DEVELOPMENT OF AN IMPROVED OVERLAY DESIGN PROCEDURE FOR THE STATE OF ALASKA

VOLUME III

FIELD MANUAL

by

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16. Abstract

This manual describes a mechanistic overlay design procedure for use in the state of Alaska. This procedure is based upon the fundamental characteristics of pavement layer properties and uses a linear elastic program ELSYM5 to determine strains at critical locations. The tensile strain at the bottom of the surface layer is used to control fatigue, while the compressive strain on top of the subgrade is used to control rutting. Failure criteria developed by the Asphalt Institute are used to determine pavement life. Seasonal effects on pavement layer properties and traffic are also considered. Miner's rule is used to address total pavement damage for all seasons. A comprehensive example illustrating the design procedure is presented.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views of policies of the Alaska Department of Transportation and Public Facilities or the Federal Highway Administration.

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1.0 INTRODUCTION

This manual describes a fully mechanistic overlay design procedure for use in the state of Alaska. The concepts and methodologies are based on the work performed at Oregon State University and presented in a two-volume report prepared for Alaska DOTPF in August 1987 (1,2). Volume I is an executive summary and Volume II describes the entire development of the procedure.

This manual, which constitutes Volume III, presents detailed guidelines for the use of the design procedure. Four major sections are included. Section 2.0 discusses the preliminary work which emphasizes the deflection measurement and the best utilization of the data collected. Section 3.0 presents techniques that can be used to determine pavement layer moduli. Section 4.0 describes the overlay thickness design procedure. Finally, Section 5.0 presents a comprehensive example illustrating how the design procedure can be implemented in routine design work.

The overlay design procedure has been computerized; however, the methodologies described in this manual should provide a conceptual and comprehensive look of the procedure. Volume IV of this report series presents a detailed description of the computer programs used and/or developed as a part of the overall study.

2.0 PRELIMINARY WORK

At the present time, ADOTPF is using the falling weight deflectometer (FWD) for measuring pavement surface deflections. Purposes of deflection measurements are to analyze and evaluate the existing pavement structural capacity and to determine the overlay requirements if necessary and to determine seasonal load restrictions. The following sections describe the steps which need to be considered before and after measuring deflection so that data collected can be best utilized.

2.1 Selection of Time for Deflection Measurement

For an identical road section, deflections measured at different times of the year can be different. This is because either the moisture content in the base and/or subgrade or the temperature of the asphalt layer can impact the pavement strength. For design purposes, deflection data collected from the critical season is especially important. In the state of Alaska, this critical season will most likely appear in spring or early summer, when the roadbed is thawing and at its weakest. Generally, the critical season occurs between March and July. The length of each season varies for different roadways. Table 2.1 presents the typical first day of the season for the three regions of Alaska.

2.2 Determination of Number of Deflection Measurements

The number of deflection tests is based primarily on the purpose of the measurement. The following summarizes guidelines suggested in ASTM D4695-87 (11).

Table 2.1. Typical First Day of the Season.

Season	Fairbanks	Anchorage	Juneau
Spring	April 8	March 15	January 22
Summer	May 22	May 21	May 29
Fall	August 27	September 5	September 17
Winter	October 10	November 10	—

Preliminary screening survey - Type 1 testing

A. General overview of pavement condition and variability

B. Test spacing:

   1. Single lane and single direction
      a. 500 foot spacing between tests, i.e. 10 tests/mile
   2. Single lane and both directions
      a. 1,000 foot spacing in each direction
      b. stagger tests in opposing directions by 500 feet
   3. Multiple lanes
      a. 1,000 foot spacing in each lane
      b. stagger tests between lanes by 500 feet

C. Test location: Outer wheelpath

Routine Design Testing - Type 2 testing

A. Provide data for routine overlay/rehab. analysis/design

B. Basic objective is to get enough tests to define:

   1. Average response at 95% confidence interval
   2. Areas that require special treatment

C. Need to identify analysis units

   1. Sections of pavement that may be expected to have statistically uniform response characteristics
      a. review "as-builts" (pavement type, age, pavement section, subgrade, traffic levels, cut/fill limits and treatments)
      b. analyze visual condition
      c. analyze deflection response

D. Number of tests determines degree of error in estimate

Let $E(\%)$ = Error in estimating the true mean response

$$= 100(U - x)/x$$

where,

U = "True Mean"

x = sample average

Then at the $100(1-\alpha)$ confidence level, $E(\%)$ may be estimated by

$$E(\%) \leq t_\alpha cv/\sqrt{n}$$

where,

t_α = Student's t distribution deviate evaluated at $(1-\alpha)$ confidence level for $n-1$ degrees of freedom

cv = coefficient of variation

$= 100(s/\bar{x})$

s = sample standard deviation

n = number of tests in sample average

The value of cv must be determined from the field data but typically it will vary between 15% to 45%.

Figure 2.1 shows the variation in $E(\%)$ as function of n and cv for 95% confidence level estimate of $E(\%)$. As can be seen from the figure, when the number of tests is 20 or greater, the percent of error is about the same.

E. Random vs. regular interval test spacing

1. Random spacing
   a. requires less points
   b. must be confident of analysis unit boundaries before testing

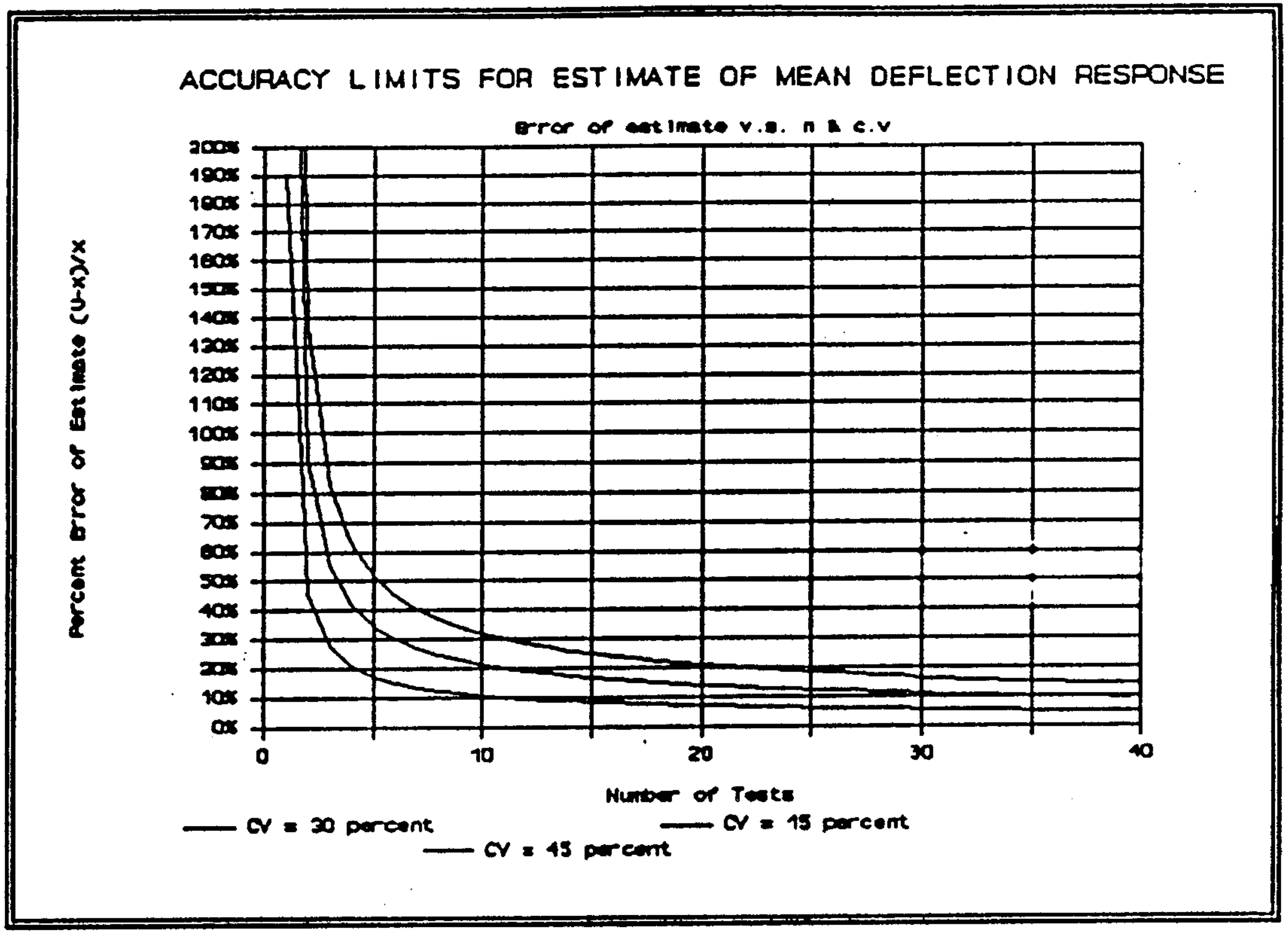


Figure 2.1. Accuracy Limits for Estimate of Mean Deflection Response

    2. Regular spacing
        a. gives continuous profile of roadway
        b. allows determination of analysis units from deflection data
        c. procedure that is most often used

F. Typical spacing for flexible pavement: Test outer wheelpath of each lane
    1. 50 to 100 foot spacing between tests in urban areas
    2. 100 to 200 foot spacing between tests in suburban and rural areas

2.3 Determination of Sensor Spacing

For FWD devices, all available sensors should be used for obtaining the best representative deflection basin data. Most FWD's have seven sensors, and a sensor spacing of 0, 8, 11.8, 24, 36, 47, and 59 in. is suggested by Dynatest. For a layered pavement structure as shown in Fig. 2.2, the deflection at a certain distance reflects the response of the layer directly below the sensor and dashed line. Thus, to obtain only the response of the subgrade, it is necessary to extend the last sensor far enough away from the load center.

In overlay design, determination of the subgrade strength is particularly important. A good estimate can be achieved if the deflection measurement is correctly performed. This includes a correct setting of the outer sensor location.

Figures 2.3 and 2.4 illustrate a procedure for determining the outer sensor location. This procedure is based on the concept that the location of the outer sensor should be greater than the equivalent pavement depth. This assures that only the response from the subgrade can be obtained.

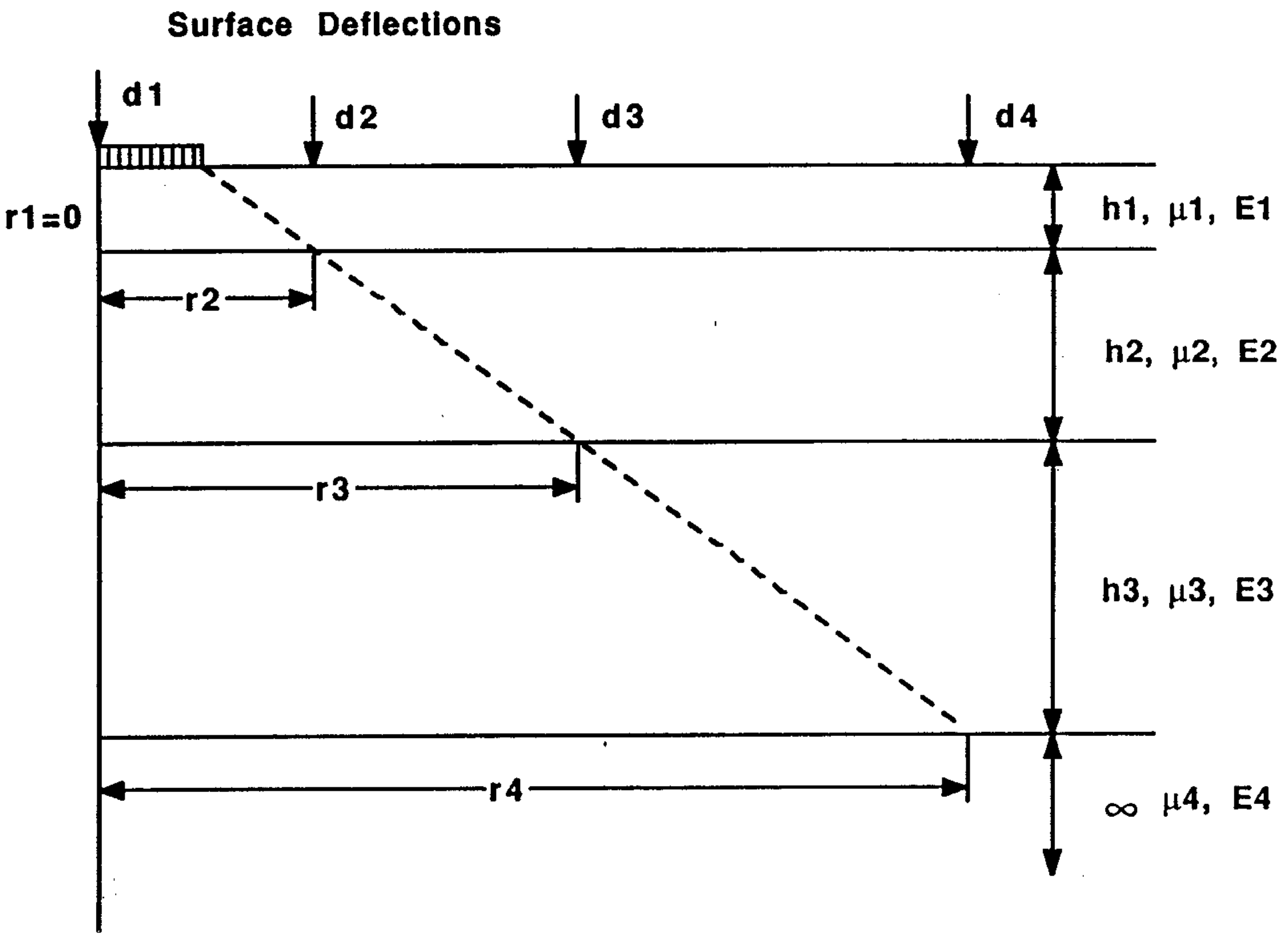


Figure 2.2. Four Layer Elastic Representation of a Pavement System (3)

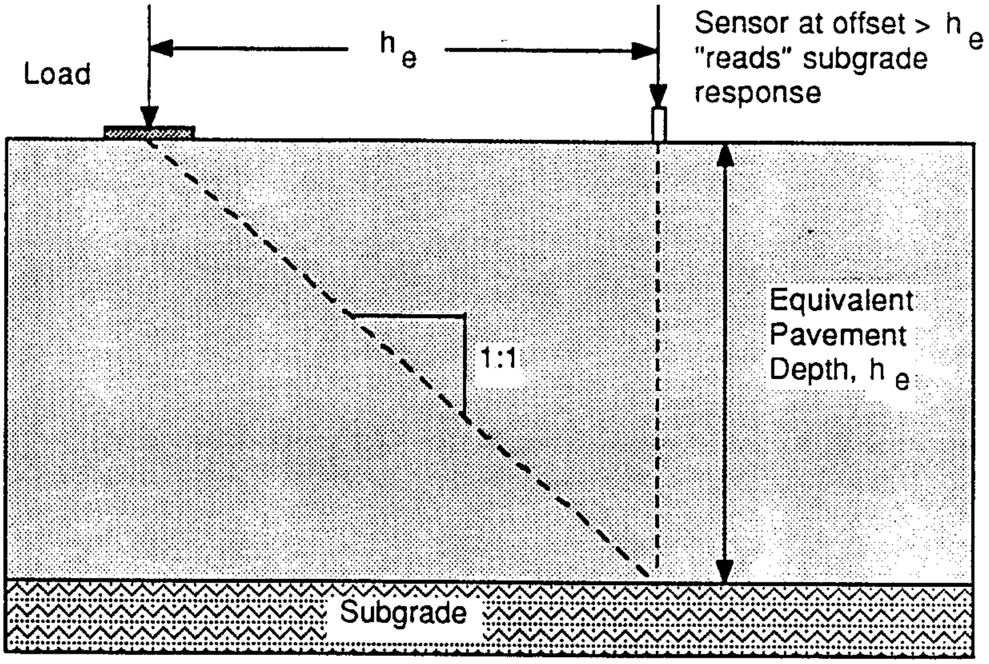


Figure 2.3. Location of Outer Sensor Beyond Equivalent Depth of Pavement Section.

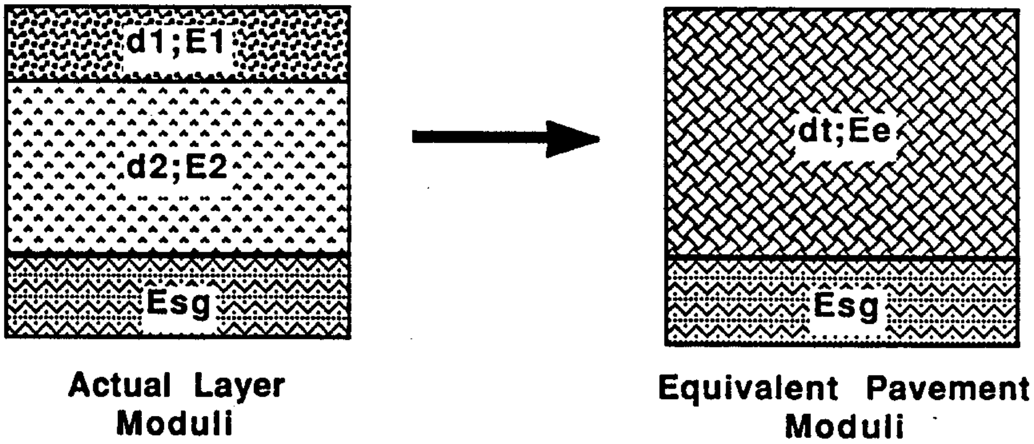


Figure 2.4. Equivalent Thickness Concept.

The procedure is based upon the method of equivalent thickness (MET). A detailed description of MET can be found in reference (4). In this procedure the layers above the subgrade may be converted into an equivalent thickness, (h_e), of subgrade material using the formula:

$$h_e \cong f \sum_{i=1}^{n-1} t_i \left[\frac{E_i}{E_n}\right]^{1/3}$$

where: n = total number of pavement layers, including subgrade,

f = correction factor; $f = 0.9$ if $n = 2$

$f = 0.8$ if > 2

i = ith layer,

E_i = modulus value of ith layer, psi,

E_n = modulus of subgrade, psi, and

t_i = thickness of ith layer, in.

Table 2.2 shows the example calculation for h_e for several typical pavement structures. The h_e values indicate that the last sensor location should be at least 54.4 in. away from the load center for case 1, 57.3 in. for case 2, and 63.2 in. for case 3.

2.4 Presentation of Data

Deflection data collected can be presented in several ways so that the pavement response along the roadway may be easily identified. An example of data presentation can be seen in Figure 2.5.

Deflection versus distance: Figure 2.5a shows the deflection variation for 4 sensors along the roadway. From this sort of plot, any peculiar pavement response can be noticed.

Table 2.2. Example Calculations of Equivalent Depth (Subgrade M_r = 8,000 psi)

<u>Case 1</u>

2 in. AC @ E_1 = 400,000 psi

42 in. AB @ E_2 = 24,000 psi

$$h_e = 0.8 \left[2\left(\frac{400,000}{8,000}\right)^{1/3} + 42 \left(\frac{24,000}{8,000}\right)^{1/3} \right] = 54.4 \text{ in.}$$

<u>Case 2</u>

3 in. AC @ E_1 = 400,000 psi

42 in. AB @ E_2 = 24,000 psi

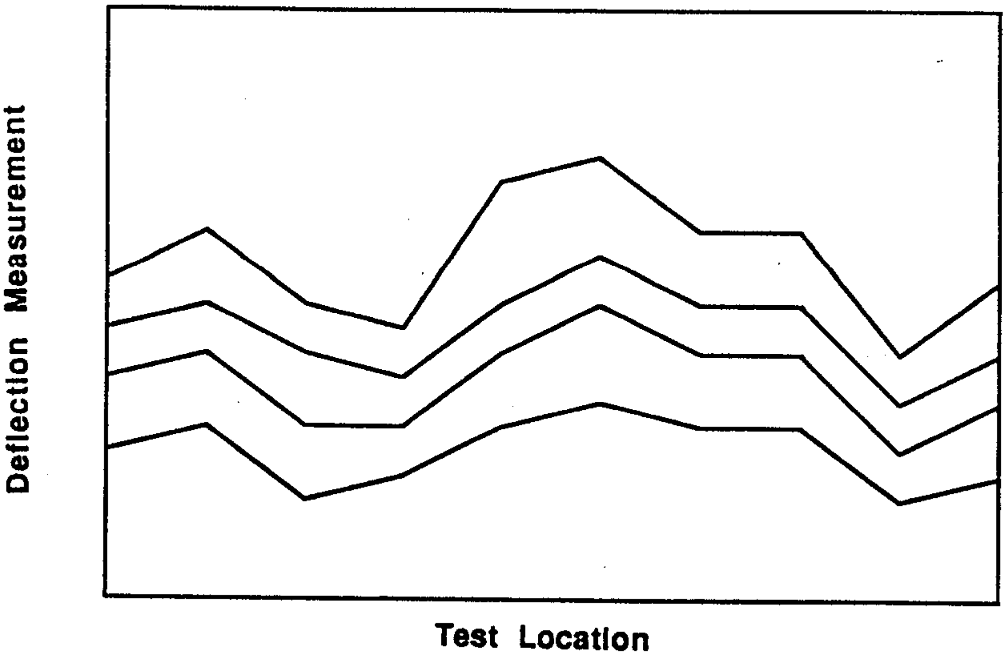
$$h_e = 0.8 \left[3\left(\frac{400,000}{8,000}\right)^{1/3} + 42 \left(\frac{24,000}{8,000}\right)^{1/3} \right] = 57.3 \text{ in.}$$

<u>Case 3</u>

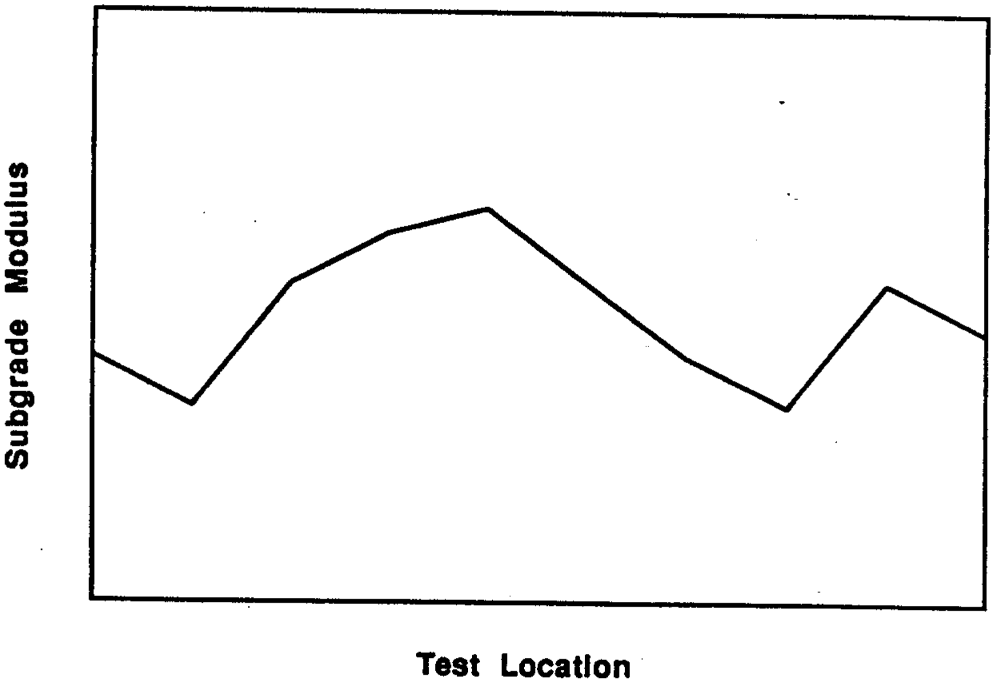
5 in. AC @ E_1 = 400,000 psi

42 in. AB @ E_2 = 24,000 psi

$$h_e = 0.8 \left[5\left(\frac{400,000}{8,000}\right)^{1/3} + 42 \left(\frac{24,000}{8,000}\right)^{1/3} \right] = 63.2 \text{ in.}$$



a) Distance versus Deflection



b) Distance versus Subgrade Modulus

Figure 2.5. Presentation of Deflection Data.

Subgrade modulus versus distance: Figure 2.5b shows the modulus of roadbed soil along the roadway. Because of its importance in overlay design, variations in the subgrade modulus can be easily noted.

2.5 Screening of Deflection Data

The purpose of screening the deflection data is to determine analysis unit boundaries so that pavement sections that have smilar characteristics can be grouped into one analysis unit, thus, saving a significant amount of time. The following describes the cumulative different techniques that can be used to serve this purpose:

1. Development of concept
    a. Explained in AASHTO Guide Appendix J (5)
2. Steps in process
    a. Plot response variable (e.g. area function or maximum deflection at load center) as function of distance - see Figure 2.6a
    b. Determine average increase in area under response curve per station and plot - see Figure 2.6b
    c. Plot actual increase in area under response curve by station - see Figure 2.6b
    d. Plot differences in cumulative area by station - see Figure 2.6c
    e. Analysis unit boundaries are delineated by changes in slope of differences curve - see Figure 2.6c
3. Set-up for tabular solution sequence shown in Table 2.3
4. Example calculation (Table 2.4)
5. Results are illustrated in Figure 2.7 (four units have been defined)

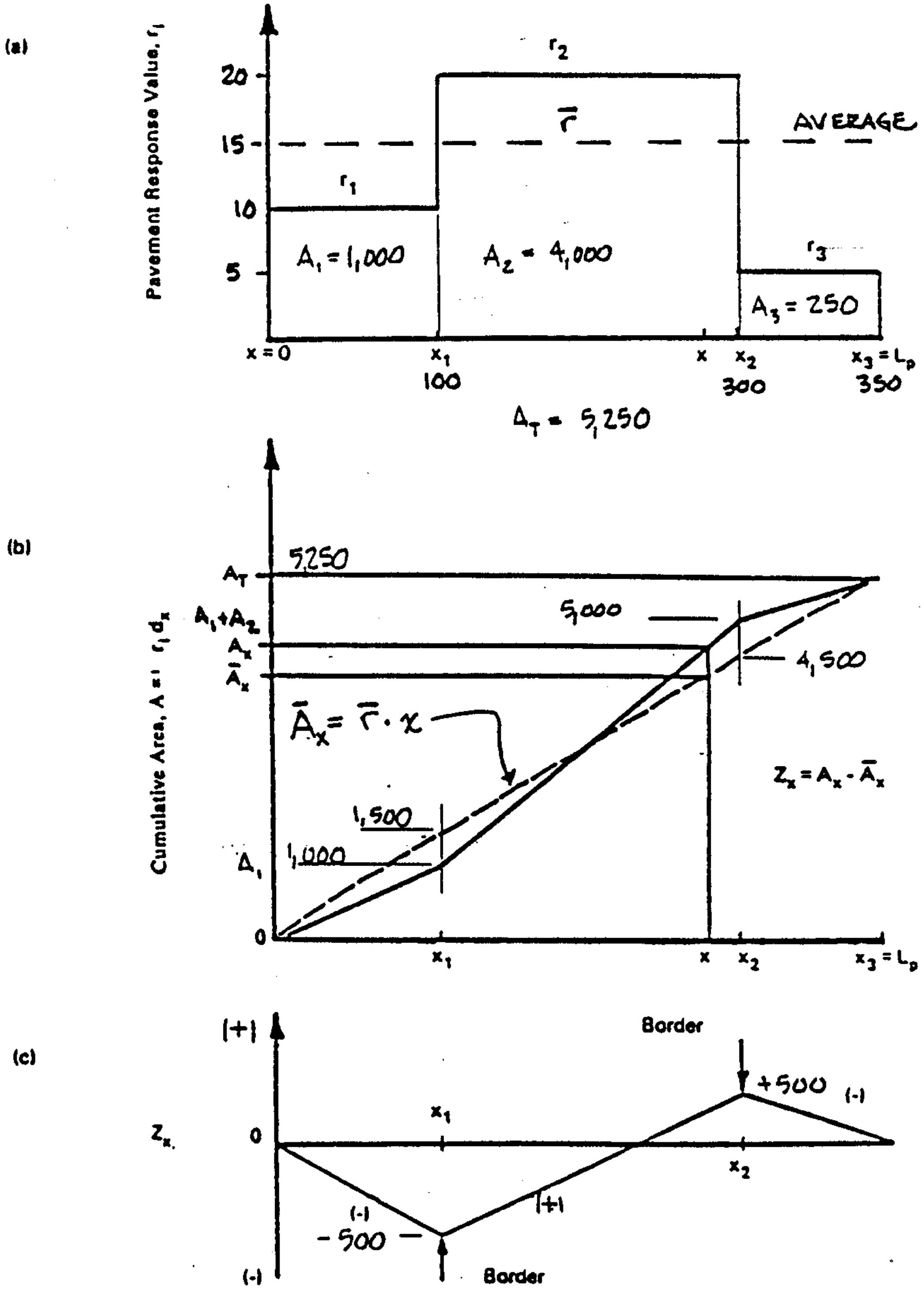


Figure 2.6. Concepts of Cumulative Difference Approach to Analysis Unit Delineation (10).

Table 2.3. Tabular Solution Sequence - Cumulative Difference Approach.

Col. (1) Station (Distance)	Col. (2) Pavement Response Value (r_i)	Col. (3) Interval Number (n)	Col. (4) Interval Distance (Δx_i)	Col. (5) Cumulative Interval Distance ($\Sigma \Delta x_i$)	Col. (6) Average Interval Response ($\bar{r}_i$)	Col. (7) Actual Interval Area (a_i)	Col. (8) Cumulative Area Σa_i	Col. (9) Z_x Value Z_x = Col.(8) - F*Col.(5)
0		1	Δx_1	Δx_1	$\bar{r}_1 = r_1$	$a_1 = \bar{r}_1 \Delta x_1$	a_1	$Z_{x1} = a_1 - F^* \Delta x_1$
1	r_1							
		2	Δx_2	$(\Delta x_1 + \Delta x_2)$	$\bar{r}_2 = \frac{(r_1+r_2)}{2}$	$a_2 = \bar{r}_2 \Delta x_2$	a_1+a_2	$Z_{x2} = (a_1+a_2) - F^*(\Delta x_1 + \Delta x_2)$
2	r_2							
		3	Δx_3	$(\Delta x_1 + \Delta x_2 + \Delta x_3)$	$\bar{r}_3 = \frac{(r_2+r_3)}{2}$	$a_3 = \bar{r}_3 \Delta x_3$	$a_1+a_2+a_3$	
3	r_3							
		N_t	Δx_{nt}	$(\Delta x_1 + .. \Delta x_{nt})$	$\bar{r}_{nt} = \frac{(r_{n-1}+r_n)}{2}$	$a_{nt} = \bar{r}_{nt} \Delta x_{nt}$	$a_1 + .. a_{nt}$	$z_{xnt} = (a_1 + ... + a_{nt}) - F^*(L_p)$
L_p	r_n							
							$A_t = \sum_{i=1}^{N_t} a_i$	
							$F^* = \frac{A_t}{L_p}$	
							note $F^* = \bar{r}$	

Table 2.4. Analysis Unit Delineation by Cumulative Differences

No. of Test	Station	Area	Int. Dist.	Cum. Dist.	Avg. Area	Int. Area	Cum. Area	Diff. Z	Sign of Slope
1	28	17.1	28	28	17.1	478	478	-29	-
2	80	16.9	52	80	17.0	884	1362	-88	-
3	200	18.6	120	200	17.8	2131	3494	-131	-
4	289	12.6	89	289	15.6	1390	4884	-355	-
5	400	17.6	111	400	15.1	1676	6559	-691	-
6	491	11.2	91	491	14.4	1310	7869	-1031	-
7	600	14.9	109	600	13.1	1423	9292	-1583	-
8	683	14.7	83	683	14.8	1229	10521	-1858	-
9	800	18.5	117	800	16.6	1943	12465	-2036	-
10	898	14.1	98	898	16.3	1595	14060	-2217	-
11	1000	16.1	102	1000	15.1	1538	15598	-2527	-
12	1093	17.2	93	1093	16.6	1547	17146	-2666	-
13	1212	17.4	119	1212	17.3	2054	19200	-2768	-
14	1294	15.4	82	1294	16.4	1341	20541	-2913	-
15	1400	18.5	106	1400	16.9	1795	22337	-3039	-
16	1500	15.9	100	1500	17.2	1720	24056	-3132	-
17	1606	19.6	106	1606	17.7	1881	25938	-3172	-
18	1673	14.8	67	1673	17.2	1152	27090	-3234	-
19	1833	18.9	160	1833	16.9	2697	29787	-3437	-
20	1896	19.1	63	1896	19.0	1197	30984	-3382	+
21	1998	22.0	102	1998	20.5	2094	33078	-3137	+
22	2100	21.1	102	2100	21.5	2196	35274	-2790	+
23	2206	19.9	106	2206	20.5	2170	37445	-2541	+
24	2303	18.3	97	2303	19.1	1852	39297	-2447	+
25	2402	16.6	99	2402	17.4	1727	41024	-2514	-
26	2503	22.7	101	2503	19.7	1985	43008	-2360	+
27	2603	22.1	100	2603	22.4	2241	45250	-1931	+
28	2674	21.0	71	2674	21.6	1532	46782	-1686	+
29	2812	22.5	138	2812	21.7	3001	49783	-1186	+
30	2902	21.4	90	2902	21.9	1974	51757	-843	+
31	3005	31.2	103	3005	26.3	2710	54468	0	+
F = 18.1									

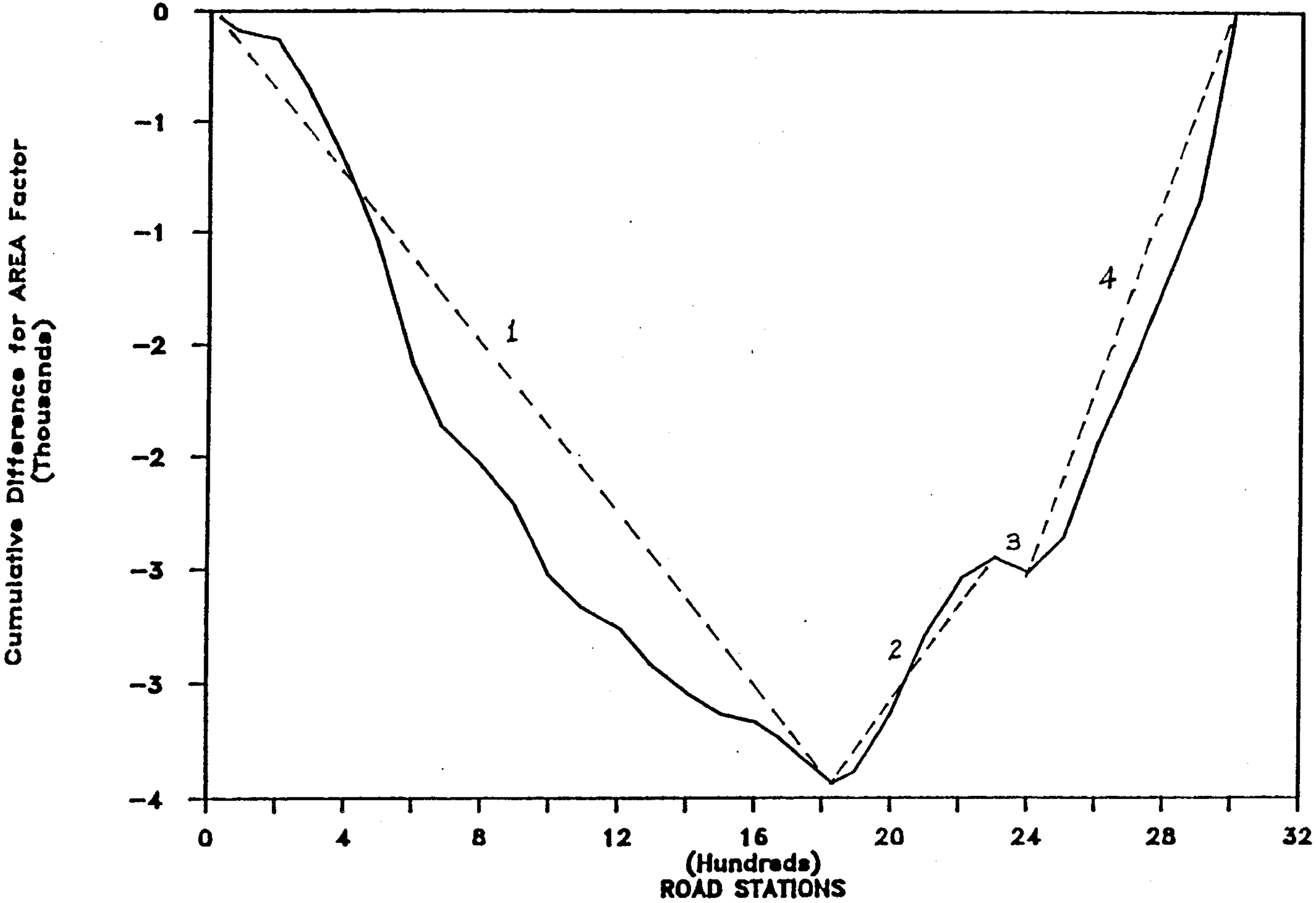


Figure 2.7. Delineation of Analysis Unit.

The results show that for all 31 test points, four units have been defined and can be used for overlaly design purposes.

2.6 Utilization of Deflection Data

Deflection data can be used for two purposes as described below:

1. Identify extreme deflection cases and similar sections to group for analysis
    a. Deflections greater than 2 standard deviations
2. Use of data in backcalculation
    a. Objective: Given deflections and layer thicknesses to find E values
    b. Problem is determining thickness
        (i) For low error in fit need to know exact layer thickness
        (ii) Core at each test location - too expensive
        (iii) Randomly core
            (a) Assume thickness constant between cores
            (b) Average core thickness within analysis unit
        (iv) Use old as-built data
    c. Backcalculation options
        (i) Backcalculate each test location individually and then average the results
        (ii) Backcalculate using average deflections plus two standard deviation and thickness within analysis units
    d. Suggested approach
    Backcalculate all deflection basins using either ELMOD or BOUSDEF and average the moduli for each analysis unit. Verify the average moduli using ELSDEF.

3.0 DETERMINATION OF LAYER MODULI

This section describes two methods for determining pavement layer moduli which are necessary for implementing the mechanistic overlay design procedure.

3.1 Laboratory Test of Layer Moduli

One method of determining pavement layer moduli is to perform laboratory tests on cores. Table 3.1 shows some typical ranges of modulus values for three regions in Alaska. Seasonal impacts on the values for modulus is also given in the table.

The asphalt concrete modulus may also be estimated using program AMOD. AMOD requires a knowledge of void ratios, original penetration values, percentages of asphalt by weight, percent of fines passing #200 sieve, temperature at time of test, and frequency of loading (Hz). A detailed description of this program is given in Volume IV of this report.

3.2 Backcalculation of Layer Moduli

Backcalculation is a technique used to determine a pavement layer material property from the surface deflections. The surface deflection is measured using a nondestructive testing device such as the Falling Weight Deflectometer. The surface deflection provides important information for evaluating a pavement structure. In general, a higher deflection value would indicate a lower pavement structural strength while a lower deflection represents higher structure capacity. Since a pavement is a composition of several layers, deflections at different radial distances reflect the structural capacity of one or more of the corresponding layers. The backcalculation technique is based upon the fundamental premise that an approprpiate set of layer moduli have been determined when the theoretically calculated deflection basin is equivalent to the measured deflection basin.

Table 3.1. Typical Ranges of Values for Moduli and Poisson's Ratios

Season	Layer Type	AC 2.5-10 Anchorage	AC 2.5 Fairbanks	AC 5 Juneau
Spring Thaw	AC	800-1200/0.35*	800-1200/0.35	800-1200/0.35
	AB	3- 60/0.45	3- 60/0.45	3- 60/0.45
	Subgrade	100- 600/0.35	100- 600/0.35	100- 600/0.35
Summer	AC	100- 700/0.35	100- 700/0.35	100- 700/0.35
	AB	20- 80/0.45	20- 80/0.45	20- 80/0.45
	Subgrade	5- 30/0.40	5- 30/0.40	5- 30/0.40
Fall	AC	300-1200/0.35	300-1200/0.35	300-1200/0.35
	AB	20- 80/0.40	20- 80/0.40	20- 80/0.40
	Subgrade	10- 30/0.40	10- 30/0.40	10- 30/0.40
Winter	AC	1500-2500/0.30	1500-2500/0.30	800-1200/0.30
	AB	400- 600/0.35	400- 600/0.35	40- 60/0.35
	Subgrade	400- 800/0.35	400- 800/0.35	400- 800/0.35

*Resilient Modulus (ksi)/Poisson's Ratio

General information needed to implement backcalculation techniques includes NDT device load, load plate radius, deflection basin data, number of layers, and layer thickness. Many programs have been developed for backcalculating pavement layer moduli, such as ELMOD, BOUSDEF, and ELSDEF. A comprehensive description on the backcalculation technique can be found in Reference (2).

Programs recommended for use in Alaska are:

1) BOUSDEF (4), developed at Oregon State University, or ELMOD, developed by Dynatest, and
2) ELSDEF (6), developed by Brent Rauhut Engineers.

BOUSDEF and ELMOD are backcalculation programs utilizing the method of equivalent thickness (MET) concept and Boussinesq theory (9). The programs determine modulus values for each pavement layer from a given deflection basin data. The backcalculated moduli may be used for either pavement structure analysis or for mechanistic overlay design. Inputs for this program include layer thickness, Poisson's ratio, deflection basin data, and NDT load force and load radius. The programs are operational on IBM-compatible microcomputers. The user manual for BOUSDEF is included in Volume IV of this report.

ELSDEF is a backcalculation program based on layered elastic theory and uses ELSYM5 as its subroutine for calculating deformation. The input and output are basically the same as those of the BOUSDEF program. The program is also operational on IBM-compatible microcomputers and its user manual can also be found in Volume IV of this report.

Because of its fast computing speed, the program BOUSDEF is recommended for deflection data screening purposes, while the program ELSDEF should be used for verifying the results calculated from BOUSDEF.

3.3 Example of Using Backcalculation Programs

The following illustrates how to use deflection data and backcalculation programs to determine moduli:

1) Given data:

FWD load = 8472 lb

Load radius = 5.90 in.

Sensor spacing (in.): 0, 8, 18, 24, 36, 60, 96

Deflection reading (mils): 12.96, 9.27, 6.85, 4.37, 3.01, 2.10, 1.57

Pavement Structure and Material Properties

	Layer Thickness (in.)	Poisson's Ratio	Minimum Modulus (psi)	Maximum Modulus (psi)	Seed Modulus (psi)
AC	3	0.35	100,000	2,000,000	1,200,000
AB	36	0.40	10,000	50,000	25,000
Subgrade	∞	0.45	1,000	30,000	15,000

2) Find:

Modulus for each layer

3) Solution:

a) Using BOUSDEF program, the calculated moduli are:

AC layer = 1,134,026 psi

AB layer = 34,422 psi

Subgrade = 18,066 psi

b) Using ELSDEF program, the calculated moduli are:

AC layer = 984,322 psi

AB layer = 40,464 psi

Subgrade = 16,123 psi

The determined moduli are the necessary input for estimating the pavement damage and overlay design as will be discussed in the next section.

4.0 OVERLAY DESIGN PROCEDURE

This section presents a comprehensive description of a mechanistic overlay design procedure proposed for use in the state of Alaska. A flowchart of this procedure is illustrated in Figure 4.1.

4.1 General Description

A mechanistic approach considers the fundamental characteristics of the materials to be used. A mechanistic design procedure characterizes the response of the pavement to a traffic load in terms of strains and/or stresses.

When using the mechanistic approach, the pavement is represented as a multilayer elastic structure, as shown in Figure 4.2, in which the stiffness characteristics of each of the layers is characterized by a modulus (E) and a Poisson's ratio (ν). The thickness of each layer above the subgrade may be determined from construction data or coring. Typical loads can be assumed for various traffic conditions.

The above parameters are then used to determine stresses, strains, and deflections under certain load conditions. The calculation is usually done by using a computer program such as BISAR or ELSYM5 (7). Stresses and/or strains at any location of a pavement structure can be determined. Many agencies, such as the Asphalt Institute, use the tensile strain at the bottom of the asphalt concrete layer as a criterion for the control of fatigue and compressive strain for the control of rutting in subgrade. A common expression used to relate the number of loads to fatigue failure as a function of tensile strain and stiffness of asphalt concrete is:

$$N_f = A \left(\frac{1}{\epsilon_t}\right)^b \left(\frac{1}{S_{mix}}\right)^c$$

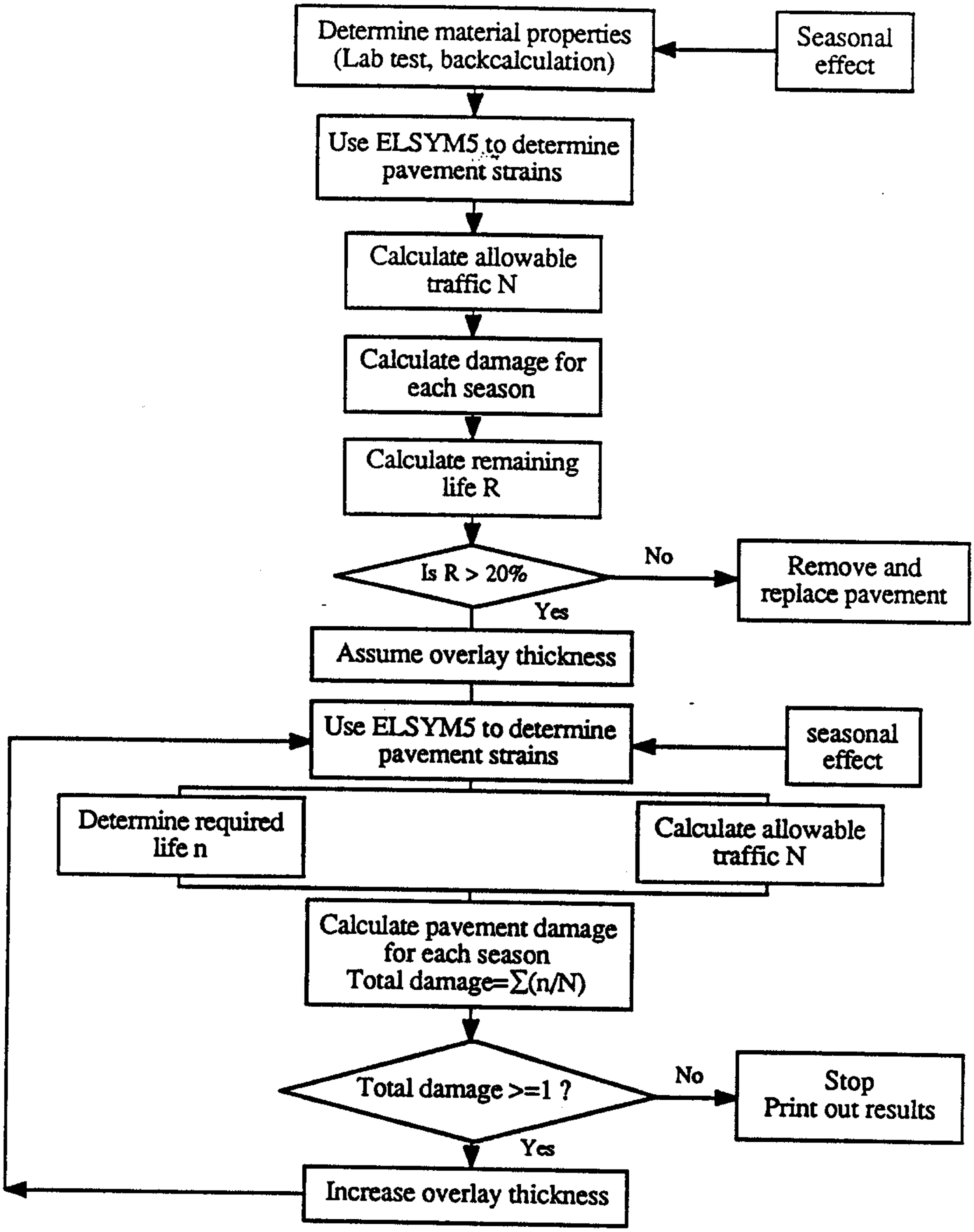


Figure 4.1. Flowchart for Alaska Approach.

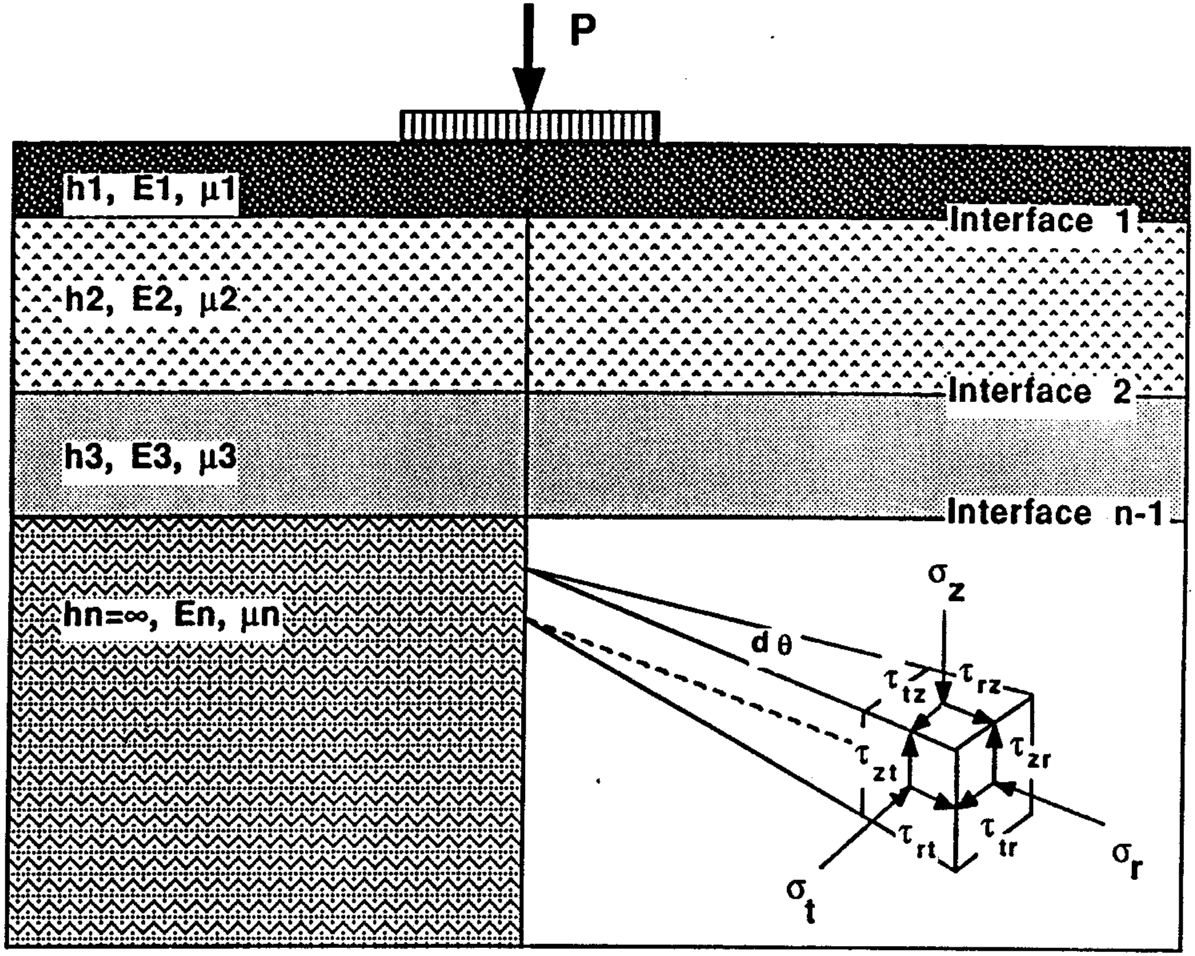


Figure 4.2. Generalized Multilayered Elastic System (7).

where:

N_f = number of applications to failure,

ϵ_t = tensile strain in asphalt concrete (in./in.),

S_{mix} = stiffness modulus of asphalt concrete (psi), and

A,b,c = constants for specific asphalt mix.

A similar expression is used to relate the number of loads to rutting failure as a function of compressive strain on the top of the subgrade, except that the stiffness of the asphalt concrete is disregarded.

Damage of the pavement or seasonal load effects may then be determined using Miner's hypothesis, a cumulative damage theory, as is given by:

$$\sum_{i=1}^{r} \frac{n_i}{N_i} \leq 1$$

where:

i = season i in analysis,

n_i = actual number of cycles of stress or strain applied to the pavement within season i,

N_i = allowable number of cycles to failure based on failure criteria for season i (such as fatigue or rutting), and

r = number of seasons considered.

The overlay thickness is determined based primarily on the projected traffic repetitions and damage previously done to the existing pavement. These two parameters, together with the material characteristics, determine the allowable damage that pavement should tolerate. An iterative procedure is used by applying additional thicknesses of overlay to the surface to find the most economic overlay design.

4.2 Analysis of Existing Pavement

The procedure recommended for Alaska actually has two major components. One is for the analysis of the existing pavement, the other is for overlay thickness design.

For the analysis of existing pavement, two items need to be considered: 1) seasonal effects, and 2) total pavement damage. Seasonal effects include modulus variation and changes in failure criteria for each season as shown in Figure 4.3. These variations are required to estimate pavement damage for each season.

With the knowledge of modulus for each layer, and layer thickness, strains at specified locations can be calculated using ELSYM5 program. Tensile strain at the bottom of the asphalt concrete layer is used to control fatigue. Compressive strain on the top of the subgrade is used to control rutting. At present, failure criteria developed by the Asphalt Institute are adopted for control of fatigue and rutting (8). The equation used for control of fatigue is:

$$N = 18.4 * C * 0.004325 * \epsilon_t^{-3.291} * E_{AC}^{-0.854} \qquad (4\text{-}1a)$$

where:

N = number of 18-kip equivalent single axle loads,

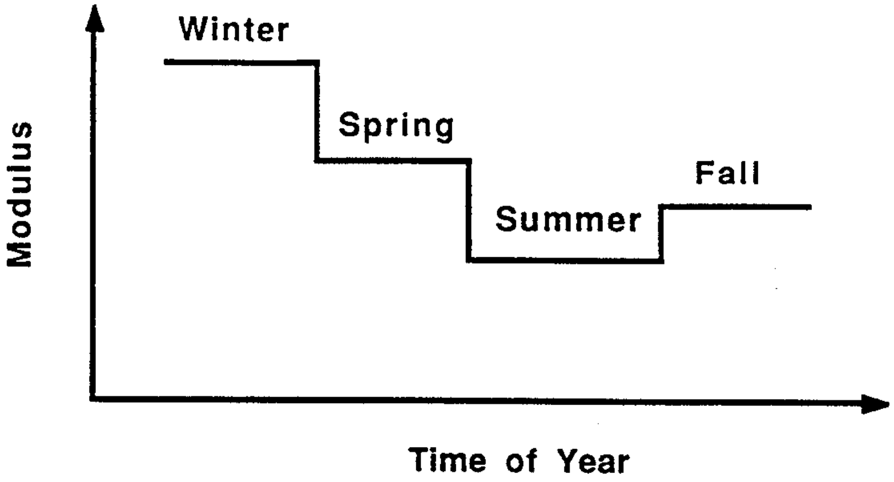
ϵ_t = horizontal tensile strain on underside of AC layer,

E = modulus of AC layer, psi, and

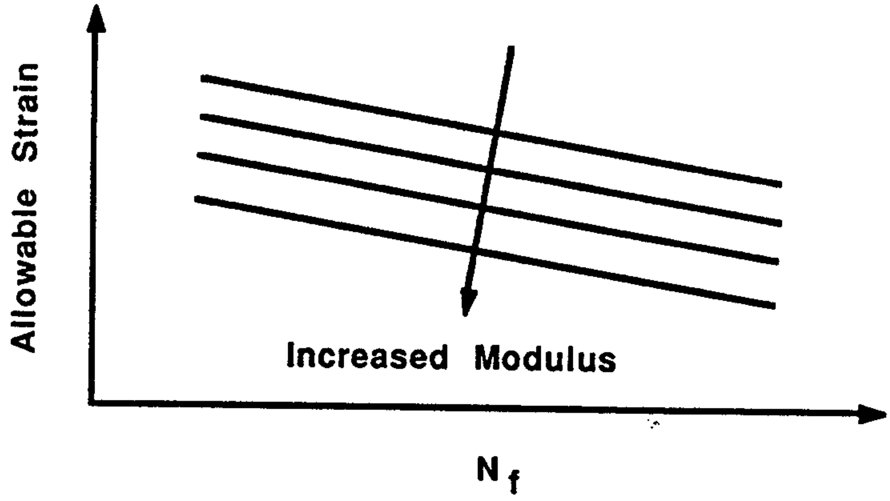
C = a function of voids and volumes of asphalt in the mix design, and can be determined by following:

$$C = 10^M \qquad (4\text{-}1b)$$

where:



a) Asphalt Modulus



b) Failure Criteria

Figure 4.3. Seasonal Influence on Layer Modulus and Failure Criteria.

$$M = 4.84 * [V_b/(V_v+V_b) - 0.69] \quad (4\text{-}1c)$$

V_b = volume of asphalt, %, and

V_v = volume of air voids, %.

Coetzee (12) developed similar regression equations based on laboratory tests on different asphalt grades under different temperature conditions. A general equation is shown below:

$$N = 4.391*10^6*\epsilon^{-7.25}E^{-4.423} \quad (4\text{-}2)$$

For the Alaska condition, this equation may be more appropriate since the equation was developed based on data which were predominantly tested at lower temperatures.

For control of permanent deformation, the equation is

$$N = 1.36 * 10^{-9} * \epsilon_c^{-4.48} \quad (4\text{-}3)$$

where

ϵ_c = vertical compressive strain on the top of the subgrade.

Pavement damage for each season may then be determined from the knowledge of historical traffic applications, required pavement life, and allowable traffic repetitions. Total pavement damage is calculated using Miner's hypothesis, which is the sum of all damages for all seasons.

$$\text{Total Damage} = \frac{n_{summer}}{N_{summer}} + \frac{n_{fall}}{N_{fall}} + \frac{n_{spring}}{N_{spring}} + \frac{n_{winter}}{N_{winter}} \leq 1$$

where:

n_i = number of EAL's for a given season, and

N_i = number of allowable EAL's for the same season.

4.3 Overlay Thickness Design

The need for an overlay is based on pavement condition and total pavement damage. Quantitatively, when remaining life is less than 20% or fatigue cracking is greater than 40%, the pavement should be removed and replaced. Otherwise, an overlay should be considered. The determination of an overlay thickness involves an iterative process as described below:

1) Assume an overlay thickness.
2) Use the ELSYM5 program to compute strains for each season.
3) Determine required life and allowable traffic for each season.
4) Calculate total pavement damage.
5) If the total pavement damage is greater than one, increase the overlay thickness, go to step 2.

The above procedure is repeated until the total pavement damage is less than one. The most economic thickness is the one with calculated pavement damage less than, but closest to, 100%.

5.0 EXAMPLE OF OVERLAY DESIGN

This section presents an example to illustrate the entire mechanistic overlay design process.

5.1 Assumptions

A highway located in a rural area has been in service for 15 years and the total cumulative 18 kip EALs repetitions is approximately 750,000. It is expected that in the next 20 years, the projected traffic will be approximately 2,050,200 EALs. The pavement structure consists of three layers; asphalt concrete surface, aggregate base and soil subgrade, as show in Figure 5.1. A 9000-lb FWD load is used to correspond to the standard axle of 18,000 lbs. A 5.9-in. load radius is selected to represent a falling weight deflectometer's load plate. Material properties for each layer and season and traffic data for each season are shown in Table 5.1.

5.2 Determination of Existing Pavement Strains

Using the ELSYM5 program with the data given, calculate the pavement strains. The results are:

Calculated Strain (μ-strain)	Spring	Summer	Winter
Maximum tensile strains in AC layer	342	447	25
Maximum compressive strains on subgrade	6	92	4

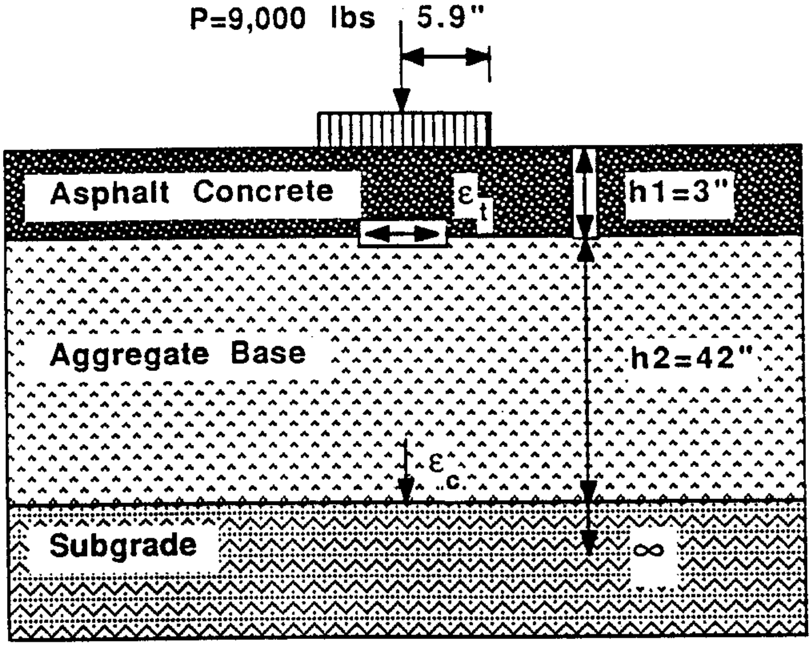


Figure 5.1. Pavement Structure and Loading Condition for the Example.

Table 5.1. Materials Properties and Traffic Data for the Example.

Season	Layer	Modulus* (ksi)	Poisson's* Ratio	Traffic	
				Historical	Future
Spring	Asphalt concrete Aggregate base Subgrade	1000 12.5 500	0.35 0.45 0.40	50,000	140,700
Summer/ Fall	Asphalt concrete Aggregate base Subgrade	200 30 20	0.35 0.45 0.40	450,000	1,206,000
Winter	Asphalt concrete Aggregate base Subgrade	2000 500 500	0.30 0.35 0.40	250,000	703,500

Mixture properties:

Bulk specific gravity = 2.500
Percent of asphalt by weight = 6.0
Percent of air voids = 3.0
Specific gravity of asphalt = 1.02

*Modulus and Poisson's ratios are assumed from Table 3.1

5.3 Determination of Pavement Life

The Asphalt Institute (TAI) equations are used to determine the allowable fatigue life:

$$N_f = 18.4*C*0.004325*\epsilon_t^{-3.291}*E_{AC}^{-0.854}$$

in which:

$$C = 10^M = 4.78998$$

$$M = 4.84*[V_b/(V_b + V_v) - 0.69]$$

$$= 4.84*[14.7/(14.7+3) - 0.69]$$

$$= 0.6803$$

$$V_b = \frac{6*2.5}{1.02} = 14.7$$

For spring, the allowable life is determined as follows

$$\epsilon_t = 342*10^{-6}$$

$$E_{AC} = 1{,}000{,}000 \text{ psi}$$

$$N_f = 18.4*4.78998*0.004325*0.00342^{-3.291}*1{,}000{,}000^{-0.854}$$

$$= 730{,}563$$

For summer/fall, the allowable life is

$$\epsilon_t = 447*10^{-6}$$

$$E_{AC} = 200{,}000 \text{ psi}$$

$$N_f = 18.4*4.78998*0.004325*0.000447^{-3.291}*200{,}000^{-0.854}$$

$$= 1{,}196{,}453$$

For winter, the allowable life is

$$\epsilon_t = 25*10^{-6}$$

$$E_{AC} = 2{,}000{,}000 \text{ psi}$$

$$N_f \approx 2.16\text{x}10^9$$

For control of rutting, the allowable number of repetitions is determined using

$$N_f = 1.36*10^{-9}*\epsilon_c^{-4.48}$$

This yields a life for spring of:

$$\epsilon_c = 6*10^{-6}$$

$$N_f = 1.36*10^{-9}*(6*10^{-6})^{-4.48}$$

$$= 3.39*10^{14}$$

and for summer/fall of:

$$\epsilon_c = 96*10^{-6}$$

$$N_f = 1.36*10^{-9}*(92*10^{-6})^{-4.48}$$

$$= 1.64*10^9$$

and for winter of:

$$\epsilon_c = 4*10^{-6}$$

$$N_f = 2.07*10^{15}$$

The results are summarized below

	Calculated Strains ($*10^{-6}$)		Allowable Pavement Life	
Season	AC	Subgrade	AC	Subgrade
Spring	342	6	$7.31*10^5$	$3.39*10^{14}$
Summer/ Fall	447	92	$1.20*10^6$	$1.64*10^9$
Winter	25	4	$2.16*10^9$	$2.07*10^{15}$

5.4 Determination of Pavement Damage and Remaining Life

To determine pavement damage Miner's rules are used where

$$\sum_{i=1}^{n} \frac{n_i}{N_i} \leq 1$$

or

$$\sum_{i=1}^{seasons} \frac{n_{spring}}{N_{spring}} + \frac{n_{summer/fall}}{N_{summer/fall}} + \frac{n_{winter}}{N_{winter}} \leq 1 \quad .$$

Damage and remaining life for both AC layer and subgrade should be examined as illustrated below.

For existing pavement:

For AC layer:

$$\text{Damage} = \frac{50,000}{7.31*10^5} + \frac{450,000}{1.20*10^6} + \frac{250,000}{2.16*10^9}$$

$$= 0.0684 + 0.375 + 0.0001 = 0.444 = 44.4\% < 100\%$$

Remaining life:

for spring: $R_f = 1 - 0.0684 = 0.9316$

for summer/fall: $R_f = 1 - 0.375 = 0.625$

for winter: $R_f = 1 - 0.0001 = 0.9999$

These results indicate that for this example, most of the fatigue damage is occurring in the summer/fall season.

For subgrade:

$$\text{Damage} = \frac{50{,}000}{3.39*10^{14}} + \frac{450{,}000}{1.64*10^{9}} + \frac{250{,}000}{2.07*10^{15}}$$

$$= 1.47*10^{-10} + 2.74*10^{-4} + 1.21*10^{-10} = 0.03\%$$

Remaining life:

for spring: $R_f = 1 - 1.47*10^{-10} \approx 1$

for summer/fall: $R_f = 1 - 2.74*10^{-4} \approx 1$

for winter: $R_f = 1 - 1.21*10^{-10} \approx 1$

For this example the results indicate that there has been no rutting damage at all.

5.5 Determination of Required Pavement Life

Required pavement life for each season is:

Season	Required Life
spring	N_{sp} = 140,700
summer/fall	N_{su} = 1,206,000
winter	N_{wi} = 703,500

These values will be used to determine whether an overlay is required.

5.6 Determination of Total Pavement Damage

For the AC layer, the total pavement damage is determined using the both historical and future traffic

$$\text{spring: } \frac{50{,}000 + 140{,}700}{7.31*10^5} = \frac{190{,}700}{7.31*10^5} = 0.261$$

$$\text{summer/fall: } \frac{450{,}000 + 1{,}206{,}000}{1.20*10^6} = \frac{1{,}656{,}000}{1.20*10^6} = 1.38$$

$$\text{winter: } \frac{250{,}000 + 703{,}500}{2.16*10^9} \approx \frac{953{,}500}{2.16*10^9} \approx 0$$

$$\text{Total pavement damage} = 0.261 + 1.38 + 0 = 1.641$$

$$= 164.1\% > 100\%$$

This indicates an overlay is needed for the projected traffic since the total pavement damage is greater than 100%.

5.7 Overlay Design

Assume a half-inch overlay (illustrates the procedures of overlay design. In practice, minimum overlay thickness should be used) and that the material properties of the overlay are the same as the existing surface. Use ELSYM5 program to calculate pavement strains after adding an overlay. The other data are the same as given in the assumptions.

Calculated Strains (μ-strain)	Spring	Summer/ Fall	Winter
Maximum tensile strains in original AC layer	291	436	26
Maximum compressive strains in subgrade	5	90	4

5.8 Determination of Pavement Life After Overlay

Use TAI equations to determine the pavement life.

For control of fatigue

spring: $N_f = 18.4*4.78998*0.004325*(291*10^{-6})^{-3.291}*1{,}000{,}000^{-0.854}$

$= 1{,}242{,}985 = 1.25*10^{6}$

summer/fall: $N_f = 18.4*4.78998*0.004325*(436*10^{-6})^{-3.291}*200{,}000^{-0.854}$

$= 1{,}298{,}697 = 1.30*10^{6}$

winter: $N_f = 18.4*4.78998*0.004325*(26*10^{-6})^{-3.291}*2{,}000{,}000^{-0.854}$

$= 1.95*10^{9}$

For control of rutting:

spring: $N_f = 1.36*10^{-9}*(5*10^{-6})^{-4.48}$

$= 7.62*10^{14}$

summer/fall: $N_f = 1.36*10^{-9}*(90*10^{-6})^{-4.48}$

$= 1.81*10^{9}$

winter: $N_f = 1.36*10^{-9}*(4*10^{-6})^{-4.48}$

$= 2.07*10^{15}$

Note: the tensile strains are on the underside of the original AC layer. These values are reduced after adding an overlay. The remaining life factor is not used in this part of the calculation.

5.9 Determination of Pavement Damage After Overlay

Use Miner's rule to determine the damage after the overlay.

For AC layer:

spring: $\text{Damage} = \dfrac{190{,}700}{1.24*10^6} = 0.154$

summer/fall: $\text{Damage} = \dfrac{1{,}656{,}000}{1.30*10^6} = 1.274$

winter: $\text{Damage} = \dfrac{953{,}500}{1.95*10^9} \approx 0$

Total damage = 0.154 + 1.274 + 0 = 1.428 > 1.0

For subgrade:

spring: $\text{Damage} = \dfrac{190{,}700}{7.62*10^{14}} \approx 0$

summer/fall: $\text{Damage} = \dfrac{1{,}656{,}000}{1.81*10^9} \approx 0$

spring: $\text{Damage} = \dfrac{953{,}500}{1.95*10^9} \approx 0$

Total damage ≈ 0

The results indicate that the total damage for AC layer is still greater than one, the overlay needs to be thickened.

Add another half-inch of overlay and go to section 5.7. Per calculations as illustrated in sections 5.7 to 5.9. Repeat this process until the total damage for both AC layer and subgrade is less than one.

Table 5.2 summarizes the calculation results. The calculations show that a 1.5-in. overlay is required. The total damage is 95.8% for the AC layer and 0% for the subgrade.

Table 5.2. Summary of the Example Calculation.

Overlay Thickness (in.)	Season	Calculated Strains*		Traffic Repetitions		Failure Repetitions		Damage (%)		Total Damage (%)	
		AC**	Subgrade	Historical	Future	Surface	Subgrade	AC	Subgrade	AC	Subgrade
0	Spring	342	6	50,000	70,000	$7.31*10^5$	$3.39*10^{14}$	26.1	0		
	Summer/ Fall	447	92	450,000	600,000	$1.20*10^6$	$1.64*10^9$	138.4	0		
	Winter	25	4	250,000	350,000	$2.16*10^9$	$2.07*10^{15}$	0	0	164.5	0
0.5	Spring	291	5			$1.24*10^6$	$5.01*10^{14}$	15.4	0		
	Summer/ Fall	436	90			$1.30*10^6$	$1.85*10^9$	127.4	0		
	Winter	26	4			$1.92*10^9$	$2.58*10^{15}$	0	0	142.8	0
1.0	Spring	251	5			$2.02*10^6$	$6.68*10^{14}$	9.4	0		
	Summer/ Fall	416	87			$1.52*10^6$	$2.08*10^9$	109.3	0		
	Winter	26	4			$1.95*10^9$	$2.90*10^{15}$	0	0	118.7	0
1.5	Spring	218	5			$3.22*10^6$	$8.90*10^{14}$	5.9	0		
	Summer/ Fall	392	85			$1.84*10^6$	$2.34*10^9$	89.9	0		
	Winter	25	4			$2.50*10^9$	$3.24*10^{15}$	0	0	95.8	0

*microstrain (10^{-6} in./in.)
**strain values at the bottom of the existing AC layer

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