickness to achieve the design SN was allocated to the HMA Class E.

The above might suggest that the two sections will have equal performance, this is unlikely.

Frost Considerations

By use of Figure G-5 (Appendix G), the expected depth of freeze in the vicinity of Spokane is about 45 inch (1100 mm) based on the severe winter of 1949-1950. By classifying the subgrade as fine-grained, the maximum depth of freeze is about 35 inch (890 mm) based on Figure G-7 (Appendix G). By selecting an approximate depth of freeze equal to 40 inches, then one-half of this depth is 20 inches. The pavement section shown above has a total depth of 16.2 inches. If the subgrade soil is classified as frost susceptible, then increase the pavement section to one-half the expected frost depth (i.e. 20 inches) by adding additional thickness of CS.

6.2.2 Rigid Structural Design

WSDOT input values can be found in the WSDOT Pavement Guide Volume 1[11]. The AASHTO DARWin® pavement design system will be used in the determination of pavement depths for this case study.

6.2.2.1 Input Values

18 KESALs Over Initial Performance Period	=	65,000,000
Initial Serviceability	=	4.5
Terminal Serviceability	=	3.0
28-day mean PCC Modulus of Rupture (psi)	=	650
28-day mean Elastic Modulus of Slab (psi)	=	4,000,000

Mean Effective k-value (psi/in)[1]	=	490 (assumes use of HMA base)
Reliability (percent)	=	95
Overall Standard Deviation	=	0.40
Load Transfer Coefficient, J	=	2.7 (use of dowel bars)
Overall Drainage Coefficient, Cd	=	1.20

[1]Note: Assumes HMA base @ 100,000 psi and subgrade @ 15,000 psi for 5 months per year and @ 20,000 psi for 7 months per year. Loss of support = 0.5.

Stage Construction	=	1
Calculated Design Thickness (in)	=	11.98

Therefore, a rigid pavement section would include:

12.0 inches of doweled concrete pavement
4.0 inches HMA base
4.0 inches CSBC or geotextile[2]
20 inches Total

[2]Note: The geotextile or CSBC material is needed to act as a filter layer for the HMA base.

Reconstruction of this section of I-90 involved removing the existing concrete pavement and base material, installation of the drainage system, and rebuilding with 11.0 inches of doweled concrete pavement (15 foot joint spacing) over 4.0 inches of ATB, over 2.4 inches of crushed surfacing.

6.2.2.2 Frost Considerations

From Paragraph 6.2.2.1 above, one-half of the design frost depth is about 20 inches. The recommended pavement section has a total depth of 20 inches. If the subgrade soil is frost susceptible, then no additional thickness is needed to meet the minimum frost requirement.

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Appendix A
Nondestructive Testing Interpretation Techniques

Clearly, there are all kinds of NDT data which can be collected on or about pavements but concentration is placed on measured surface deflections.

DEFLECTION BASIN PARAMETERS

Over the years numerous techniques have been developed to analyze deflection data from various kinds of pavement deflection equipment. A fairly complete summary of deflection basin parameters was provided by Horak at the Sixth International Conference Structural Design of Asphalt Pavement [15] and is shown in Table A-1.

Table A-1. Summary of Deflection Basin Parameters [modified from 15]

Parameter	Formula	Measuring device
Maximum deflection	D_0	Benkelman Beam, Lacroux deflectometer, FWD
Radius of curvature	$R = \frac{r^2}{2D_0(D_0/D_r - 1)}$ r = 5"	Curvaturemeter
Spreadability	$S = \left(\frac{[(D_0 + D_1 + D_2 + D_3)/5]100}{D_0}\right)$ D1 … D3 spaced 12" apart	Dynaflect
Area	$A = 6[1 + 2(D_1/D_2) + 2(D_2/D_0) + (D_3/D_0)]$ 0, 1, 2, 3 feet	FWD
Shape factors	$F1 = (D_0 - D_2) / D_1$ $F2 = (D_1 - D_3) / D_2$	FWD
Surface curvature index	$SCI = D_0 - D_r$ where r = 12" or r = 20"	Benkelman Beam Road Rater FWD
Base curvature index	$BCI = D_{24"} - D_{36"}$	Road Rater
Base damage index	$BDI = D_{12"} - D_{24"}$	Road Rater
Deflection ratio	$Q_r = D_r/D_0$ where $D_r = D_0/2$	FWD
Bending index	BI = D/a where a = Deflection basin	Benkelman Beam
Slope of deflection	$SD = \tan^{-1} (D_0 - D_r)/r$ where r = 24 inches	Benkelman Beam

All of these parameters tend to focus on four major areas:

(a) Plate or center load deflection which represents the total defection of the pavement. This was obviously the first deflection parameter which came with the Benkelman

Beam. It has been used for many years as the primary input for several overlay design procedures.

(b) The slope or deflection differences close to the load such as Radius of Curvature (R), Shape Factor (F1), and Surface Curvature Index (SCI). These parameters tend to reflect the relative stiffness of the bound or upper regions of the pavement section.

(c) The slope or deflection differences in the middle of the basin about 11.8 inches to 35.4 inches from the center of the load. These parameters tend to reflect the relative stiffness of the base or lower regions of the pavement section.

(d) The deflections toward the end of the basin. Deflections in this region relate quite well to the stiffness of the subgrade below the pavement surfacing.

The subsequent parameters to be presented were developed to provide a means of obtaining the resilient modulus values of the surfacing layers more easily or quickly than full backcalculation. In general, the success of these regression equations to predict the resilient modulus of the surfacing layers has been limited. There is a clear consensus; however, that the deflections measured beyond the primary effects of the load stress bulb relate quite well to the resilient modulus of the subgrade, (ESG).

AREA PARAMETER

Over the years WSDOT has found that the use of selected indices and algorithms provide a "good picture" of the relative conditions found throughout a project. This picture is very useful in performing backcalculation and may at times be used by themselves on projects with large variations in surfacing layers.

WSDOT is currently using deflections measured at the center of the test load combined with Area values and E_{SG} computed from deflections measured at 24 inches presented in a linear plot to provide a visual picture of the conditions found along the length of any project (as illustrated in Figure A-1).

The Area value represents the normalized area of a slice taken through any deflection basin between the center of the test load and 3 feet. By normalized, it is meant that the area of the slice is divided by the deflection measured at the center of the test load, D_0. Thus the Area value is the length of one side of a rectangle where the other side of the rectangle is D_0. The actual area of the rectangle is equal to the area of the slice of the deflection basin between 0 and 3 feet.

The original Area equation is:

$$A = 6(D_0 + 2D_1 + 2D_2 + D_3)/D_0$$

where D_0 = surface deflection at center of test load,
D_1 = surface deflection at 1 foot,
D2 = surface deflection at 2 feet, and
D3 = surface deflection at 3 feet.

The approximate metric equivalent of this equation is:

$$A = 150(D0 + 2D300 + 2D600 + D900)/D0$$

where D0 = deflection at center of test load,
D300 = deflection at 300 mm,
D600 = deflection at 600 mm, and
D900 = deflection at 900 mm.

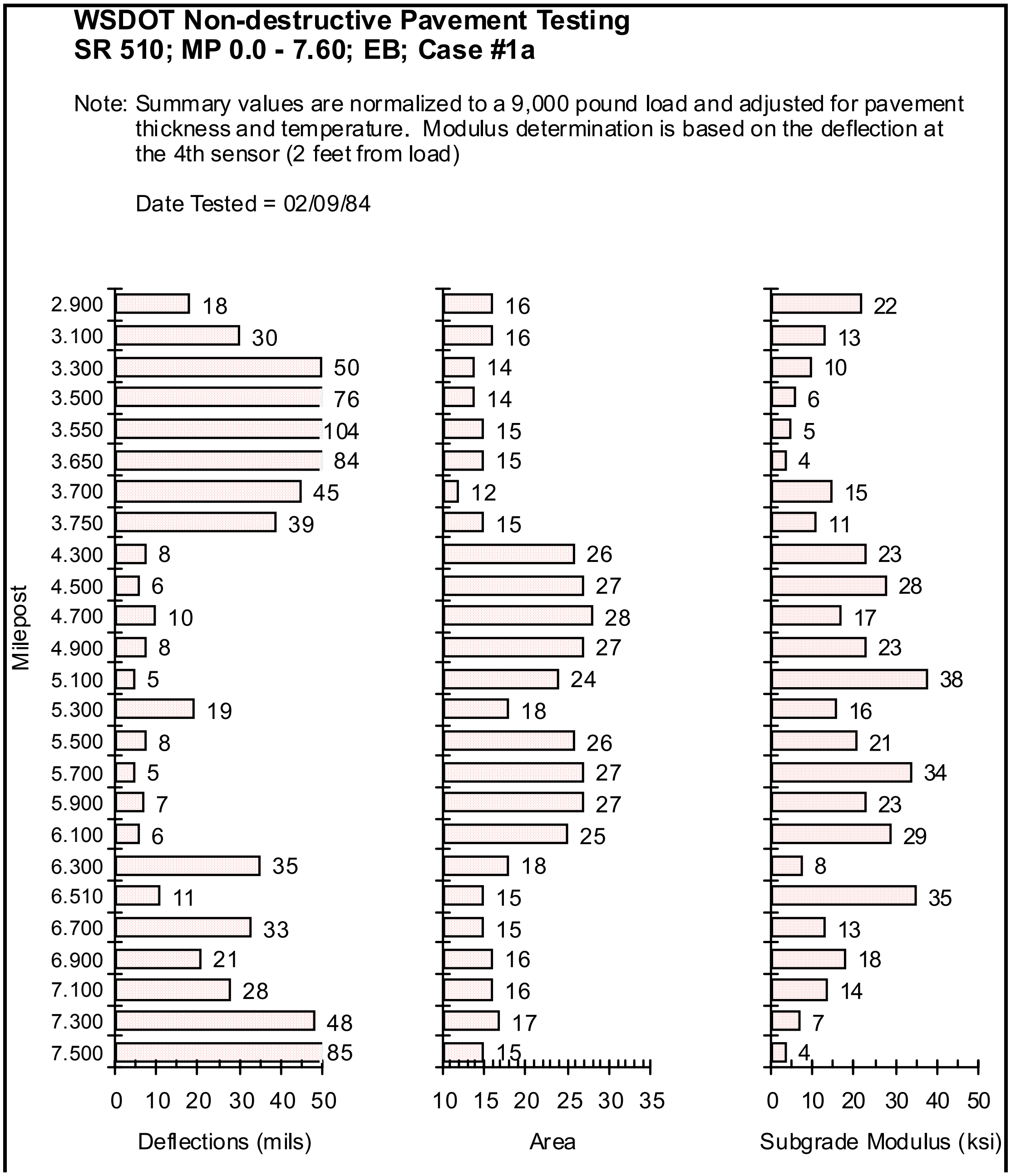


Figure A-1. Illustration of Basic NDT Parameters as used by WSDOT

Figure A-2 shows the development of the normalized area for the Area value using the Trapezoidal Rule to estimate area under a curve.

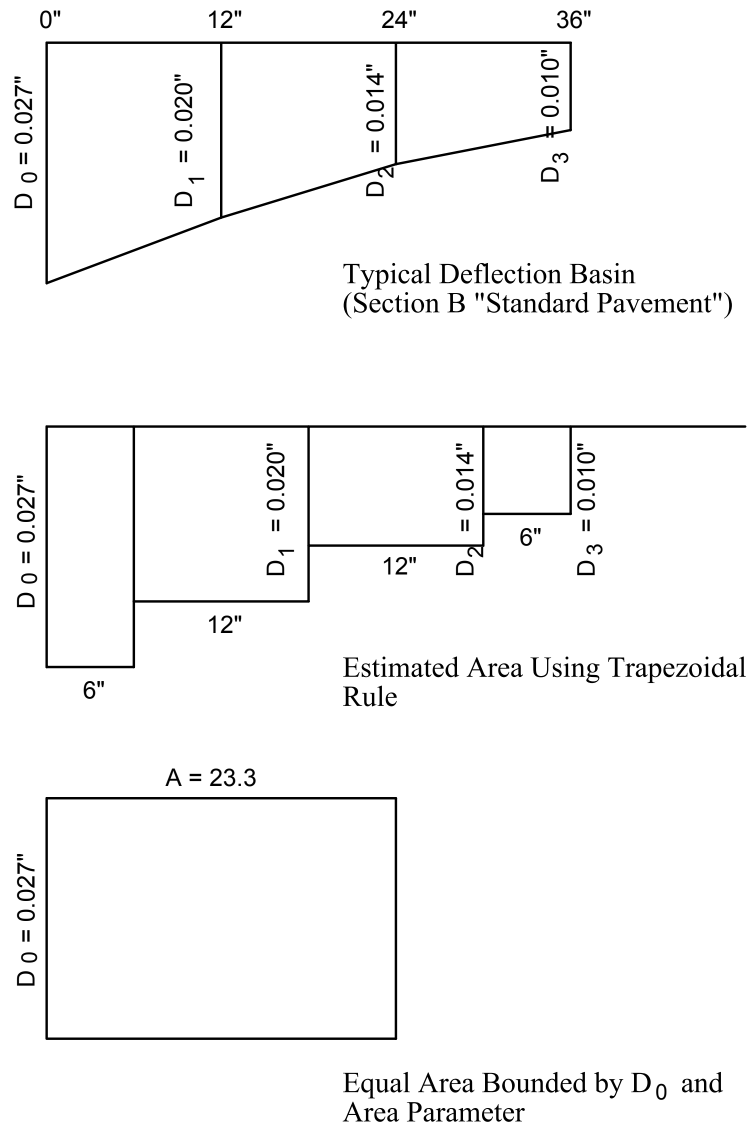


Figure A-2. Computing an Area Parameter

The basic Trapezoidal Rule is:

$$K = h\left(\frac{1}{2}y_0 + y_1 + y_2 + \frac{1}{2}y_3\right)$$

where K = any planar area,
y_0 = initial chord,
y1, y2 = immediate chords,
y3 = last chord, and
h = common distance between chords.

Thus, to estimate the area of a deflected basin using D_0, D_1, D_2, and D_3, and h = 6 inches, then:

K = 6 (D0 + 2D1 + 2D2 + D3)

Further, normalize by dividing by D_0:

$$\text{Area} = \frac{6}{D0}(D0 + 2D1 + 2D2 + D3) \quad \text{or} \quad \text{Area} = 6\left(1 + \frac{2D1}{D0} + \frac{2D2}{D0} + \frac{D3}{D0}\right)$$

Thus, since we normalized by D_0, the Area Parameter's unit of measure is inches (or mm) not in^2 or mm^2 as one might expect.

The maximum value for Area is 36.0 inches and occurs when all four deflection measurements are equal (not likely to actually occur) as follows:

If, $D_0 = D_1 = D_2 = D_3$

Then, Area = 6(1 + 2 + 2 + 1) = 36.0 inches

For all four deflection measurements to be equal (or nearly equal) would indicate an extremely stiff pavement system (like portland cement concrete slabs or thick, full-depth HMA.)

The minimum Area value should be no less than 11.1 inches.

This value can be calculated for a one-layer system which is analogous to testing (or deflecting) the top of the subgrade (i.e., no pavement structure). Using appropriate equations, the ratios of

$$\frac{D_1}{D_0}, \frac{D_2}{D_0}, \frac{D_3}{D_0}$$

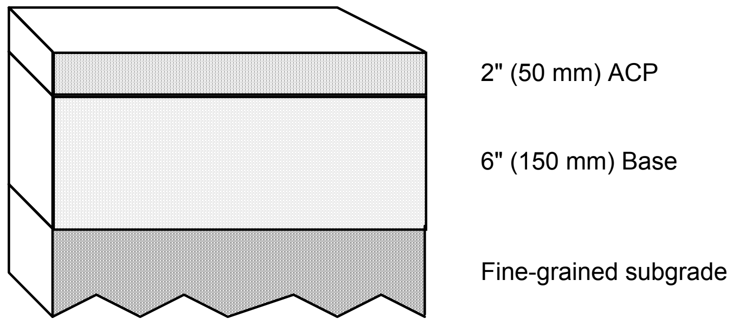
always result in 0.26, 0.125, and 0.083, respectively. Putting these ratios in the Area equation results in

Area = 6(1+ 2(0.26) + 2(0.125) + 0.083) = 11.1 inches

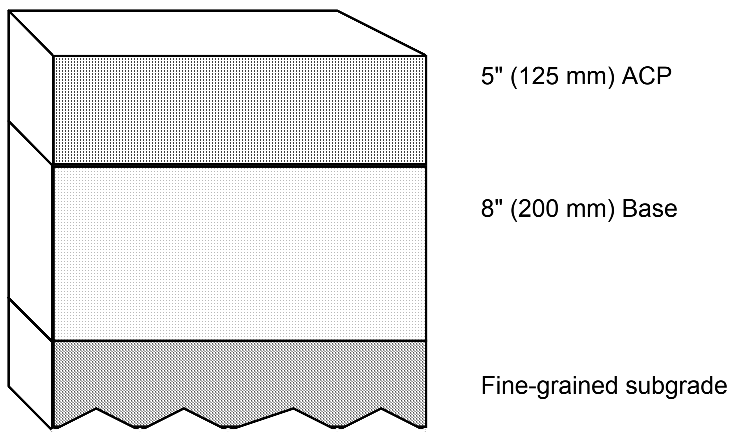
Further, this value of Area suggests that the elastic moduli of any pavement system would all be equal (e.g., $E_1 = E_2 = E_3 = \ldots$). This is highly unlikely for actual, in-service pavement structures. Low area values suggest that the pavement structure is not much different from the underlying subgrade material (this is not always a bad thing if the subgrade is extremely stiff — which doesn't occur very often).

Typical Area values were computed for pavement Sections A, B, and C (refer to Figure A-3) and are shown in Table A-2 (along with the calculated surface deflections (D_0, D_1, D_2, D_3)). The following provides a general guide in the use of Area values obtained from FWD pavement surface deflections.

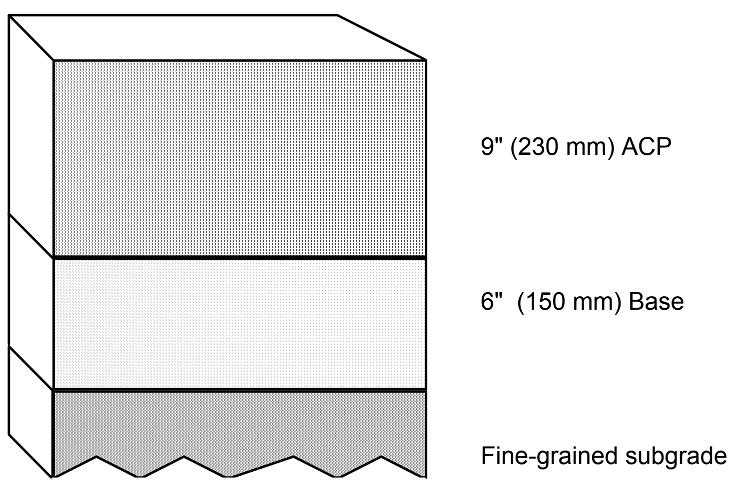
Pavement	**Area**	
	(inch)	**(mm)**
PCCP	24-33	610-840
"Sound" PCC*	29-32	740-810
Thick HMA (≥ 0.35 feet)	21-30	530-760
Thin HMA (< 0.35 feet)	16-21	410-530
BST flexible pavement (relatively thin structure)	15-17	380-430
Weak BST	12-15	300-380



Section A (Thin Thickness Section)



Section B (Medium Thickness Section)



Section C (Thick Section)

Figure A-3. "Typical" Pavement Sections

Table A-2. Estimates of Area from Pavement Sections — Cases A, B, and C

Pavement Cases	Pavement Surface Deflections, inches				Area	
	D_0	D_1	D_2	D_3	(inch)	(mm)
Standard Pavement						
Section A (thin)	0.048	0.026	0.014	0.009	17.1	(434)
Section B (med)	0.027	0.020	0.014	0.010	23.3	(592)
Section C (thick)	0.018	0.015	0.012	0.009	27.0	(686)
Stabilize Subgrade						
Section A (thin)	0.036	0.020	0.013	0.009	18.5	(470)
Section B (med)	0.023	0.017	0.012	0.009	23.5	(597)
Section C (thick)	0.016	0.013	0.011	0.009	27.4	(696)
Asphalt Treated Base						
Section A (thin)	0.021	0.018	0.013	0.010	26.6	(676)
Section B (med)	0.014	0.012	0.010	0.009	28.7	(729)
Section C (thick)	0.012	0.011	0.009	0.008	30.0	(762)
Moisture Sensitivity						
Section A (thin)	0.053	0.026	0.014	0.009	16.1	(409)
Section B (med)	0.033	0.022	0.014	0.009	20.7	(526)
Section C (thick)	0.024	0.018	0.013	0.010	24.0	(610)

Table A-3. Trends of D0 and Area Values

FWD Based Parameter		Generalized Conclusions*
Area	Maximum Surface Deflection (D_0)	
Low	Low	Weak structure, strong subgrade
Low	High	Weak structure, weak subgrade
High	Low	Strong structure, strong subgrade
High	High	Strong structure, weak subgrade

*Naturally, exceptions can occur

Appendix B
Seasonal Temperature for Washington State

INTRODUCTION

The Everpave© program requires seasonal mean air temperatures (winter, spring, summer, fall). A summary of NOAA temperature data was prepared at the WSDOT Materials Laboratory and is included in this appendix.

MEAN SEASONAL TEMPERATURES

The NOAA temperature data is summarized in Table B-1 (monthly, yearly means) and Table B-2 (seasonal means) by NOAA designated "divisions." The means are based on monthly means measured from 1957 through 1989.

EXCEPTIONS

The data contained in Tables B1 and B-2 is very general. Specific project locations may have unique temperature conditions due to local microclimate effects, etc. Local temperature effects should be used if known.

NOAA DIVISIONS

"Typical" weather stations used in developing Tables B-1 and B-2 include:

NOAA Division 1:
Western Olympic Peninsula — Coastal Area

- Neah Bay
- Forks
- Clearwater
- Quinault Ranger Station
- Cushman Dam
- Aberdeen
- Montesano
- Westport
- Raymond
- Long Beach

NOAA Division 2:
Northeast Olympia Peninsula — San Juan Islands

- Port Angeles
- Sequim
- Port Townsend
- Anacortes
- Mount Vernon

NOAA Division 3:
Puget Sound Lowlands

- Blaine
- Bellingham
- Sedro Wooley
- Burlington
- Monroe
- Seattle
- Sea-Tac Airport
- Kent
- Tacoma
- Puyallup
- Olympia
- Centralia
- Bremerton

NOAA Division 4:
Eastern Olympic-Western Cascade Foothills

- Quilcene
- Shelton
- Elma
- Toledo
- Longview
- Vancouver
- Mud Mountain Dam
- Snoqualmie Falls
- Startup
- Arlington
- Concrete

NOAA Division 5:
Western Cascade Mountains

- Ross Dam
- Marblemount Ranger Station
- Stevens Pass
- Snoqualmie Pass
- Stampede Pass
- Paradise
- Cougar

NOAA Division 6:
East Slope of Cascades

- Mazama
- Winthrop
- Stehekin
- Lake Wenatchee
- Plain
- Leavenworth
- Peshastin
- Easton
- Cle Elum
- Naches
- Mount Adams Ranger Station
- Glenwood
- Status Pass

NOAA Division 7: Okanogan-Big Bend

- Tonasket
- Conconully
- Omak
- Methow
- Nespelem
- Chief Joseph Dam
- Grand Coulee Dam
- Chelan
- Mansfield
- Waterville
- Hartline
- Wilbur
- Davenport
- Odessa

NOAA Division 8: Central Basin

- Wenatchee
- Ephrata
- Quincy
- Moses Lake
- Ritzville
- Othello
- Ellensburg
- Yakima
- Wapato
- Sunnyside
- Dallesport
- Goldendale
- Prosser
- Richland/Kennewick/Pasco
- Connell
- Walla Walla

NOAA Division 9:
Northeastern

- Wauconda
- Republic
- Northport
- Colville
- Chewelah
- Newport
- Spokane

NOAA Division 10:
Palouse-Blue Mountain

- Rosalia
- Tekoa
- St. John
- Colfax
- Pullman
- Pomeroy
- Dayton
- Asotin

Table B-1. Monthly and Yearly Mean Temperatures (Years 1957-1989)

Region (NOAA Division)	Monthly Means (°F)												Yearly Mean (°F)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1 West Olympic-Coastal	39.6	42.5	44.2	47.4	52.5	56.7	59.9	60.5	58.0	51.5	44.7	40.8	49.9
2 Northeast Olympic-San Juans	39.2	42.2	44.6	48.3	53.6	57.9	61.0	61.3	57.7	50.8	44.1	40.6	50.1
3 Puget Sound Lowlands	38.6	42.4	45.0	49.2	55.2	60.2	63.9	64.0	59.4	51.8	44.2	39.9	51.1
4 East Olympic-West Cascades Foothills	—	40.7	43.6	47.8	54.0	59.2	63.3	63.4	58.7	50.8	42.7	38.2	49.9
5 Western Cascade Mountains	29.5	33.2	36.3	41.0	48.2	54.5	60.0	60.2	54.7	46.4	36.4	31.4	44.3
6 East Slope of Cascades	25.6	31.4	37.3	44.2	52.3	59.4	65.0	64.6	56.5	46.2	34.7	27.4	45.4
7 Okanogan-Big Bend	24.7	31.8	39.8	47.7	56.2	63.6	69.6	68.9	59.9	48.1	35.6	27.3	47.8
8 Central Basin	29.9	36.9	44.0	50.6	58.8	66.3	72.2	71.2	62.6	51.5	39.6	31.7	51.3
9 Northeastern	24.1	30.6	37.5	45.3	53.8	60.8	66.7	65.9	56.9	45.6	33.6	26.3	45.6
10 Palouse-Blue Mountains	29.8	36.3	41.5	47.6	55.2	62.4	68.8	68.3	60.0	49.7	38.7	31.9	49.2

Table B-2. Seasonal Mean Temperatures (Years 1957-1989)

Region (NOAA Division)	Seasonal Mean Temperature (°F)			
	Spring • March • April • May	**Summer** • June • July • August	**Fall** • September • October • November	**Winter** • December • January • February
1 West Olympic-Coastal	48.0	59.0	51.4	41.0
2 Northeast Olympic-San Juans	48.8	60.1	50.9	40.7
3 Puget Sound Lowlands	49.8	62.7	51.8	40.3
4 East Olympic-West Cascades Foothills	48.5	62.0	50.7	38.6
5 Western Cascade Mountains	41.8	58.2	45.8	31.4
6 East Slope of Cascades	44.6	63.0	45.8	28.1
7 Okanogan-Big Bend	47.9	67.4	47.9	27.9
8 Central Basin	51.1	69.9	51.2	32.8
9 Northeastern	45.5	64.5	45.4	27.0
10 Palouse-Blue Mountains	48.1	66.5	49.4	32.7

Appendix C
Moduli Seasonal Variation

UNSTABILIZED MODULI

Based on FWD deflections obtained over a three-year period (1985 to 1987), the ratio of the moduli for the different seasons were estimated. These initial estimates are shown in Table C-1.

The data in Table C-1 suggest a greater variation in the base course (seasonally) than the subgrade. Clearly, this phenomenon can be quite site-specific. As such, the ratios are only, at best, "rules of thumb."

For dense graded base materials, numerous sources have suggested that moisture levels exceeding 85 percent of saturation can result in significant moduli reductions.

SEASONAL TEMPERATURES

Seasonal air temperatures are required inputs. These temperatures are used to adjust the AC moduli seasonally. These mean monthly air temperatures (MMAT) are converted to mean monthly pavement temperatures (MMPT) by use of the following equation:

$$MMPT = MMAT\left(1 + \left(\frac{1}{z + 4}\right)\right) - \left(\frac{34}{z + 4}\right) + 6$$

where MMPT = mean monthly pavement temperature (°F),
MMAT = mean monthly air temperature (°F), and
z = depth below pavement surface (inch).

For example, if the MMAT = 65 °F and z = 3 inch, then

$$= (65)\left(1 + \left(\frac{1}{3 + 4}\right)\right) - \left(\frac{34}{3 + 4}\right) + 6$$

$$= 75.4\ °F$$

Table C-1. Design Moduli Ratios for Western and Eastern Washington Base Course and Subgrade Materials[1]

Region		Spring	Summer	Fall	Winter
		Seasonal Period			
Western Washington	Climate:	Cool/Wet	Warm/Dry	Cool/Damp	Cool/Wet
	Months:	March April May	June July August September	October November	December January February
	Base	0.85	1.00	0.90	0.75
	Subgrade	0.85	1.00	0.90	0.85
Eastern Washington	Climate:	Thaw	Hot/Dry	Cool/Dry	Freeze
	Months:	February March April May	June July August September	October November December	January
	Base	0.65	1.00	0.90	1.10
	Subgrade	0.90	1.00	0.90	1.10

[1]Design moduli ratios are appropriate for use if stress sensitive moduli relationships are not used. If stress sensitive moduli relationships are used (e.g., $E = k_1 \theta^{k_2}$), then use of these ratios may overestimate seasonal effects.

Appendix D
Case Study Photographs

Photo 1. MP 207.90, NB lane, area of longitudinal and alligator cracking

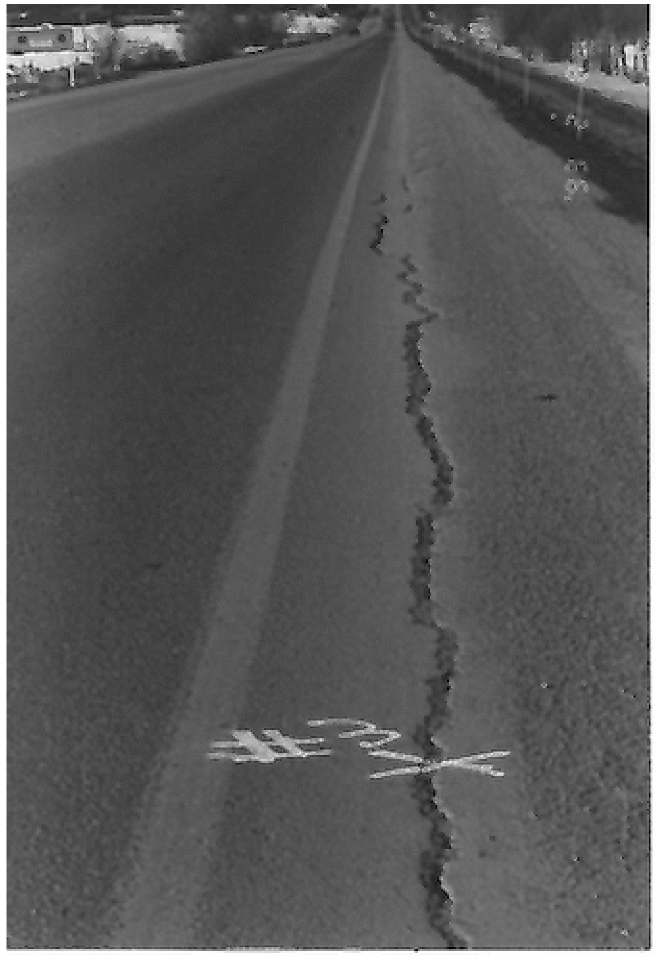


Photo 2. MP 208.00, NB shoulder cracking, occurring from MP 207.82 to MP 208.29

Photo 3. MP 208.07, cracking within the NB shoulder

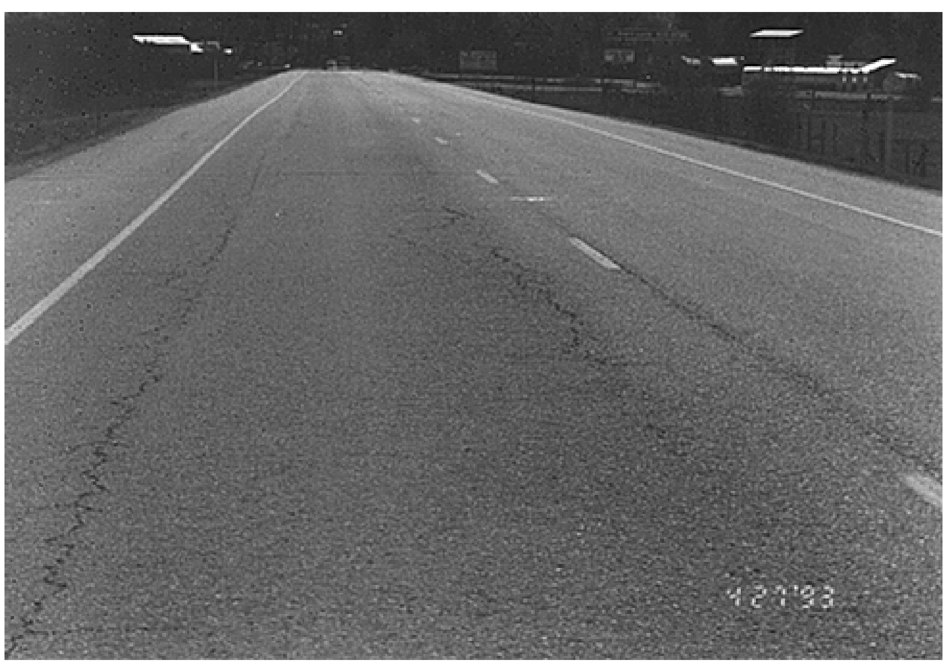


Photo 4. MP 208.18, NB lane, longitudinal cracking progressing to alligator cracks

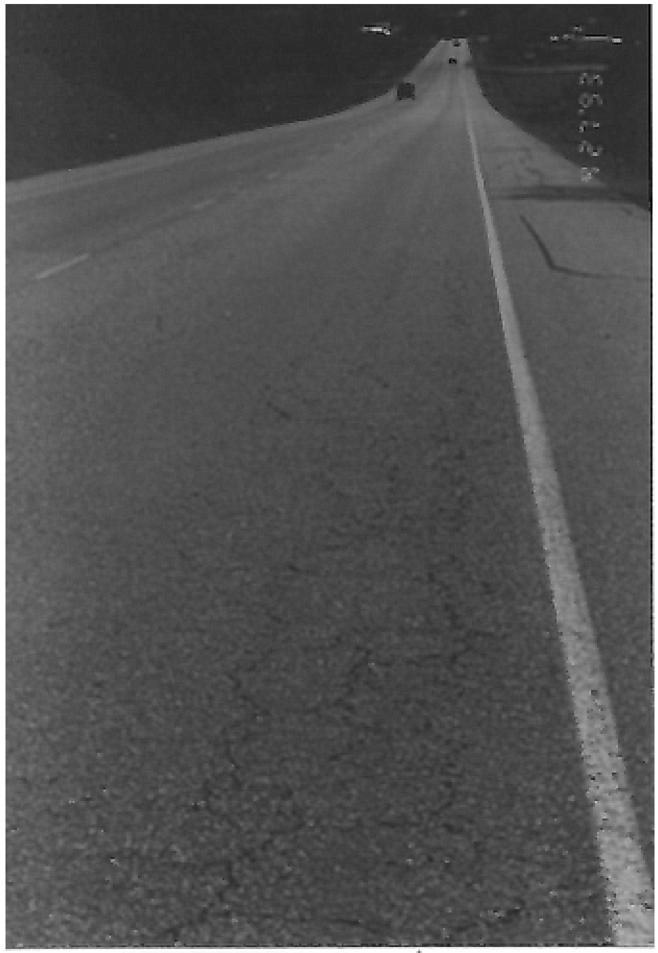


Photo 5. MP 208.56, NB lane, typical alligator cracking within the wheel paths

Photo 6. MP 208.56, SB shoulder (typical from MP 208.52 to MP 208.56)

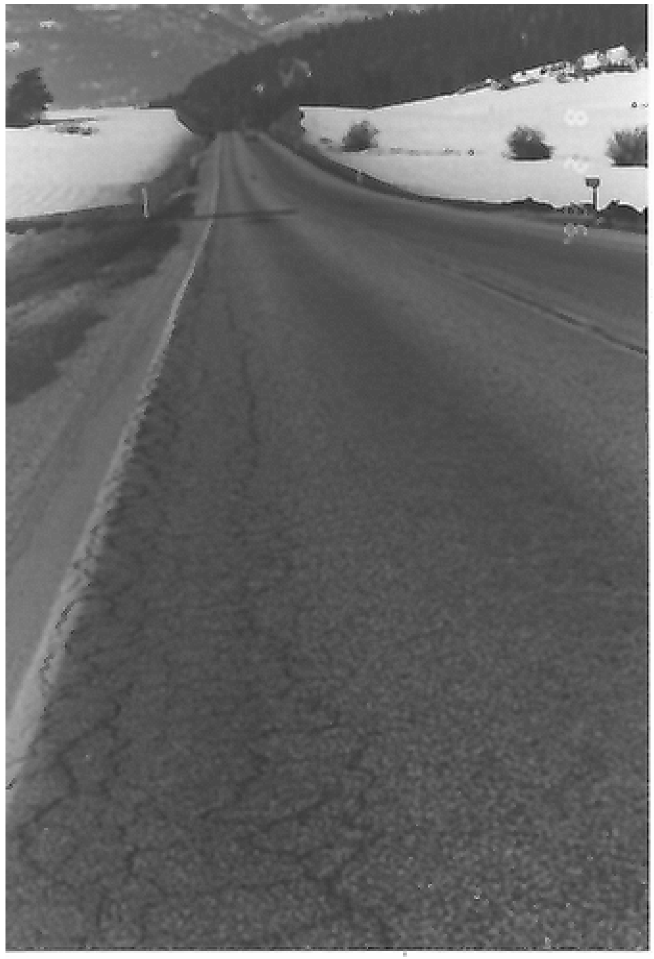


Photo 7. MP 209.00, SB lane, looking north, alligator cracking within outside wheel path

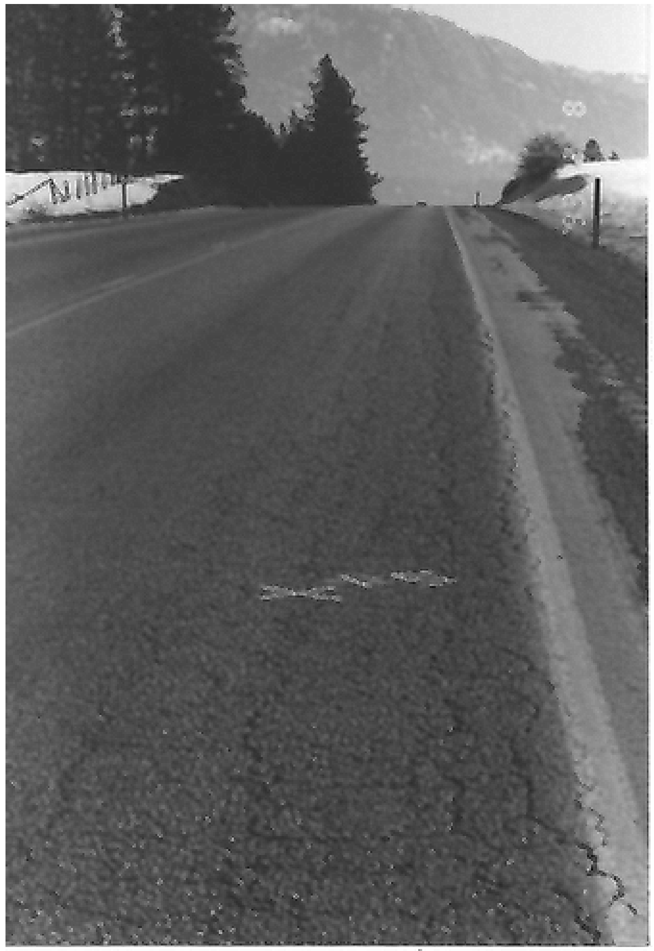


Photo 8. MP 209.00, SB lane, looking south, alligator cracking within outside wheel path

Photo 9. MP 209.05, SB lane, frost heave causing 150 to 200 mm of differential movement

Photo 10. MP 209.40, NB lane, alligator cracking, which occurs in both wheel paths

Photo 11. MP 209.60, NB lane, alligator and longitudinal cracking

Photo 12. MP 209.82, NB lane, frost heave that affects the NB lane and shoulder

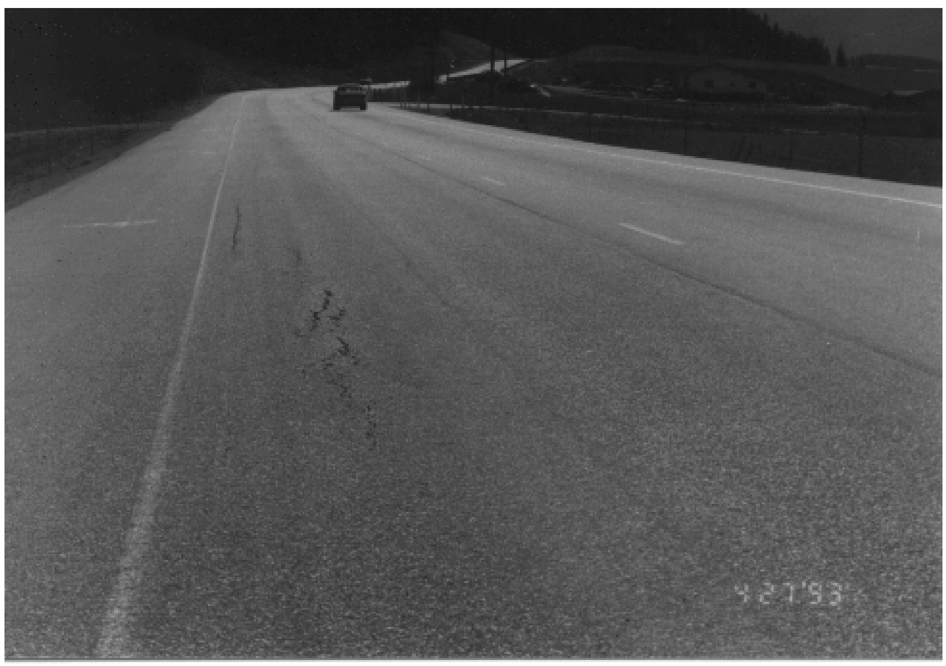


Photo 13. MP 211.91, NB lane, isolated distress occurring from MP 210.55 to MP 212.67

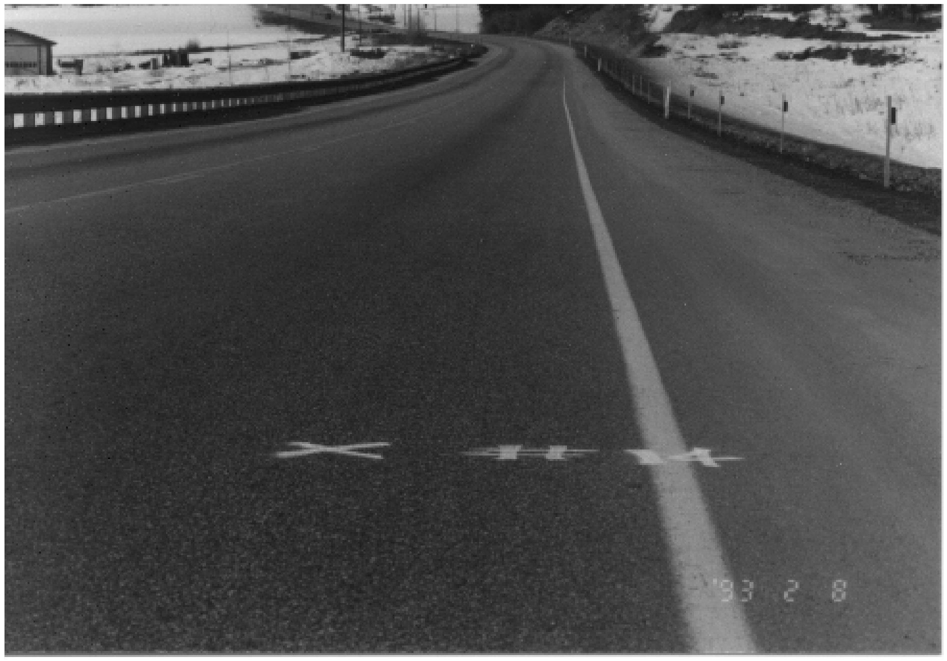


Photo 14. MP 211.50, NB lane, pavement is generally in good condition

Appendix E
Asphalt institute Component Analysis (MS-1)

This component analysis design approach (termed "effective thickness" by the Asphalt Institute) uses relationships between subgrade strength, pavement structure, and traffic [17]. The existing structural integrity of the pavement is converted to an equivalent thickness of HMA, which is then compared to that required for a new design. The structural evaluation procedure developed by the Asphalt Institute allows for determining the required thickness of HMA overlay or to estimate the length of time until an overlay is required.

The essential parts of this overlay design procedure will be briefly described:

(a) Subgrade analysis,
(b) Pavement structure thickness analysis, and
(c) Traffic analysis

Subgrade Analysis

Testing of the subgrade materials is encouraged even if original design records are available. The resilient modulus (M_R), soaked CBR or R-value tests appear to be the easiest to use with this procedure. For actual design, the design strength of the subgrade must be characterized in terms of resilient modulus. Associated correlations for CBR and R-value are:

M_R (psi) = 1500 (CBR)

= 1155 + 555 (R-value)

If test data in terms of M_R, CBR, or R-value are not available, subgrades can be placed into one of three classes for design purposes as follows:

(a) Poor soils. Soft and plastic when wet, generally composed of silts or clays. Typical properties: M_R = 4,500 psi, CBR = 3, R-value = 6.

(b) Medium soils. Include soils such as loams, silty sands, and sand-gravels which contain moderate amounts of clay and silt. These soils can be expected to lose only a moderate amount of strength when wet. Typical properties: M_R = 12,000 psi, CBR = 8, R-value = 20.

(c) Good soils. These soils can be expected to retain a substantial amount of their strength when wet and include clean sands and sand-gravels. Typical properties: M_R = 25,000 psi, CBR = 17, R-value = 43.

Assuming that at least six to eight individual subgrade tests are available, a conservative value is chosen as a function of the design traffic (ESALs). To do this a plot is prepared of the percent equal to or greater than (y axis) versus resilient modulus test results (x axis). Basically, one must create a cumulative frequency plot. Following this, the design subgrade resilient modulus is selected from the plot as follows:

Design ESALs	Design Subgrade Percentile Value (%)
10,000 or less	60
10,000 to 1,000,000	75
greater than 1,000,000	87.5

For more information, refer to The Asphalt Institute's MS-1 (September 1981 Edition).

Pavement Structure Thickness Analysis

The goal of this portion of the design method is to determine the "Effective Thickness (Te)" of the existing pavement structure. The Asphalt Institute has two approaches that can be used; only one will be illustrated here. First, the significant pavement layers are identified and their condition determined. Second, "Conversion Factors" are selected for each layer (judgment by the designer is very important at this point). Third, the Effective Thickness for each layer is determined by multiplying the actual layer thickness by the appropriate Conversion Factor. The Effective Thickness of the complete pavement structure is the sum of the individual Effective Thicknesses. Typical layer thickness Conversion Factors are shown in Table E-1Table .

Traffic Analysis

The Asphalt Institute treatment of traffic includes consideration of volume composition, and axle weights, with the goal being to develop the equivalent number of 18,000 lb equivalent single axle loads (ESALs).

Table E-1. Example of Asphalt Institute Conversion Factors for Estimating Thickness of Existing Pavement Components to Effective Thickness [17]

Description of Layer Material	Conversion Factor*
1. Native subgrade	0.0
2. a. Improved subgrade - predominantly granular materials b. Lime modified subgrade of high PI soils	0.0
3. a. Granular subbase or base - CBR not less than 20 b. Cement modified subbases and bases constructed from low PI soils	0.1 - 0.3
4. a. Cement or lime-fly ash bases with pattern cracking b. Emulsified or cutback asphalt surfaces and bases with extensive cracking, rutting, etc. c. PCC pavement broken into small pieces	0.3 - 0.5
5. a. Hot mix asphalt surface and base that exhibit extensive cracking	0.5 - 0.7
6. a. Hot mix asphalt - generally uncracked b. PCC pavement - stable, undersealed and generally uncracked pavement	0.9 - 1.0
7. Other categories of pavement layers listed in Reference 17	

*Equivalent thickness of new HMA

To estimate the ESALs for the overlay design period, at least two approaches can be used, depending on availability of site-specific traffic information. One approach provides broad traffic classifications and the associated 18,000 lb (80 kN) ESAL amounts, as illustrated in Table E-2. The second approach includes the use of "truck factors" along with the number and type of trucks that are expected to use the facility. This approach can accommodate a wide variety of truck information ranging from only an estimate of the percent of the Average Daily Traffic (ADT) that constitutes trucks to estimates of trucks broken into the categories of single and multi-units (as illustrated by "vehicle type" in Table E-2).

The term "truck factor" represents the average 18 KESAL per truck. Truck factors are shown in Table E-3 for a variety of vehicle types, with the average being 0.4 ESAL per truck averaged over all highway and truck types. Thus, if a given "average" highway is expected to have 1,000,000 trucks during the design period, the resulting ESALs would be 400,000.

Table E-2. Asphalt Institute Traffic Classifications [17]

Type of Street or Highway	Estimated 18,000 lb (80 kN) ESALs
▪ Parking lots ▪ Light traffic residential streets and farm roads	5,000
▪ Residential streets ▪ Rural farm and residential roads	10,000
▪ Urban and rural minor collectors	100,000
▪ Urban minor arterial and light industrial streets ▪ Rural major collector and minor arterial highways	1,000,000
▪ Urban freeways and other principal arterial highways ▪ Rural interstate and other principal arterial highways	3,000,000
▪ Some interstate highways ▪ Some industrial roads	10,000,000

Table E-3. Average Truck Factors Compiled from FHWA Data [17]

	Truck Factors				
Vehicle Types	Rural Highways			Urban Highways	Combined
	Interstate	Other	All	All	All
1. Single-units					
(a) 2-axle, 4-tire	0.02	0.02	0.03	0.03	0.02
(b) 2-axle, 6-tire	0.19	0.21	0.20	0.26	0.21
(c) 3-axles or more	0.56	0.73	0.67	1.03	0.73
(d) All single-units	0.07	0.07	0.07	0.09	0.07
2. Tractor semi-trailers					
(a) 3-axle	0.51	0.47	0.48	0.47	0.48
(b) 4-axle	0.62	0.83	0.70	0.89	0.73
(c) 5-axles or more	0.94	0.98	0.95	1.02	0.95
(d) All multiple units	0.93	0.97	0.94	1.00	0.95
3. All trucks	0.49	0.31	0.42	0.30	0.40

Appendix F
case study photographs

Photo 1. MP 0.23 SB, full depth longitudinal crack at the core location

Photo 2. MP 0.29 NB, beginning of curbed section through the town of Morton

Photo 3. MP 0.44 SB, transverse cracking at the core location (marked with an "X")

Photo 4. MP 0.99 NB, core taken at full depth longitudinal crack. This section has numerous Maintenance patches

Photo 5. MP 2.83 SB, pavement in relatively good condition, pavement rutting is present

Photo 6. MP 3.68 NB, core taken at localized pavement distress

Photo 7. MP 6.48 NB, highly distressed pavement

Photo 8. MP 7.18 SB, pavement has several maintenance patches and rutting

Photo 9. MP 9.96 SB, location of freeze/thaw damage, which is typical of this section for several km. Damage could be caused by snowplows and heavy truck traffic

Photo 10. MP 9.98 NB, location of wide longitudinal cracking. Damage may be caused by snowplows

Photo 11. MP 15.08 NB, Maintenance has placed several HMA or BST patches

Appendix G
Washington State Climate Data

Figure G-1 and Table G-1 provide an overview of Washington State mean FI data (summarized for 1951 to 1980). Figure G-2 is a contour map of Washington for design FI data. The FI contours for both Figure G-1 and Figure G-2 are only approximate. FI's should be obtained at specific sites (projects) if possible.

DEPTH OF FREEZE — IMPLICATIONS FOR PAVEMENT DESIGN

One of the implications of the preceding calculations, FI contour maps, etc., is that the total depth of the pavement structure should be influenced in some way by such results. For example, several SHAs use the rule-of-thumb that the pavement structure should equal at least one-half of the expected depth of freeze. To this end, Figure G-7 and Figure G-4 were prepared. These contour maps show the expected depths of freeze corresponding to the design FI (refer to Figure G-2) for fine-grain soil (Figure G-7) and coarse-grain soil (Figure G-4). The fine-grain soil calculations assumed a γ_d = 100 lb/ft^3 (1600 kg/m^3) and water content = 20 percent. The coarse-grain soil calculations assumed a γ_d = 130 lb/ft^3) (2080 kg/m^3) and water content = 5 percent.

Figure G-5 shows contours of measured depths of freeze as determined during the extremely cold winters of 1949 and 1950 (letter correspondence from B. Tremper, State Materials and Research Engineer to W.A. Bugge, Director of Highways, dated, October 17, 1951). The freeze depths were measured in dug holes often along the edge of the main lanes. The freeze depths were measured during February 1949 and January and February 1950 (a total of 401 holes). Figure G-5 is, in general, similar to Figure G-7 (calculated freeze depths based on Design Freezing Indices and fine-grained soil) with the exception of the Olympic Peninsula which is closer to those results shown in Figure G-4 (coarse-grained soil). Some observations made by Highway Department personnel during the winters of 1949 and 1950:

- Greatest freeze depths were observed in sandy or gravelly soils
- Snow or ice cover substantially reduced the depth of the freeze
- Frost heaving
  - Most heaving observed in coastal areas (higher availability of water)
  - Heaving somewhat infrequent in Eastern Washington but more severe when it did occur (again, likely related to the availability of water (or lack of))
  - Maximum differential heave of 9 inch (225 mm) noted in North Central Region
  - Silty sands showed the largest amount of ice lenses
- Specific Region Comments
  - Northwest Region: Maximum frost depth was measured between Issaquah and North Bend 30 inches (0.8 m). On Camano Island, a 20 inches (0.5 m) frost depth was measured. Maximum differential heave was 4 inches (100 mm) (several district locations).
  - North Central Region: Maximum depth of freeze was 36 inches (0.9 m) measured in 1949 (Wauconda Summit) and 51 inches (1.3 m) in 1950 (between Brewster and Okanogan).
- Olympic Region: Maximum depth of freeze in 1949 was 24 inches (0.6 m) and 17 inches (0.4 m) in 1950.
- Southwest Region: Maximum frost depth was 20 inches (0.5 m) in 1950.

- South Central Region: Maximum frost depth was 30 inches (0.8 m) measured in 1950 with a district-wide average of 24 inches (0.6 m) Differential heave of 6 inches (150 mm) was noted.
- Eastern Region: The maximum depth of freeze was 43 inches (1.1 m) with a district average of 35 inches (0.9 m) measured in 1949. In 1950, the maximum was 48 inches (1.2 m) with a district average of 28 inches (0.7 m)

The statement about SHA frost design needs a bit of explanation. A survey conducted during 1985 [18] revealed the following from several "northern" states:

Agency	Use of Frost Protection in Thickness Design
• Alaska DOT	• More than 50 percent but not full
• Maine DOT	• More than 50 percent but not full
• Montana DOT	• Frost protection not included in design
• North Dakota DOT	• Frost protection not included in design
• Oregon DOT	• More than 50 percent but not full
• Washington DOT	• Depth > 50 percent of maximum frost depth expected

Thus, states such as Alaska, Maine, Oregon, and Washington use knowledge about expected frost depths in the design process. Presumably, limiting the depth of frost into the subgrade soils limits, adequately, the potential for frost heave and thaw weakening for most projects/locations.

The above percentages (pavement structural section as a percentage of expected frost depth) are further reinforced by Japanese practice. Kono et al. [19] reported in 1973 that on the island of Hokkaido the pavement structure is set at 70 percent of the expected frost penetration (the pavement materials are non-frost susceptible).

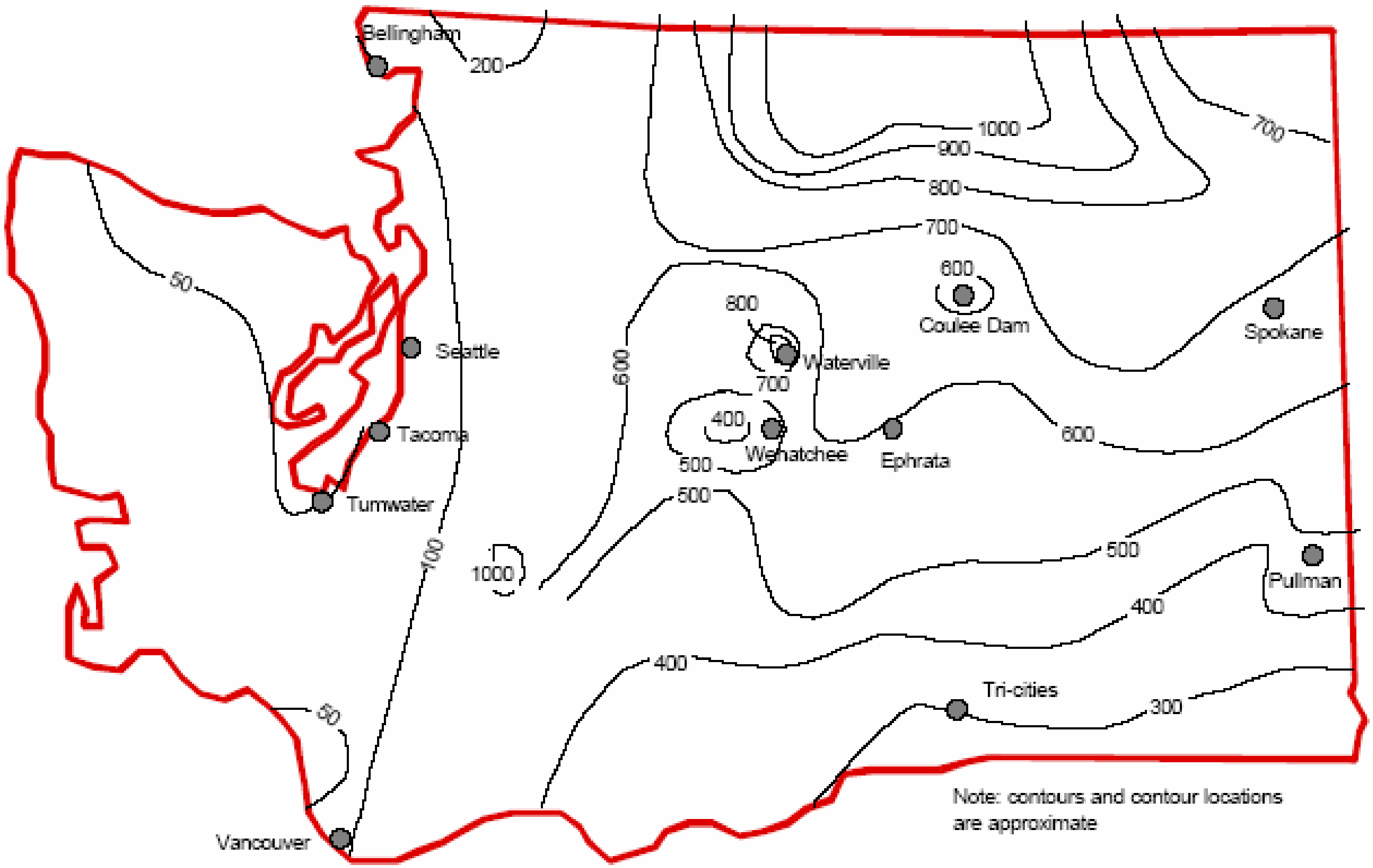


Figure G-1. Mean Annual Freezing Index Contour Map

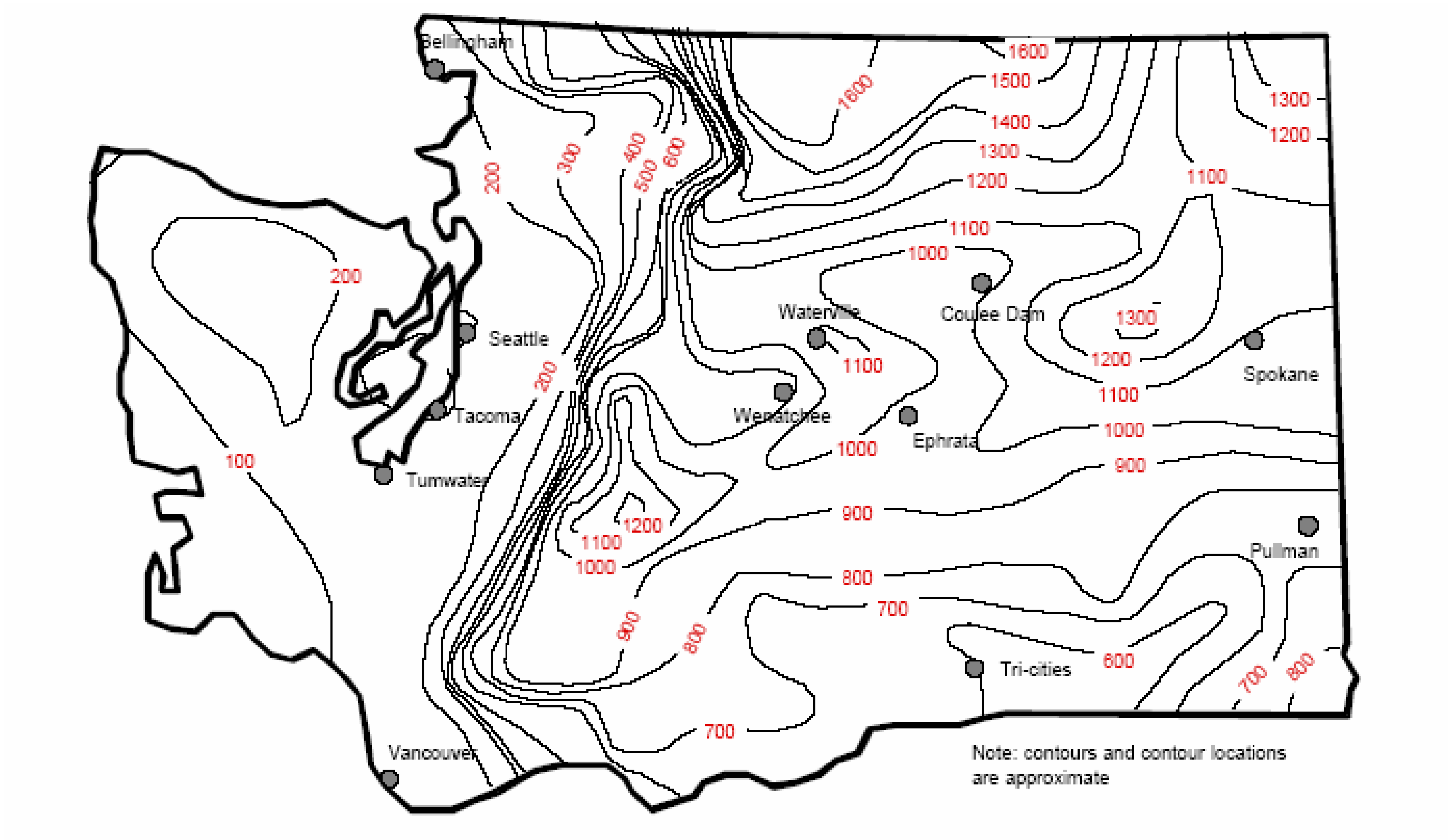


Figure G-2. Design Annual Freezing Index Contour Map

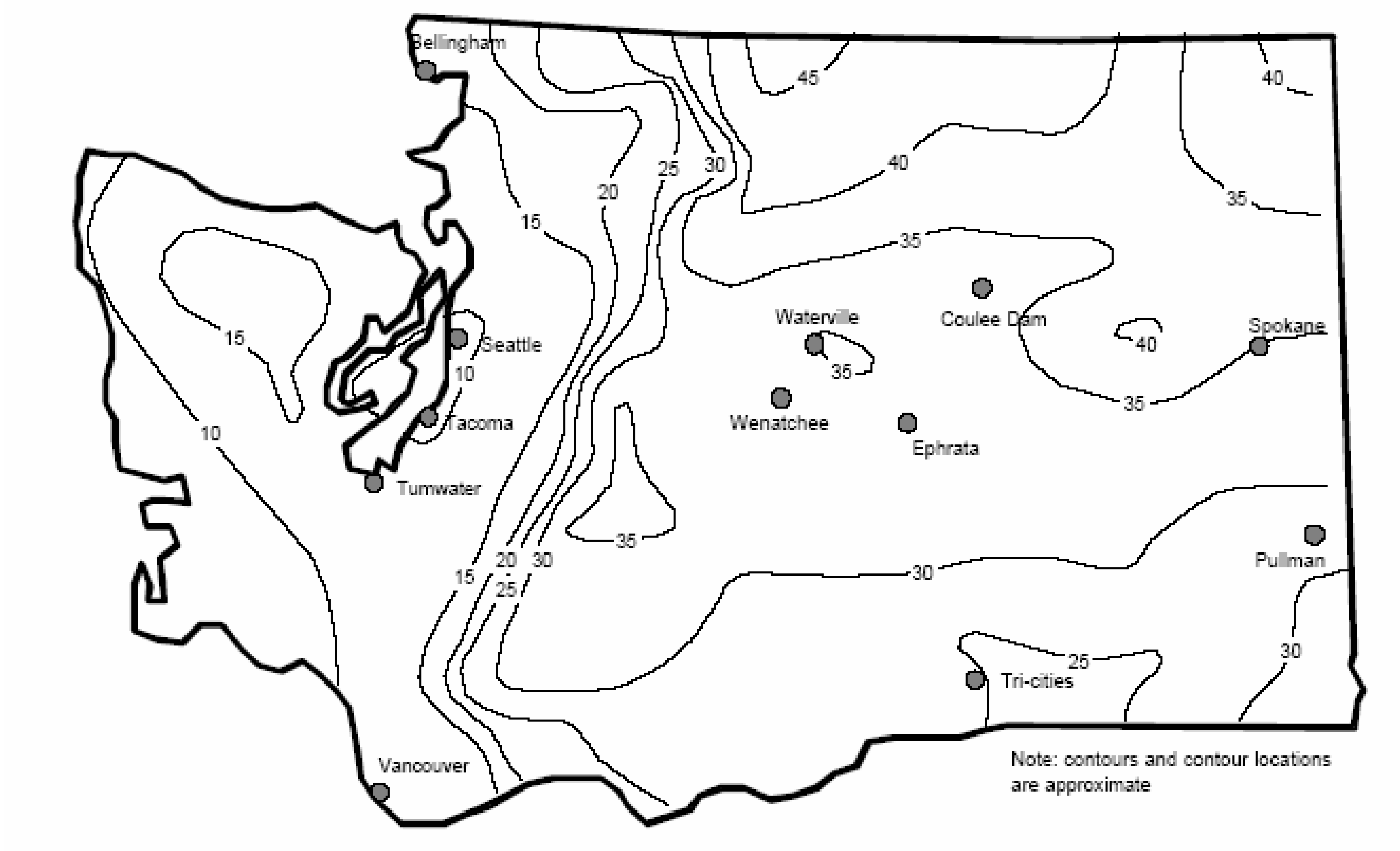


Figure G-3. Frost Depth Contour Map (inches) for Fine Grained Soil (dry density = 100 pcf, wc = 20%)

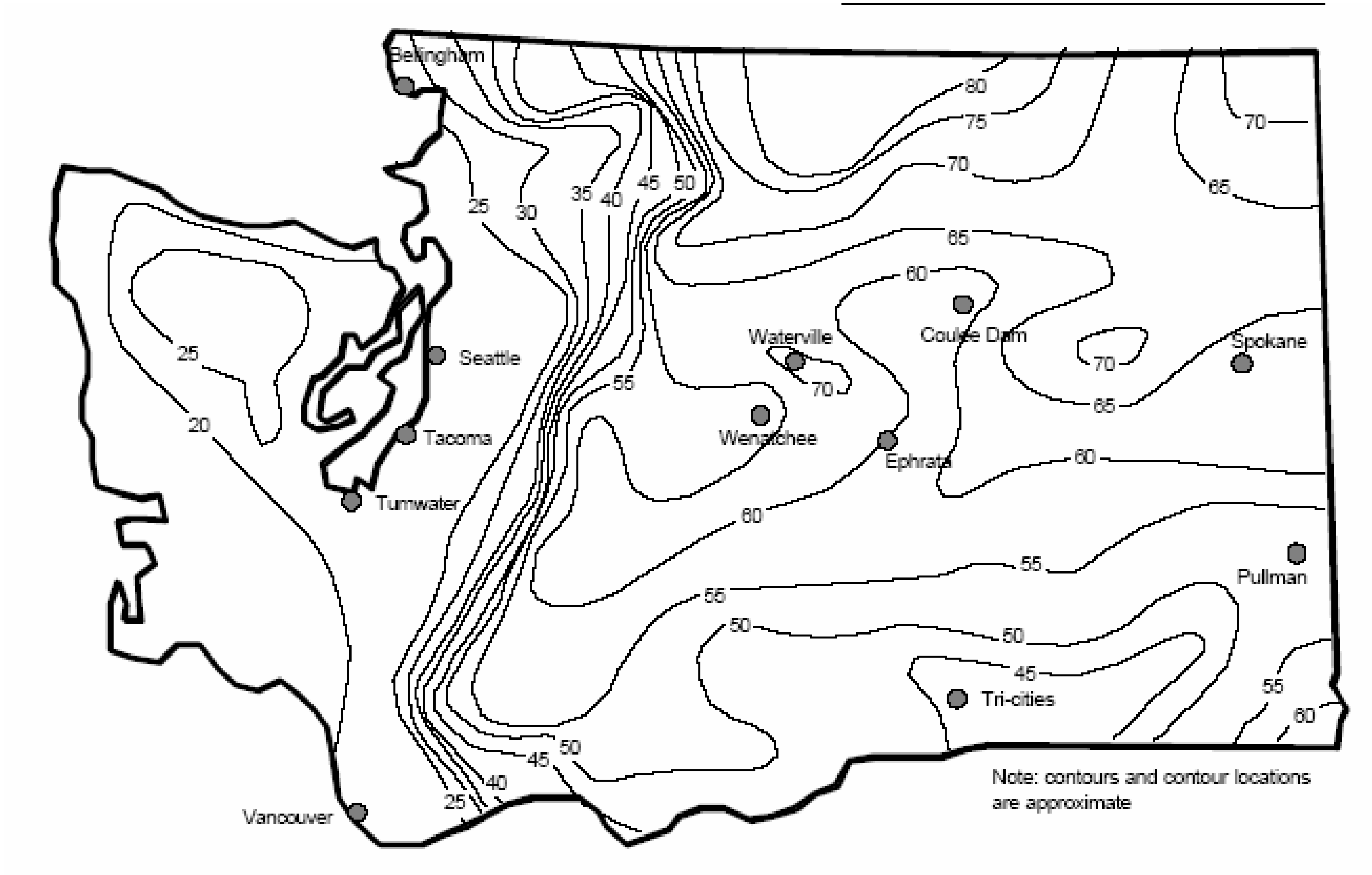


Figure G-4. Frost Depth Contour Map (inches) for Coarse Grained Soil (dry density = 130 pcf, wc = 5%)

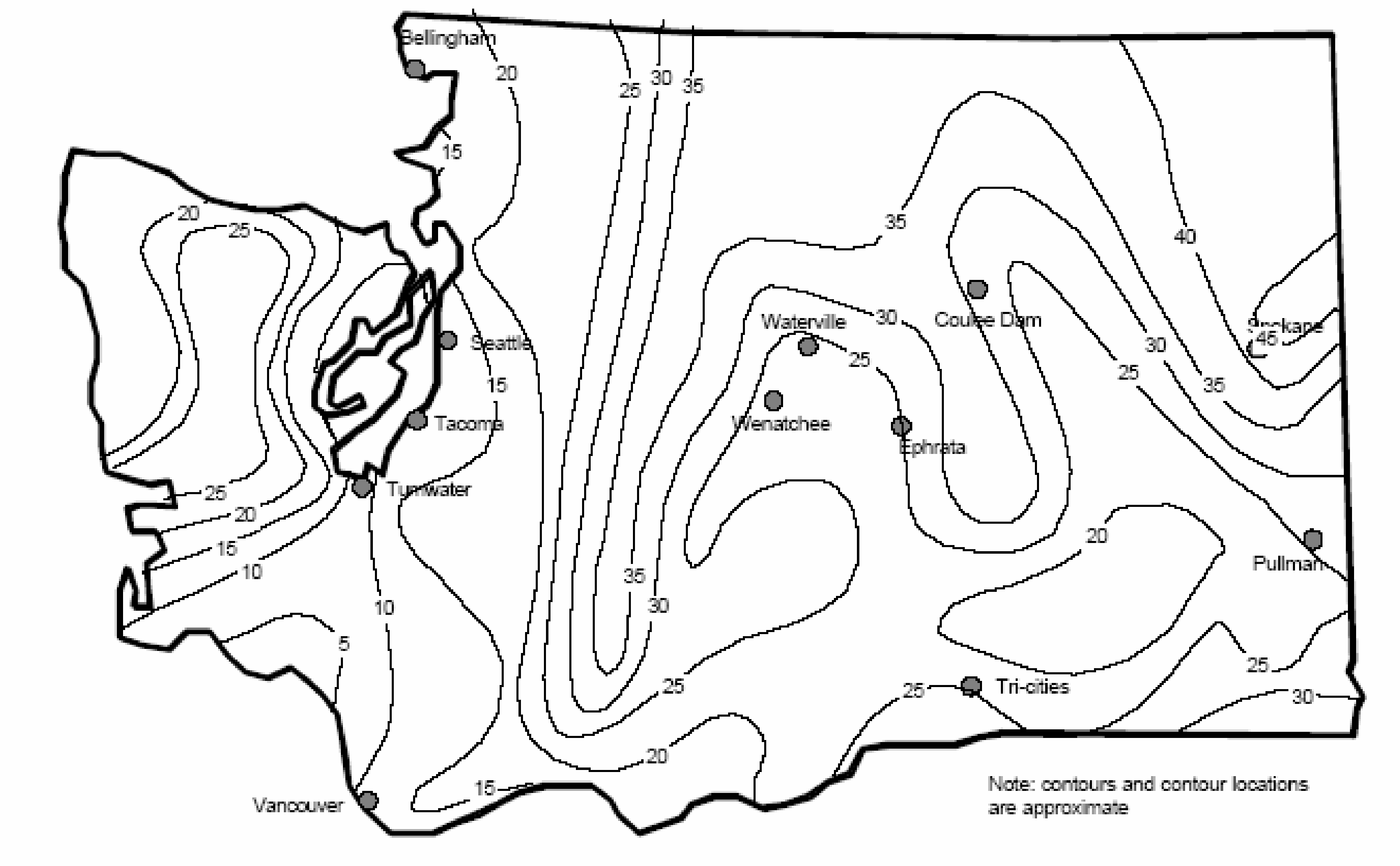


Figure G-5. Frost Depth Contour Map (inches) Based on Field Measurements – Winters of 1949 and 1950

Table G-1. Mean Freezing Indices for Washington State (based on temperature data from 1951 through 1980)

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Aberdeen	18	0	0	0	0	0	0	0	0	0	0	6	24
Anacortes	30	0	0	0	0	0	0	0	0	0	0	7	37
Battle Ground	45	0	0	0	0	0	0	0	0	0	0	8	53
Bellingham	59	6	0	0	0	0	0	0	0	0	0	18	83
Bellingham Airport	67	7	0	0	0	0	0	0	0	0	0	23	97
Bickleton	231	68	18	7	0	0	0	0	0	0	0	42	120
Blaine	68	7	0	0	0	0	0	0	0	0	0	25	100
Bremerton	20	0	0	0	0	0	0	0	0	0	0	8	28
Buckly	40	8	0	0	0	0	0	0	0	0	0	17	65
Cedar Lake	85	26	10	0	0	0	0	0	0	0	9	140	70
Centralia	29	0	0	0	0	0	0	0	0	0	0	8	37
Chelan	262	110	10	0	0	0	0	0	0	0	29	149	560
Chewelah	339	150	35	0	0	0	0	0	0	0	62	216	802
Chief Joseph Dam	293	136	17	0	0	0	0	0	0	0	34	175	655
Clearbrook	103	13	0	0	0	0	0	0	0	0	6	39	161
Clearwater	22	0	0	0	0	0	0	0	0	0	0	6	28
Cle Elum	268	94	22	0	0	0	0	0	0	0	48	151	583
Colfax	226	45	9	0	0	0	0	0	0	0	29	99	408
Colville	321	119	29	0	0	0	0	0	0	0	75	221	765
Concrete	57	9	0	0	0	0	0	0	0	0	0	18	84
Coulee Dam	284	107	14	0	0	0	0	0	0	0	35	155	595
Coupeville	28	0	0	0	0	0	0	0	0	0	0	11	39
Dallesport Airport	179	14	0	0	0	0	0	0	0	0	8	52	253
Davenport	315	133	25	0	0	0	0	0	0	0	66	198	737
Dayton	206	30	0	0	0	0	0	0	0	0	18	61	315
Diablo Dam	126	23	9	0	0	0	0	0	0	0	10	54	222
Electron Headworks	78	20	8	0	0	0	0	0	0	0	8	40	154
Elma	22	0	0	0	0	0	0	0	0	0	0	7	29
Elwha Rngr Station	47	6	0	0	0	0	0	0	0	0	0	14	67
Ephrata Airport	285	98	5	0	0	0	0	0	0	0	41	167	596
Everett	35	0	0	0	0	0	0	0	0	0	0	11	46
Forks	22	5	0	0	0	0	0	0	0	0	0	10	37
Glenoma	47	9	0	0	0	0	0	0	0	0	0	17	73
Grapeview	17	0	0	0	0	0	0	0	0	0	0	7	24
Hatton	266	54	0	0	0	0	0	0	0	0	43	124	487
Hoquiam	15	0	0	0	0	0	0	0	0	0	0	9	24
Kennewick	202	26	0	0	0	0	0	0	0	0	18	54	300
Kent	28	0	0	0	0	0	0	0	0	0	0	8	36
Kid Valley	43	8	0	0	0	0	0	0	0	0	0	16	67

Table G-1. Freezing Indices for Washington State, continued

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Lacrosse	248	42	0	0	0	0	0	0	0	0	30	103	423
Landsburg	48	8	0	0	0	0	0	0	0	0	0	15	71
Laurier	350	121	35	0	0	0	0	0	0	0	82	238	826
Lind	266	62	0	0	0	0	0	0	0	0	43	126	497
Longview	36	0	0	0	0	0	0	0	0	0	0	6	42
Millin Reservoir	42	6	0	0	0	0	0	0	0	0	0	13	61
Monroe	38	0	0	0	0	0	0	0	0	0	0	14	52
Moses Lake	292	92	0	0	0	0	0	0	0	0	50	153	587
Mt. Adams Rngr Sta.	197	48	22	0	0	0	0	0	0	0	31	90	388
Moxee City	263	63	0	0	0	0	0	0	0	0	31	134	491
Mud Mtn. Dam	56	15	5	0	0	0	0	0	0	0	0	21	97
Newhalem	88	18	6	0	0	0	0	0	0	0	7	39	158
Newport	306	112	49	0	0	0	0	0	0	0	73	199	739
Northport	275	94	19	0	0	0	0	0	0	0	46	174	608
Oakville	35	0	0	0	0	0	0	0	0	0	0	10	45
Odessa	273	82	9	0	0	0	0	0	0	0	41	144	549
Olga	29	0	0	0	0	0	0	0	0	0	0	11	40
Olympia	31	5	0	0	0	0	0	0	0	0	0	15	51
Omak	344	175	28	0	0	0	0	0	0	0	67	234	848
Othello	276	64	0	0	0	0	0	0	0	0	35	125	500
Palmer	58	14	5	0	0	0	0	0	0	0	0	25	102
Pomeroy	201	32	7	0	0	0	0	0	0	0	22	66	328
Port Angeles	14	0	0	0	0	0	0	0	0	0	0	6	20
Prosser	240	46	0	0	0	0	0	0	0	0	22	84	392
Pullman	243	77	0	0	0	0	0	0	0	0	38	118	476
Puyallup	30	0	0	0	0	0	0	0	0	0	0	11	41
Quilcene	39	5	0	0	0	0	0	0	0	0	0	14	58
Quillayute	22	5	0	0	0	0	0	0	0	0	0	9	36
Quincy	303	106	9	0	0	0	0	0	0	0	51	189	658
Paradise	254	161	161	85	27	9	0	0	9	19	103	219	1047
Republic	408	170	73	0	0	0	0	0	0	0	117	304	1072
Richland	199	28	0	0	0	0	0	0	0	0	13	54	294
Ritzville	281	94	10	0	0	0	0	0	0	0	42	143	570
Rosalia	269	94	22	0	0	0	0	0	0	0	49	142	576
Seattle	11	0	0	0	0	0	0	0	0	0	0	6	17
Sea-Tac	24	6	0	0	0	0	0	0	0	0	0	9	39
Sea U.W.	14	0	0	0	0	0	0	0	0	0	0	6	20
Sedro Wooley	46	6	0	0	0	0	0	0	0	0	0	15	67
Sequim	20	0	0	0	0	0	0	0	0	0	0	8	28
Shelton	21	0	0	0	0	0	0	0	0	0	0	8	29
Snqlm. Falls	44	10	0	0	0	0	0	0	0	0	0	16	70
Spokane	299	108	24	0	0	0	0	0	0	0	58	178	667
Sprague	287	94	14	0	0	0	0	0	0	0	48	148	591

Table G-1. Mean Freezing Indices for Washington State, continued

Station	Monthly Freezing Index (°F-day)												Mean Annual Freezing Index (°F-days)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Stampede Pass	283	150	116	48	13	0	0	0	0	9	105	213	937
Startup	38	7	0	0	0	0	0	0	0	0	0	13	58
Stehekin	195	70	12	0	0	0	0	0	0	0	44	127	448
Sunnyside	216	35	0	0	0	0	0	0	0	0	16	73	340
Tacoma City Hall	17	0	0	0	0	0	0	0	0	0	0	7	24
Vancouver	57	0	0	0	0	0	0	0	0	0	0	8	65
Walla-Walla Airport	192	24	0	0	0	0	0	0	0	0	18	59	293
Walla-Walla	188	20	0	0	0	0	0	0	0	0	14	50	272
Wapato	214	36	0	0	0	0	0	0	0	0	18	80	348
Waterville	349	152	51	0	0	0	0	0	0	0	84	246	882
Wenatchee	233	83	0	0	0	0	0	0	0	0	22	128	466
Wilbur	306	126	20	0	0	0	0	0	0	0	53	189	694
Willapa Harbor	12	0	0	0	0	0	0	0	0	0	0	0	12
Wilson Creek	276	79	6	0	0	0	0	0	0	0	42	163	566
Winthrop	451	206	65	0	0	0	0	0	0	0	108	342	1172
Yakima	258	63	0	0	0	0	0	0	0	0	31	123	475

Source: U.S. Department of Commerce, "Degree Days to Selected Bases," National Climatic Center, Federal Building, Asheville, N.C., December 1982.