AN ABSTRACT OF THE THESIS OF

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Title: Development of a Mechanistic Overlay Design Procedure for Flexible Pavements

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Abstract approved ______________________________

R. Gary Hicks

This dissertation describes the development of a mechanistic overlay design procedure. The mechanistic analysis represents a new trend in both new pavement and overlay design. The greatest advantage of the mechanistic pavement analysis is that it considers the fundamental characteristics of materials to be used, is capable of considering changes in loading and tire pressure, and characterizes the response of the pavement to traffic loads in terms of strains and/or stresses. This type of analysis allows practicing engineers to more realistically address pavement structure, materials, and other influential variables such as environmental impacts so that the behavior of the pavement may be better understood.

One of the critical steps in using the mechanistic type pavement analysis is the determination of pavement layer properties (e.g, resilient modulus). In this study, methods commonly used for determining resilient modulus have been reviewed. Three existing mechanistic overlay design procedures were also reviewed. Based on the review, improved procedures for determining pavement layer moduli

and overlay design seem to be necessary.

Significant contributions of this study are the development and computerization of an improved backcalculation procedure (BOUSDEF) for determining pavement layer moduli and an improved mechanistic overlay design procedure (MECHOD).

Initial evaluations on both procedures were performed. For BOUSDEF, three approaches were used: 1) comparing with hypothesized theoretical moduli, 2) comparing with other developed backcalculation programs, and 3) comparing with laboratory tested modulus values. The evaluation showed BOUSDEF provided favorable comparisons. Therefore, the program can be effectively used as a tool to make initial evaluation of deflection testing data for determining pavement layer moduli. For MECHOD, actual pavement data from the states of Oregon and Alaska were used. All pavements evaluated are conventional structures consisting of an asphalt concrete surface, an aggregate base and/or a subbase, over subgrade. The evaluation showed that the improved method provided very similar results to those of standard procedures (ODOT, AASHTO, and The Asphalt Institute).

The BOUSDEF and MECHOD programs can be implemented together as a pavement evaluation and overlay design system. That is; 1) use BOUSDEF to backcalculate pavement layer moduli, and 2) use MECHOD to perform overlay design.

DEVELOPMENT OF A MECHANISTIC OVERLAY DESIGN PROCEDURE FOR FLEXIBLE PAVEMENTS

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure		Page

Figure | Page

Figure | Page

LIST OF TABLES

DEVELOPMENT OF A MECHANISTIC OVERLAY DESIGN PROCEDURE FOR FLEXIBLE PAVEMENTS

1.0 INTRODUCTION

1.1 Problem Statement

As the nation's highways age and are subjected to ever increasing loads and volume of traffic, they will inevitably deteriorate and eventually require some type of treatment to be able to provide a safe and serviceable facility for the user (Finn, 1984). The types of treatment that are appropriate to maintain pavement serviceability can range from relatively simple maintenance to complete reconstruction. For pavements subjected to moderate and heavy traffic, asphalt overlays provide one of the most cost-effective methods of improving existing pavements (The Asphalt Institute, 1983). Asphalt overlays can be used to strengthen existing pavements, to reduce maintenance costs and increase pavement life, to provide a smooth ride, and to reduce safety hazards by improving pavement surface skid resistance.

The design approach used to determine the thickness of the overlay can range from engineering judgement to a fully mechanistic analysis. Generally, the design procedures may be categorized into four types: 1) engineering judgement, 2) component analysis, 3) nondestructive testing with limiting deflection criteria, and 4) mechanistic analysis based on interpretation of nondestructive testing or laboratory data with appropriate failure criteria.

Current overlay design procedures generally fall in the first three categories. The major limitations for each of the current design procedure are listed below:

1) Engineering judgement - no theoretical background, subjective, and vulnerable to personnel changes.
2) Component analysis - primarily based on empirical relationships developed from the AASHO Road Test and is difficult to evaluate changes in loads and environmental impacts.
3) Limiting deflection methods - maximum deflection does not reflect individual layer properties and is limited to materials and constructions for which correlations are established.

The mechanistic type of analysis represents a new trend for overlay design. The greatest advantage of the mechanistic type of pavement analysis is that it considers the fundamental characteristics of materials to be used, is capable of considering changes in loading and tire pressure, and characterizes the response of the pavement to traffic loads in terms of strains and /or stresses. This type of analysis allows practicing engineers to more realistically address pavement structure, material, and other influential factors such as environmental impacts so that the behavior of the pavement may be better understood. Some of the advantages and disadvantages of these four types of overlay design procedures are summarized in Table 1.1.

Table 1.1 Advantages and Disadvantages of Overlay Design Procedures (Hicks, 1988)

Procedure	Advantages	Disadvantages
Engineering Judgment	Simple.	No theoretical basis. Subjective.
Component Analysis	Assesses individual layers as they exist in the pavement. Related to existing conventional design procedures that have large amount of background information.	Limited amount of sampling and testing (to minimize cost). Conditions at the time of sampling may not represent general state of materials. Time required for sampling and testing. Oriented to distress mode for which associated design procedure was developed; e.g., CBR procedure associated with plastic deformation. Not applicable to new materials
Deflection Based	Areal coverage. Measurements representative of in-situ conditions. Relatively inexpensive. Relatively fast. Relatively high degree of reliability possible.	Does not measure materials properties. Limited to materials and constructions for which correlations are established. Related to one mode of distress; e.g., fatigue cracking.
Analytically Based (mechanistic)	Appropriate distress modes can be considered individually; e.g., fatigue, rutting, low-temperature cracking. Capable of considering: • changed loading and tire pressure effects, • new materials, • environmental influences, • aging effects, and • influence of changed subsurface drainage conditions.	Unfamiliar to most current designers. Requires new and different equipment. Limited experience to date. May require the use of a computer.

1.2 Objectives

The major objectives of this study are to develop a fully mechanistic overlay design procedure for flexible pavements and a fully computerized procedure for routine design work. Specifically, the objectives are to:

1. develop an improved mechanistic overlay design procedure,
2. develop an improved backcalculation procedure for determining existing pavement structural capacity,
3. evaluate the developed backcalculation procedure,
4. evaluate the developed overlay design procedure on selected projects, and
5. prepare recommendations for implementation of the procedures.

1.3 Scope

To accomplish the objectives, the following tasks were undertaken:

1. review of stresses, strains, and deformations in pavement structures, including consideration of non-linearity of pavement materials and overburden stresses (Chapter 2),
2. review of current methods for backcalculating layer moduli (Chapter 3),
3. development and evaluation of an improved backcalculation procedure for determining pavement layer moduli (Chapter 4),
4. Review of modulus determination using laboratory tests and correlations (Chapter 5),

5. review of current mechanistic overlay design procedures and development of an improved mechanistic overlay design procedure, (Chapter 6),
6. evaluation of the improved procedures on selected projects (Chapter 7), and
7. recommendations for implementation (Chapter 8).

Task 1: This task reviewed background information necessary for mechanistic analysis of pavement structures. In particular, stresses, strains, and deformations in pavements resulting from traffic loads were reviewed. Methods that are commonly used to calculate stresses, strains, and deformations were discussed.

Many researchers have shown that pavement materials, especially coarse-grained and fine-grained, are load dependent. That is, these materials behave differently under different stress conditions. For coarse-grained materials, which are usually used for base layers, the resilient modulus increases as the applied load or stress increases. For fine-grained materials, which are usually used for subgrade, the resilient modulus decreases as the stress magnitude increases. These non-linear properties of pavement materials should be carefully considered for the design condition. Static pressure or overburden stress of pavement materials were also reviewed.

Task 2: In using a mechanistic approach, one of the most important considerations is the determination of resilient modulus values for each pavement layer. This fundamental material property represents the structural capacity of the material and has a great impact on design thicknesses needed to carry the anticipated traffic applications. Two methods have been used for determining the modulus values of a pavement material, laboratory tests and backcalculation. Laboratory tests are performed on materials sampled from field using specialized equipment. Backcalculation is conducted using a computer program to calculate modulus values for each layer from deflection basin data which can be measured using a non-destructive device. Several backcalculation programs have been developed and are widely used for determining modulus values. These existing procedures can be broadly categorized into three groups: 1) equivalent thicknesses methods, 2) elastic layer methods, and 3) finite element methods. Two programs in the category of method of equivalent thicknesses were reviewed. They are ELMOD and SEARCH. Several programs in the group of elastic layer method were also looked into. These programs are CHEVDEF/BISDEF, ELSDEF, MODCOMP2, MODULUS, PFEDDI, and ISSEM4. A single backcalculation procedure ILLI-CALC which uses finite element method was also reviewed.

It is difficult to conclude if one program is superior to the others. In general, the programs which use the method of equivalent thicknesses take much less computing time than both elastic layer theory and finite element methods.

Task 3: Preliminary use of three backcalculation programs, BISDEF, ELSDEF, and MODCOMP2, shows that both BISDEF and ELSDEF do not consider the non-linearity of the pavement materials. MODCOMP2 is capable of handling non-linearity of the pavement materials; however, this capability does not always operate properly. Very often, unknown errors occur during computation. And all three programs take a fair amount of computing time to solve a data set. This significantly impairs the use of the backcalculation method. Task 3, therefore, was to develop an improved method for backcalculation. This improved backcalculation method uses much less computing time for backcalculation and also considers the non-linearity of the base and subgrade materials.

Initial evaluation on the developed backcalculation procedure was made. The evaluation was performed using three approaches: 1) comparing backcalculated moduli with preassumed theoretical moduli, 2) comparing with other backcalculation programs, and 3) comparing backcalculated moduli with laboratory test results. The evaluation shows that the moduli backcalculated using the BOUSDEF program compare very well with the preassumed theoretical values and are very compatible with the other programs used for comparison. The comparison with the laboratory test results on the two projects also compared favorably.

Task 4: This task reviewed several techniques for determining resilient modulus through laboratory tests and using developed correlations, which are widely used around the United States. These techniques include laboratory tests to determine resilient moduli of pavement materials and correlations to estimate the resilient modulus.

The advantage of the laboratory tests to determine resilient modulus is its ability to measure the strength of a particular material directly. The disadvantage is that the samples tested in the laboratory may represent a portion of pavement material rather than an average condition one would find in the field. Moreover, laboratory tests require sophisticated equipment and well trained personnel to perform the tests, and laboratory tests usually take a significant amount of time.

The advantage of using developed correlations is their availability. However, one must be aware that the correlations were developed based on certain laboratory conditions. Therefore, these correlations are best suited to situations similar to those for which the correlations were developed. Caution should be exercised when using these correlations.

Task 5: In the past years, several overlay design procedures using the mechanistic approach have been developed such as the Alaska DOT&PF, Washington State DOT, and ARE methods. This task reviewed these three methods. The review indicated that one common ground for these developed procedures is that they all use multi-layered elastic theory to model a flexible pavement structure and to determine pavement life using various design criteria. This kind of approach is also being used by an on-going research activity, NCHRP project 1-26 (Thompson, 1989). It is expected that the next edition of the AASHTO Guide on flexible pavement design will also move in this direction.

A shortcoming in all three procedures is that of characterizing the seasonal effects on the pavement materials properties. In both the ARE and the Alaska methods, pavement properties at a representative temperature of 70°F are recommended for design purposes rather than those at different seasons. In the WSDOT method, seasonal variations are considered. However, for the base and subgrade materials, modulus ratios between the dry and wet materials are used rather than a direct consideration of the base and subgrade material properties for each season. Since the seasonal effects have great influence on pavement layer properties (and some other factors such as traffic distribution), which in turn may result in varying pavement damage, therefore, an improved approach to address the seasonal effects seems to be necessary.

Based on the review, an improved mechanistic overlay design procedure was developed. The major improvement over the above three procedures is in the direct consideration of seasonal effects on pavement material properties and pavement damage due to traffic loadings within each season.

The improved procedure has been computerized and can be operated on IBM or compatible microcomputers. The resulted computer program MECHOD is easy to use and user friendly.

Task 6: This task evaluated the improved mechanistic overlay design procedure. The evaluation included the following steps:

1. Select projects for evaluation.
2. Perform deflection test using FWD.
3. Determine pavement layer moduli for overlay design.
4. Perform overlay design using the improved procedure.
5. Compare overlay design results from the improved procedure with those from standard procedures.

The initial evaluation of the improved mechanistic overlay design procedure was performed using actual pavement data from the states of Oregon and Alaska. All pavements evaluated are conventional pavements consisting of an asphalt concrete surface, an aggregate base and/or a subbase, and subgrade. The overlay design results from the improved procedure were compared with three standard procedures developed by ODOT, AASHTO, and The Asphalt Institute. The results showed that the improved method provided very compatible results to those of the standard procedures.

Task 7: This task summarizes the work accomplished during this study and provides recommendations for implementation. Specifically, these recommendations include the use of BOUSDEF, a backcalculation program, and MECHOD, an improved mechanistic overlay design program, both developed during the course of the study.

For additional research recommendations, verification of the backcalculated results and development of design criteria for local conditions are suggested. Further improvements to BOUSDEF and MECHOD programs are also discussed. The overall study approach for conducting this research is summarized in Figure 1.1.

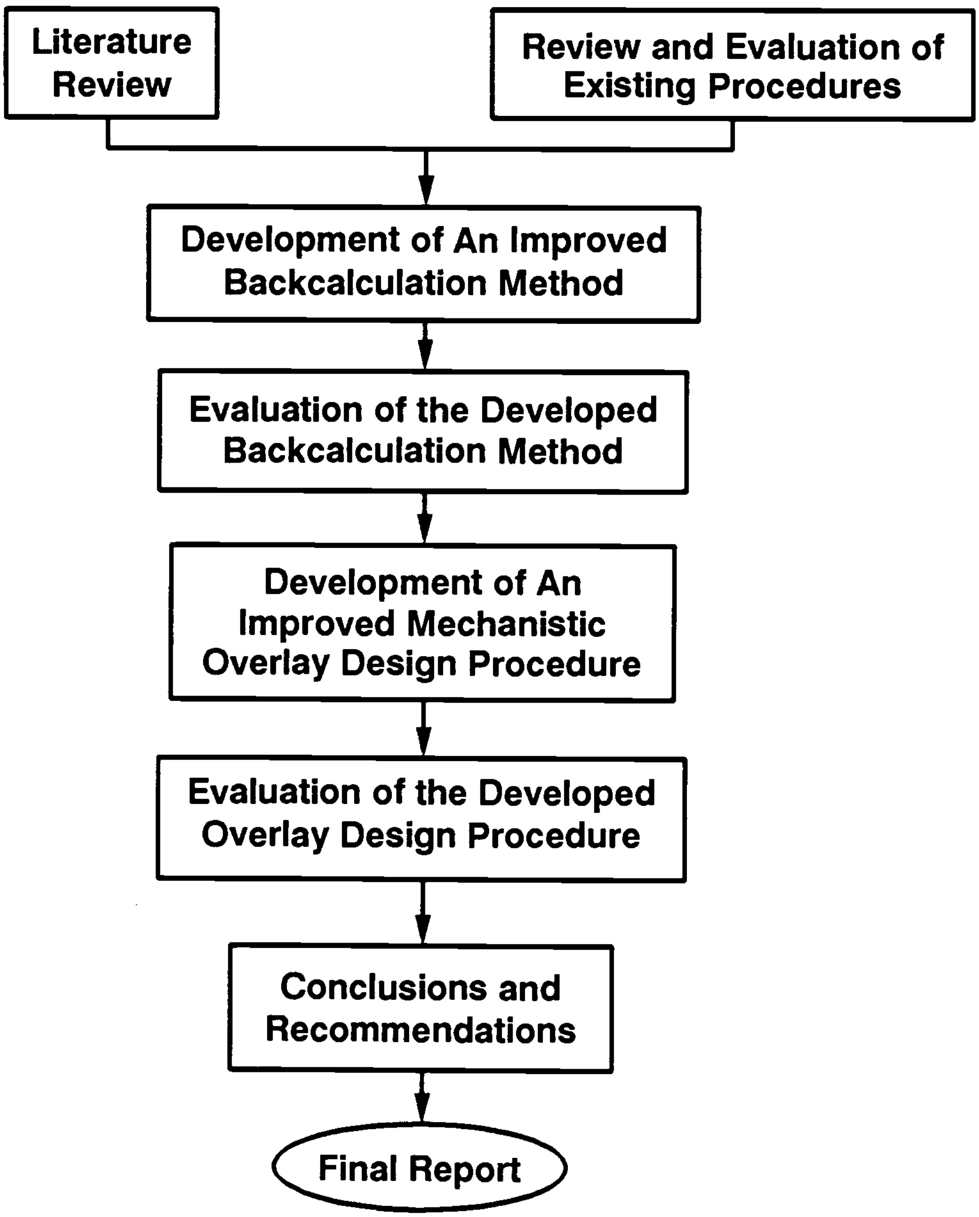


Figure 1.1 Study Approach

2.0 BACKGROUND ON MECHANISTIC ANALYSIS FOR FLEXIBLE PAVEMENTS

Pavement analysis, design and evaluation, as other engineering techniques, might be better accomplished if the engineer had the ability to analyze the pavement structure in terms of some fundamental concepts such as the stresses, strains, or deformations and the characteristics of the pavement material due to the application of traffic, environment, and the effects of aging. This chapter describes some of these basic concepts related to this research.

2.1 Stresses, Strains, and Deformations in Pavements

Pavements under traffic load application experience stresses, strains or deformations. The pavement response can be determined quantitatively using theoretical analysis. Analysis theories that have been developed or are being developed include elastic half-space system, layered elastic theory, finite element analysis, and viscoelastic analysis. The theory of elasticity is by far the most wide spread method. This research uses the theory of elasticity as a tool for the development of a mechanistic overlay design procedure.

Before developing an improved mechanistic overlay design procedure, a backcalculation program (based on elastic half-space system) is developed to determine pavement layer moduli, a key element in pavement analysis using a mechanistic approach. The following paragraphs describe first the solution techniques used to develop the backcalculation program.

2.1.1 Basic Law

The basic law used in the theory of elasticity is that developed by Hookes. Two material parameters are needed to use the theory: the coefficient of elasticity (Young's modulus, E) and Poisson's ratio (μ). The coefficient of elasticity is defined as the ratio of stress (σ) over strain (ϵ) and is a constant as stated by Hookes's law. Poisson's ratio is defined as the ratio of lateral and axial strains as shown in Figure 2.1. In the sample case, the Poisson's ratio is a constant. For the three dimensional case, generalized Hookes's law may be expressed as:

$$\begin{aligned} E * \epsilon_x &= \sigma_x - \mu\ (\sigma_y + \sigma_z) \\ E * \epsilon_y &= \sigma_y - \mu\ (\sigma_x + \sigma_z) \\ E * \epsilon_z &= \sigma_z - \mu\ (\sigma_x + \sigma_y) \end{aligned} \qquad (2\text{-}1)$$

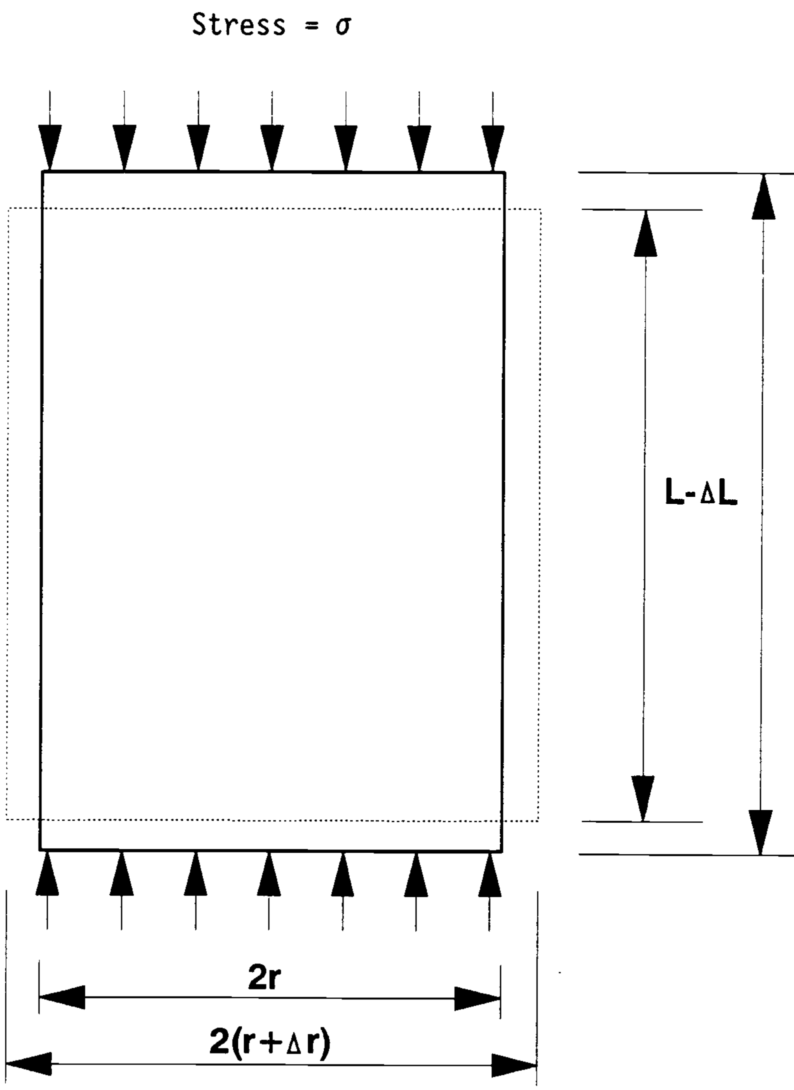
where:

E	=	coefficient of elasticity
μ	=	Poisson's ratio
σ	=	stress in indexed axis
ϵ	=	strains in indexed axis

For real pavement materials, neither the modulus (E) nor Poisson's ratio (μ) are constants but vary as functions of a number of different factors such as temperature, moisture content, and stress conditions. Therefore, care must be taken in applying elastic theory to pavement structures.

2.1.2 Elastic Half-Space System (Boussinesq Equations)

Boussinesq formulated a set of equation in 1885 for calculating



Strain: $\epsilon_1 = \Delta L / L$

Young's Modulus: $E = \sigma / \epsilon_L$

Poisson's Ratio: $\mu = \epsilon_r / \epsilon_L$

Figure 2.1 Definition of Coefficient of Elasticity and Poisson's Ratio for the Uniaxial Case the stresses, strains, and deflections for a homogeneous, isotropic, linear elastic semi-infinite space. In the development of these equations, two loading conditions were considered: a point load and a distributed load, as described below.

2.1.2.1 Point Load

Figure 2.2a shows a point load condition together with the geometrical descriptions required for solution of the equations. Various equations for calculating normal stresses (σ), normal strains (ϵ), shear stresses (τ), and displacements (δ) are given in Table 2.1.

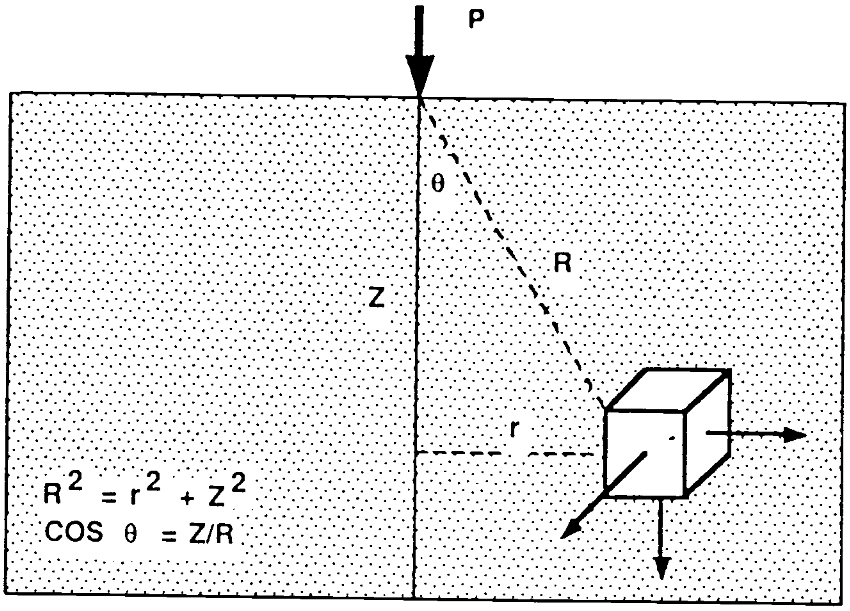
2.1.2.2 Distributed Load

For a load uniformly distributed over a certain area as shown in Figure 2.2b, the stresses, strains, and displacement under the center line of the load can be found through numeric integration. The analytical solutions are given in Table 2.2.

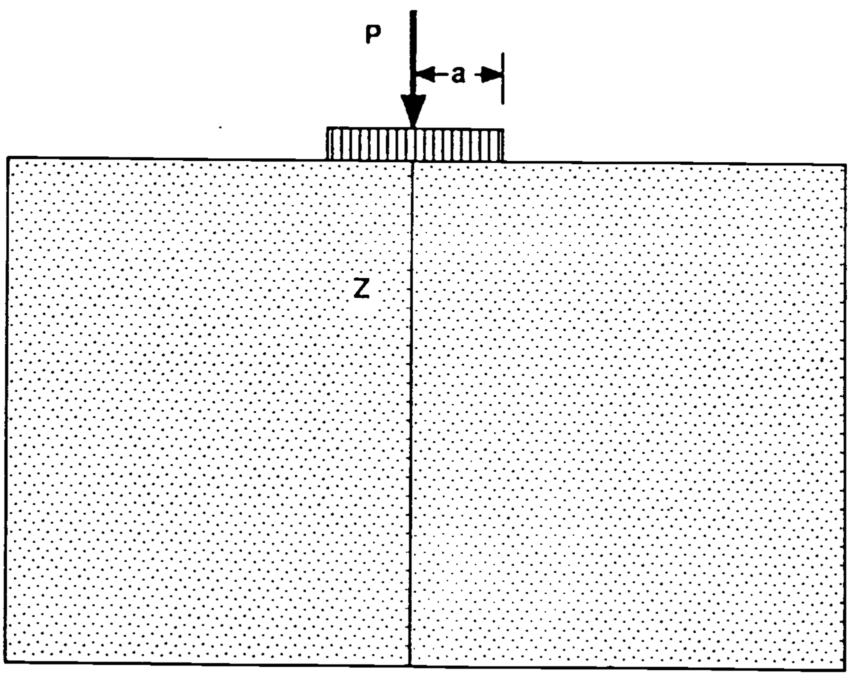
For an off-axle location, solution for a uniformly distributed load can be obtained numerically. However, unless such a location is close to the point of contact of load, the point load equations can be used without serious error (Ullidtz ,1980).

2.1.3 Layered systems

Flexible pavements normally consist of several layers of material, therefore, it is natural to use the theory of layered systems for the analysis of a pavement structure. A generalized layer system is illustrated in Figure 2.3. In a multi-layer system, each layer is represented by layer thickness, modulus of elasticity, and Poisson's ratio. Under the action of loads, stress distribution is



a) Point Load



b) Distributed Load

Figure 2.2 Conceptual Representation of Boussinesq's Half Space Loading Condition

Table 2.1 Boussinesq's Equations for a Point Load

(Ullidtz, 1987)

Normal Stresses

$$\sigma_z = \frac{3P}{2\pi R^2} * \cos^3\theta \tag{2-2}$$

$$\sigma_r = \frac{P}{2\pi R^2} * \left[3\cos\theta \sin^2\theta - \frac{1-2\mu}{1+\cos\theta}\right] \tag{2-3}$$

$$\sigma_t = \frac{P}{2\pi R^2} * (1-2\mu)\left[-\cos\theta + \frac{1}{1+\cos\theta}\right] \tag{2-4}$$

$$\sigma_1 = \frac{3P}{2\pi R^2} * \cos\theta \tag{2-5}$$

$$\sigma_v = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) = \frac{P}{3\pi R^2} * (1+\mu)\cos\theta \tag{2-6}$$

Shear Stresses

$$\tau_{rz} = \frac{3P}{2\pi R^2} * \cos^2\theta\sin\theta \tag{2-7}$$

$$\tau_{rt} = \tau_{tz} = 0$$

Normal Strains

$$\epsilon_z = \frac{(1+\mu)P}{(2\pi R^2 E)} * (3\cos^3\theta - 2\mu\cos\theta) \tag{2-8}$$

$$\epsilon_r = \frac{(1+\mu)P}{(2\pi R^2 E)} * \left[-3\cos^3\theta + (3-2\mu)\cos\theta - \frac{1-2\mu}{1+\cos\theta}\right] \tag{2-9}$$

$$\epsilon_t = \frac{(1+\mu)P}{(2\pi R^2 E)} * \left[-\cos\theta + \frac{1-2\mu}{1+\cos\theta}\right] \tag{2-10}$$

$$\epsilon_v = \epsilon_z + \epsilon_r + \epsilon_t = \frac{(1+\mu)P}{(\pi R^2 E)} * (1-2\mu)\cos\theta \tag{2-11}$$

Displacements

$$d_z = \frac{(1+\mu)P}{(2\pi RE)} * [2(1-\mu) + \cos^2\theta] \tag{2-12}$$

$$d_r = \frac{(1+\mu)P}{(2\pi RE)} * \left[\cos\theta\sin\theta - \frac{(1-2\mu)\sin\theta}{1+\cos\theta}\right] \tag{2-13}$$

$$d_t = 0$$

Table 2.2 Boussinesq Equations for Distributed Load

(Ullidtz, 1987)

$$\sigma_z = \sigma_o * \left[1 - \frac{1}{\left[1+(a/z)^2\right]^{1.5}}\right] \quad (2\text{-}14)$$

$$\sigma_r = \sigma_t = \sigma_o * \left[\frac{1+2\mu}{2} - \frac{1+\mu}{\left[1+(a/z)^2\right]^{.5}} + \frac{0.5}{\left[1+(a/z)^2\right]^{1.5}}\right] \quad (2\text{-}15)$$

$$\epsilon_z = \frac{(1+\mu)\sigma_o}{E} * \left[\frac{z/a}{\left[1+(z/a)^2\right]^{1.5}} - (1-2\mu) * \left[\frac{z/a}{\left[1+(z/a)^2\right]^{.5}} - 1\right]\right] \quad (2\text{-}16)$$

$$d_z = \frac{(1+\mu)\sigma_o}{E} * \left[\frac{1}{\left[1+(z/a)^2\right]^{1.5}} + (1-2\mu) * \left[[1+(z/a)^2]^{.5} - (z/a)\right]\right] \quad (2\text{-}17)$$

$$\epsilon_r = \epsilon_t = \frac{1}{E}\left[\frac{1-\mu}{2\ \mu} * (\sigma_z - E * \epsilon_z) - \mu * \sigma_z\right] \quad (2\text{-}18)$$

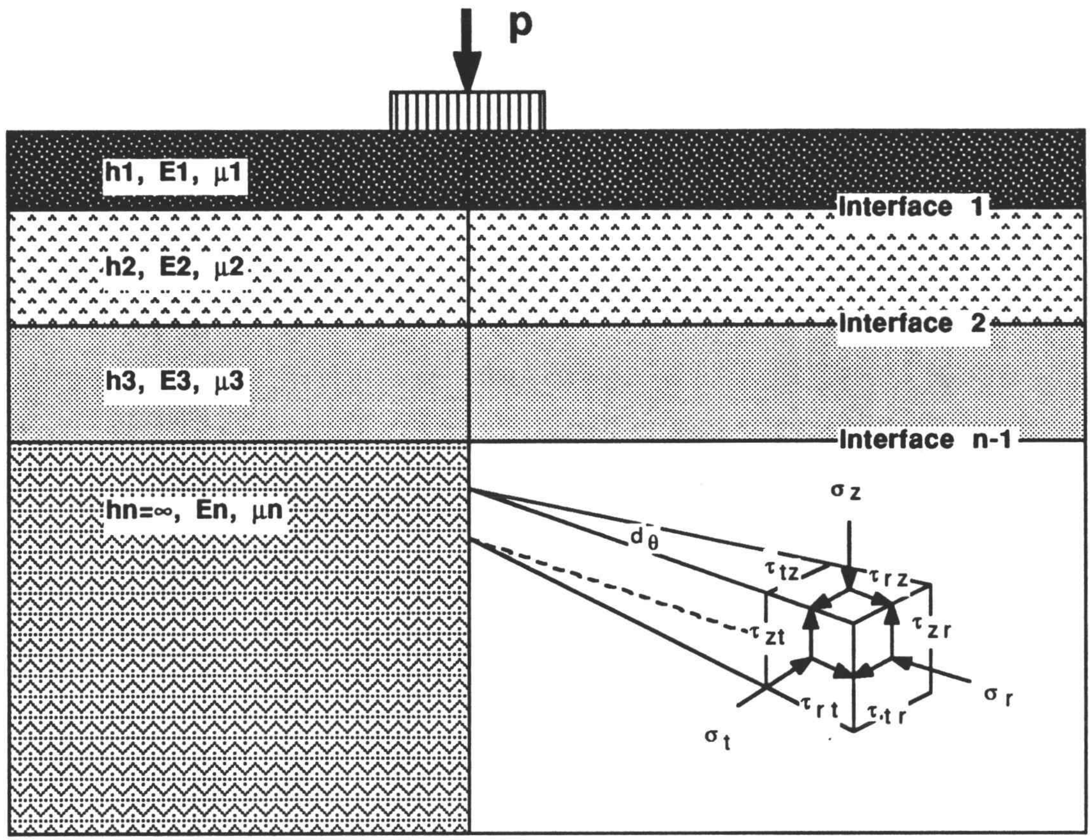


Figure 2.3 Generalized Multi-Layered Elastic System

also shown in Figure 2.3. Because of the complexity of pavement material properties, each pavement layer usually does not behave as a totally elastic body, therefore, certain basic assumptions are often made to idealize a pavement structure so that layered elastic theory can be applied.

2.1.3.1 Theoretical Assumptions

The following assumptions are generally used to idealize a pavement structure:

1) Material properties in each layer are homogeneous (elastic properties are the same at all points in a given material).
2) Material properties in each layer are isotropic (elastic properties are the same in all directions at any point).
3) Each layer has a finite thickness except the lowest layer (presumable the subgrade) and all are infinite in the lateral dimensions.

2.1.3.2 Odemark's Method

Odemark's method (1949) is often referred as the method of equivalent thickness (MET). The MET assumes that any two layers with similar structure stiffness will distribute loading in the same way. Based on this assumption, the MET can be used to transform a system consisting of layers with different moduli into an equivalent system where all layers have the same modulus. A conceptual representation of the MET is shown in Figure 2.4. The transformation is proceeded by the following relationship,

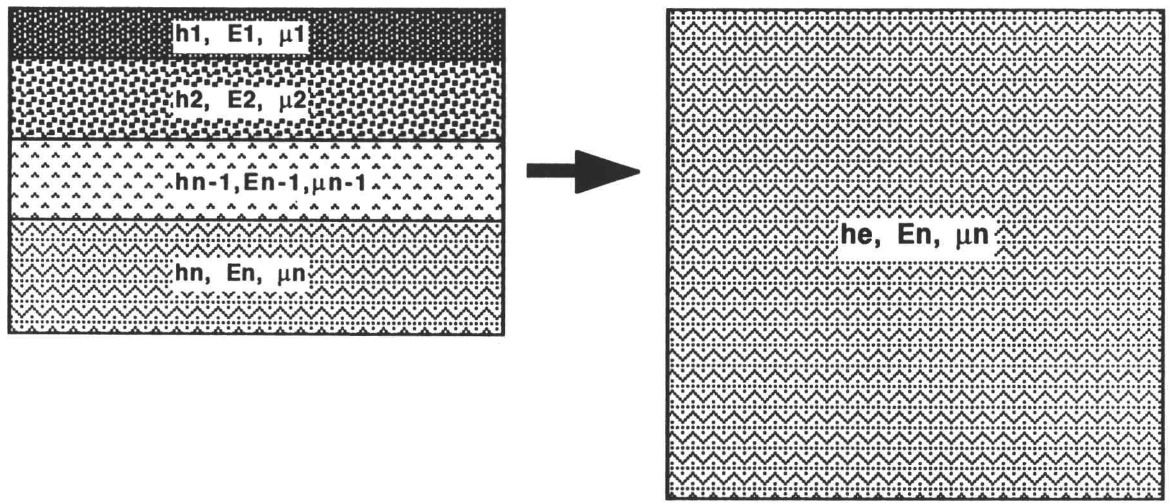


Figure 2.4 Conceptual Representation of the Method of Equivalent Thicknesses

$$D = \frac{Eh3}{12(1-\mu^2)} \qquad (2\text{-}19)$$

where:

D = stiffness,

h = layer thickness,

E = modulus of elasticity, and,

μ = Poisson's ratio.

For a two layer system, the equivalent thickness of a layer with modulus (E_2) and Poisson's ratio (μ_2) relative to a layer of thickness (h_1), modulus (E_1) and Poisson's ratio (μ_1), may be expressed by equating the stiffness of both layers, that is, $D_1 = D_2$. Therefore,

$$\frac{E_1 h_1^3}{12(1-\mu_1^2)} = \frac{E_2 h_2^3}{12(1-\mu_2^2)}$$

or rearranging the equation:

$$h_2 = h_1 * \left[\frac{E_1}{E_2} * \frac{(1-\mu_2^2)}{(1-\mu_1^2)}\right]^{1/3} \qquad (2\text{-}20)$$

By expanding this concept for a multi-layer system as conceptually illustrated in Figure 2.4, a general form of the equation may be written:

$$h_{ei} = \sum_{i=1}^{n-1} h_i * \left[\frac{E_i}{E_n} * \frac{(1-\mu_n^2)}{(1-\mu_i^2)}\right]^{1/3} \qquad (2\text{-}21)$$

where:

h_{ei} = equivalent thickness for i-th layer,

h_i = thickness of i-th layer,

E_i = modulus of i-th layer,

E_n = modulus of n-th layer,

μ_i = Poisson's ratio for i-th layer, and

μ_n = Poisson's ratio for n-th layer.

2.1.3.3 Correction Factors for the Use of Odemark's Method with Boussinesq Equations

The use of the method of equivalent thicknesses allows the Boussinesq theory to be applied in a multi-layer system. Stresses, strains, and deformation at any point in an elastic half-space can be determined by using corresponding Boussinesq equations. In order to obtain good agreement between the stresses, strains, and deflections calculated by the Boussinesq approach and by exact elastic theory, Ullidtz and Peattie (1980) suggest that correction factors should be applied to the equivalent thicknesses. For the simple case of calculations on the axis of an uniformly distributed load, equation (2-21) is modified as follows:

$$h_{ei}' = f * \sum_{i=1}^{n-1} h_i * \left[\frac{E_i}{E_n} * \frac{(1-\mu_n^2)}{(1-\mu_i^2)} \right]^{1/3} \qquad (2\text{-}22)$$

where:

f = correction factor. For a two-layer system, f = 0.9. For a multi-layer system (>2), f = 1.0 for the first layer, and f = 0.8 for the rest of layers.

Additional correction factors are required when using the point load equation for more general analysis, since the assumption that the uniformly distributed load can be approximated by a point load produces inaccuracies near the surface of the pavement. These corrections are as follows (Ullidtz, 1979):

for $Z_i < a$:

$$Z' = \frac{1.5\ a}{2(1-\mu_i^2) - (2(1-\mu_i^2) - 0.7) * (Z_i/2a)} \qquad (2\text{-}23a)$$

and

for $Z_i \geq a$:

$$Z_i' = Z_i + 0.6 * \frac{a^2}{Z_i} \qquad (2\text{-}23b)$$

where:

Z_i = h_{ei}'

a = load radius

It must be kept in mind that these correction factors only improve the agreement with layered elastic theory, and not necessarily the actual stresses or strains in real pavement structures.

2.1.3.4 Limitations of Use of the MET

There are a number of limitations with regard to the use of the method of equivalent thicknesses. One is that the moduli should decrease with depth, preferably by a factor of at least two between consecutive layers. Another is that the equivalent thickness of a layer, preferably, should be larger than the radius of the loaded area (Ullidtz, 1987).

2.1.3.5 Computer Solution to Layered Systems

Burmister (1943) provided analytical expressions for determining stresses and displacements in a two-layer system. Based on Burmister's method, Fox (1948) and Acum and Fox (1951) presented exact solutions for the boundary stresses in the center line of a circular uniformly distributed load acting on the surface of a three-layer system. Since then a large number of computer programs have been developed for calculating stresses, strains, and deflections of layered elastic systems, as listed in Table 2.3. The following briefly describes two such computer programs; ELSYM5 (Hicks, 1982) and BISAR (De Jong, 1973).

2.1.3.5.1 The ELSYM5 Program

The ELSYM5 (Elastic Layered SYsteM) program determines the various component stresses, strains, and displacements along with principal values in a three-dimensional ideal elastic layered system (Hicks, 1982). The layered system can be loaded with one or more identical uniform circular loads normal to the surface of the system.

Each layer of the system is described by its modulus of elasticity, Poisson's ratio and has a uniform thickness extending infinitely in the horizontal direction. The top of the surface is free of shear. The bottom elastic layer may be semi-infinite in thickness or may be given a finite thickness, in which case the program assumes the bottom layer is supported by a rigid base. With a rigid base, the interface between the bottom elastic layer and the base may have either a full friction interface or a non-friction interface. All elastic layer interfaces are continuous. Stresses, strains, and deformations at any location of the system may be calculated.

Table 2.3 Summary of Flexible Pavement Models

Program	Date	Number Layers	Inter-face	Loads[1]	Load-ing[2]	Output	PC Vers	Stress Depend	YLD Crit	Solution Technique
CHEV	1963	5	Rough	Vert	SWL	σ,ϵ	No	No	No	Linear Elas.
BISTRO	1968	5	Rough	Vert	MWL	σ,ϵ,δ	No	No	No	Linear Elas.
CHEV5L	1971	5	Rough	Vert	DUALS	σ,ϵ,δ	No	Yes	No	Linear Elas.
BISAR	1972	10	Any	Tng/Vert	MWL	σ,ϵ,δ	Yes	No	No	Linear Elas.
ELSYM5	1972	5	SM/Rough	Vert	MWL	σ,ϵ,δ	No	No	No	Linear Elas.
	1986	5	SM/Rough	Vert	MWL	σ,ϵ,δ	Yes	No	No	Linear Elas.
MWELP	1972	15	Rough	Vert	MWL	σ,ϵ,δ	No	No	No	Linear Elas.
ELP-15	1973	15	Rough	Vert	SWL	σ,ϵ,δ	No	No	No	Linear Elas.
SDEL	1974	5	Rough	Vert	SWL	σ,ϵ,δ	Yes	No	No	Linear Elas.
CHEVIT	1976	Any	Rough	Vert	MWL	σ,ϵ,δ	No	Yes	No	Linear Elas.
ILLI-PAVE	1980	Any	Rough	Radial/ Vert	SWL	σ,ϵ,δ	Yes	Yes	Yes	Finite Elem.

[1] All solutions are for axysymmetrical conditions

[2] SWL=Single Wheel Loading; MWL=Multi-Wheel Loading

The program requires the following information for calculating the stresses, strains and displacements:

1. The number of layers;
2. Modulus and Poisson's ratio of each layer;
3. The thickness of each layer, except for the subgrade;
4. The interface friction description at the bottom layer if this layer has finite depth;
5. The number of loads, the vertical and tangential component of each load, and the position of the loads;
6. The stress, strain and displacement components to be calculated;
7. The number of places where calculations are required along with their position (Cartesian coordinates).

2.1.3.5.2 <u>The BISAR Program</u>

The BISAR (BItumen Structures Analysis in Roads) program (De Jong, 1973) is a general purpose program for computing stresses, strains, and displacements in elastic layered systems subjected to one or more vertical uniform circular loads applied at the surface of the system. In this program, all layers extend infinitely in the horizontal direction. The top surface of the system is free of shear as in ELSYM5. All interfaces between layers have an interface friction factor which can vary between zero (full continuity) and one (frictionless slip) between the layers.

Stresses, strains and displacements are calculated in a cylindrical coordinate system for each vertical load. For more than one load, the cylindrical components are transformed to a Cartesian coordinate system and the effect of the multiple load found by summarizing the stresses, strains and displacements of each wheel. Further, the program calculates only those components that are requested as listed in Table 2.4. If all stresses and strains are calculated, the program calculates the principal stresses and strains and their accompanying directions. The principal directions denote the normals of the planes through the point considered, which are free of shear stress (strain). The highest and lowest of the three principal values give the maximum and minimum normal stresses (strains), and the difference between the principal values divided by two, gives the maximum shear stresses (strains).

The program requires the following information for calculating the stresses, strains and displacements:

1. The number of layers;
2. Modulus and Poisson's ratio of each layer;
3. The thickness of each layer, except for the subgrade;
4. The interface friction at each interface;
5. The number of loads, the vertical and tangential component of each load, and the position of the loads;
6. The stress, strain and displacement components to be calculated;
7. The number of places where calculations are required along with their position (Cartesian coordinates).

2.1.4 Comparison Between Layered Theory and Boussinesq Theory

Initial comparisons were made between the layered elastic theory and Boussinesq equations on the surface deflection calculation. This

Table 2.4 Stresses, Strains and Displacements Calculated by BISAR (Hicks, 1982)

Displacements	UR	-	Radial displacement
	UT	-	Tangential displacement
	UZ	-	Vertical displacement
Stresses	SRR	-	Radial stress
	STT	-	Tangential stress
	SZZ	-	Vertical stress
	SRT	-	Radial/Tangential
	SRZ	-	Radial/Vertical
	STZ	-	Tangential/Vertical
Strains	ERR	-	Radial strain
	ETT	-	Tangential strain
	EZZ	-	Vertical strain
	ERT	-	Radial/Tangential
	ERZ	-	Radial/Vertical
	ETZ	-	Tangential/Vertical
Total displacements	UX	-	X-displacement
	UY	-	Y-displacement
Total stresses	SXX	-	XX component of total stress
	SXY	-	XY component of total stress
	SXZ	-	XZ component of total stress
	SYY	-	YY component of total stress
	SYZ	-	YZ component of total stress
Total strains	EXX	-	XX component of total strain
	EXY	-	XY component of total strain
	EXZ	-	XZ component of total strain
	EYY	-	YY component of total strain
	EYZ	-	YZ component of total strain

comparison illustrates that the Boussinesq equations can be used as a valid approach for calculating the deflections under the application of a load as compared to layered elastic theory.

The comparison was performed using three computer programs with several pavement structures. The three programs used are ELSYM5, BISAR, and DEFLECT, a program which uses Boussinesq equations to calculate pavement surface deflection. Figure 2.5 shows ten pavement structures used for comparison. Among these pavement structures, five are conventional pavement systems, with three 3-layer structures and two 4-layer structures. Two pavement systems have a cement treated base. Three are portland cement concrete (PCC) pavement structures. Resilient modulus for flexible pavements range from 100 ksi to 1,500 ksi to represent typical field conditions. For cement treated base layers and PCC, typical design values are also used.

A 9,000 lb load with radius of 6 inches, representing a typical 18-kip single axle load, is used in the calculation. For flexible pavements, six radial distances were selected for deflection calculation. These were located at 0", 8", 12", 24", 36", and 58". For PCC pavements, seven distances were selected, which were located at 0", 12", 24", 36", 48", 60", and 84". The selection of radial distances was aimed to obtain a deflection basin that would include pavement response from all pavement layers.

Table 2.5 summarizes the calculation results. Results from the BISAR program are basically identical to those from ELSYM5 for the ten pavement structures analyzed. The results are plotted in Figures 2.6 to 2.9. As can be seen from these figures, both layered theory and Boussinesq equations generate very similar results for the

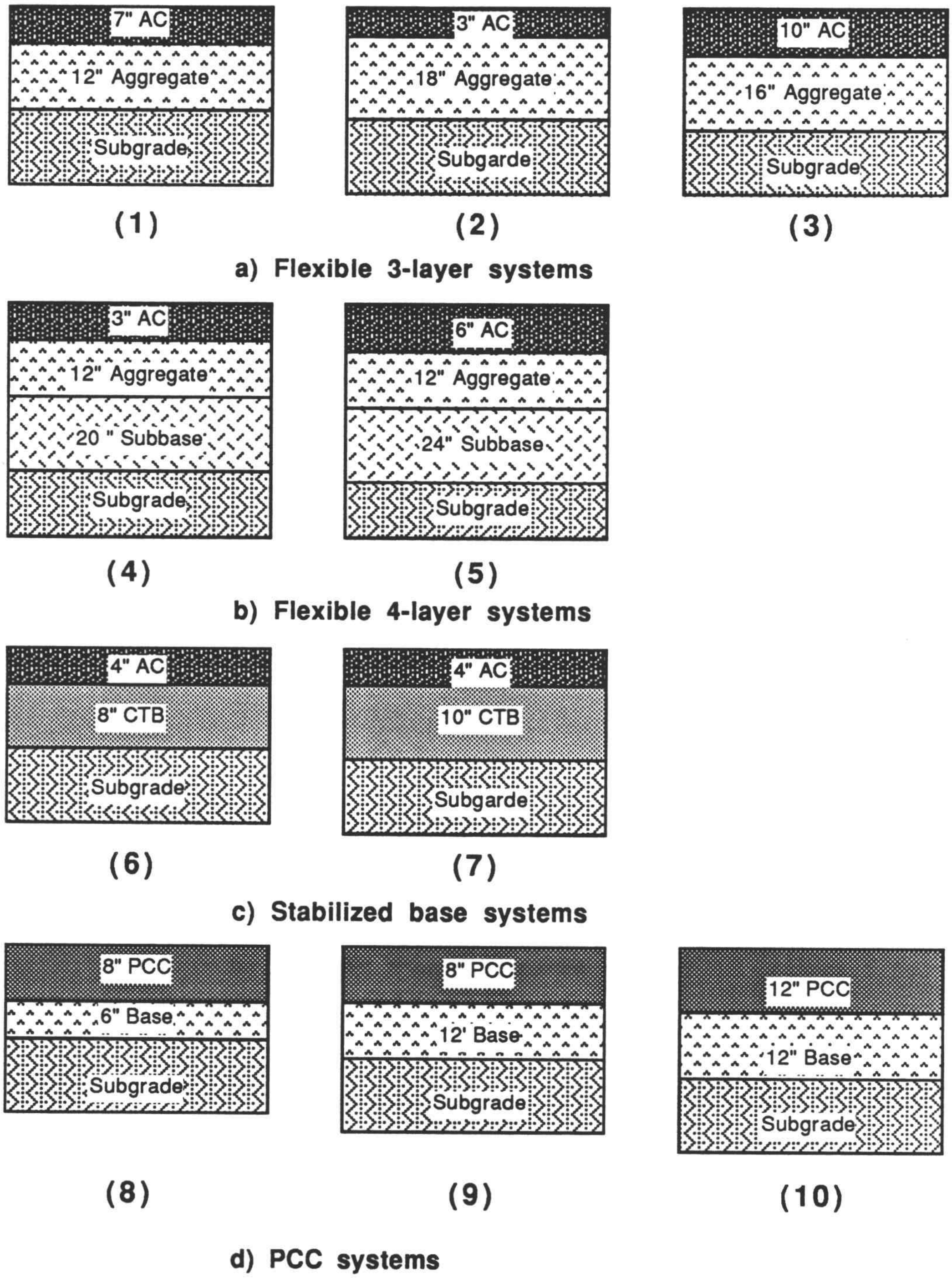


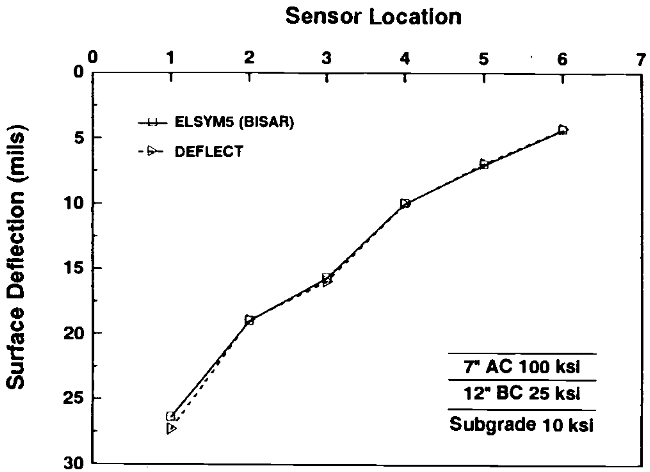
Figure 2.5 Pavement Structures Used for Comparing Surface Deflections Using Layered Theory and Boussinesq Equations

Table 2.5 Summary of Deflection Calculations

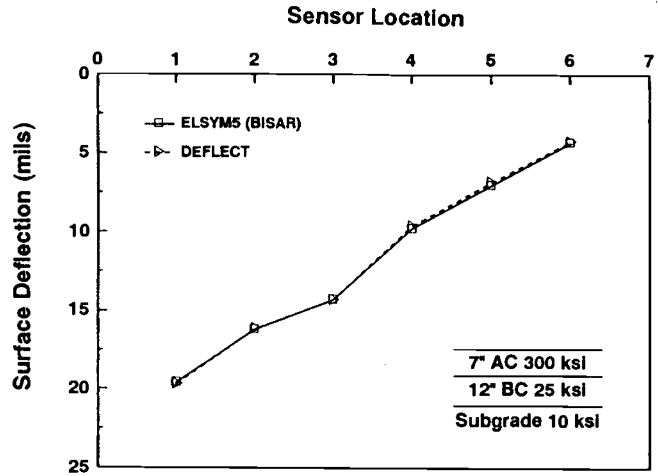
Eac (ksi)	Results from ELSYM5 (BISAR) Deflections @ sensor locations (mils) 1	2	3	4	5	6	7	Results from DEFLECT Deflections @ sensor locations (mils) 1	2	3	4	5	6	7
Structure 1														
100	26.40	19.00	15.70	9.96	7.02	4.33		27.35	18.92	15.97	10.00	6.91	4.27	
300	19.60	16.20	14.30	9.82	7.06	4.37		19.71	16.17	14.32	9.67	6.88	4.30	
600	16.30	14.30	13.00	9.54	7.08	4.44		16.17	14.17	12.93	9.29	6.79	4.32	
1,000	14.10	12.80	11.90	9.17	7.03	4.51		13.98	12.69	11.80	8.90	6.68	4.32	
1,500	12.60	11.60	11.00	8.78	6.92	4.56		12.44	11.54	10.88	8.53	6.55	4.31	
Structure 2														
100	38.20	23.20	16.80	9.71	6.86	4.29		41.13	23.04	17.66	10.10	6.86	4.23	
300	32.30	22.30	16.90	9.60	6.77	4.26		30.16	21.51	17.22	10.10	6.89	4.25	
600	28.50	21.30	16.80	9.65	6.73	4.24		27.05	20.52	16.74	10.03	6.89	4.26	
1,000	25.70	20.20	16.50	9.75	6.74	4.23		24.56	19.53	16.25	9.96	6.89	4.27	
1,500	23.60	19.20	16.10	9.84	6.78	4.23		22.57	18.59	15.75	9.88	6.88	4.28	
Structure 3														
200	17.00	13.60	12.10	8.89	6.74	4.41		17.20	13.60	12.36	8.99	6.67	4.31	
600	12.10	10.70	10.10	8.13	6.54	4.48		11.97	10.67	10.09	8.09	6.35	4.28	
1,000	10.40	9.46	9.03	7.60	6.31	4.48		10.21	9.40	9.02	7.55	6.11	4.24	
1,500	9.26	8.51	8.20	7.12	6.05	4.45		9.01	8.46	8.19	7.06	5.87	4.19	
Structure 4														
300	34.50	25.30	20.30	12.80	9.36	6.08		34.18	25.93	21.63	13.68	9.67	6.10	
600	31.10	24.30	20.00	12.80	9.30	6.05		31.05	24.67	20.87	13.49	9.62	6.10	
1,000	28.50	23.20	19.70	12.80	9.28	6.03		28.50	23.47	20.15	13.30	9.57	6.11	
1,500	26.50	22.20	19.20	12.80	9.30	6.03		26.42	22.38	19.48	13.12	9.52	6.11	

Table 2.5 Summary of Deflection Calculations (cont.)

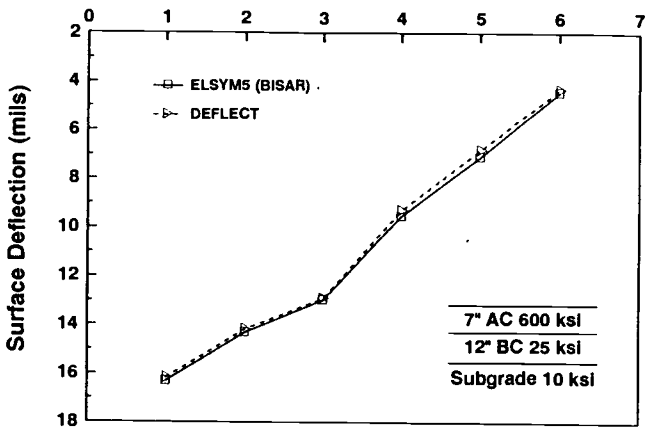
Eac (ksi)	Results from ELSYM5 (BISAR) Deflections @ sensor locations (mils)							Results from DEFLECT Deflections @ sensor locations (mils)						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Structure 5														
100	28.90	20.60	16.90	10.90	8.01	5.29		29.31	21.16	17.95	11.56	8.29	5.31	
300	22.30	18.20	15.80	10.80	7.96	5.25		22.67	18.79	16.52	11.20	8.18	5.31	
600	19.00	16.40	14.70	10.60	7.99	5.27		19.17	16.85	15.22	10.83	8.06	5.30	
1,000	16.80	15.00	13.70	10.40	7.99	5.31		16.87	15.32	14.11	10.47	7.92	5.28	
Structure 6														
300	11.50	10.20	9.86	8.35	6.88	4.74		11.81	10.42	10.03	8.27	6.51	4.33	
600	10.30	9.36	9.09	7.84	6.59	4.71		10.91	9.94	9.57	8.00	6.40	4.32	
1,000	9.53	8.71	8.49	7.42	6.34	4.65		10.29	9.51	9.16	7.76	6.29	4.30	
Structure 7														
300	10.00	8.70	8.47	7.44	6.36	4.66		10.15	8.89	8.66	7.48	6.16	4.28	
600	9.09	8.08	7.87	7.01	6.08	4.58		9.43	8.56	8.31	7.24	6.03	4.26	
1,000	8.50	7.60	7.36	6.64	5.83	4.48		8.93	8.24	8.01	7.03	5.92	4.23	
Structure 8														
4,000	9.04	8.30	7.30	6.26	5.31	4.49	3.24	9.30	8.66	7.45	6.13	5.01	4.14	3.00
Structure 9														
4,000	8.81	8.03	7.08	6.09	5.18	4.40	3.21	8.85	8.27	7.18	5.98	4.93	4.11	2.99
Structure 10														
4,000	6.63	5.62	5.29	4.83	4.37	3.92	3.14	6.19	5.89	5.47	4.92	4.34	3.80	2.93



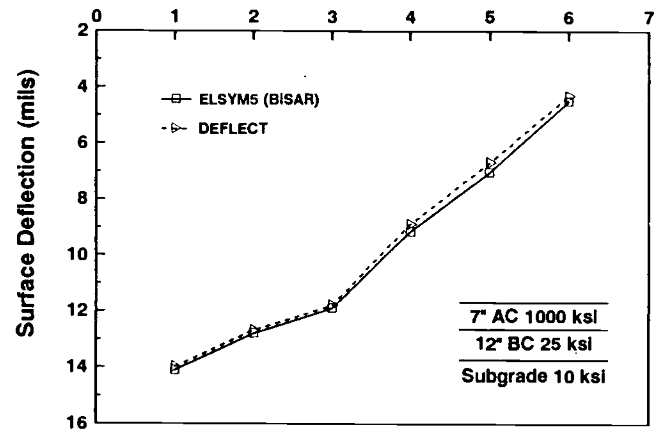
a) Structure 1 with AC Modulus of 100 ksi



b) Structure 1 with AC Modulus of 300 ksi

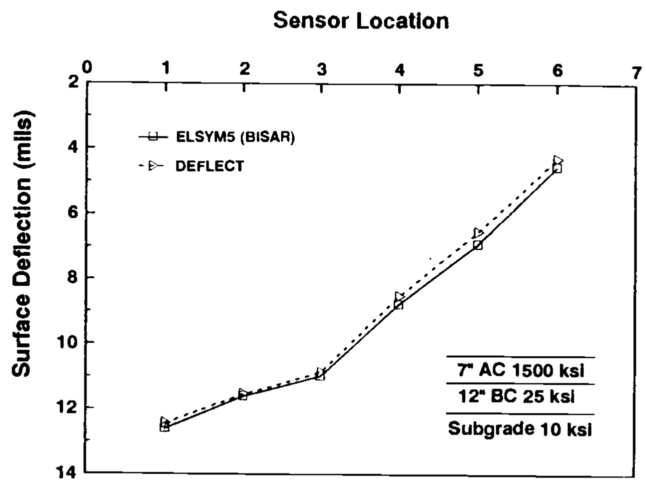


c) Structure 1 with AC Modulus of 600 ksi

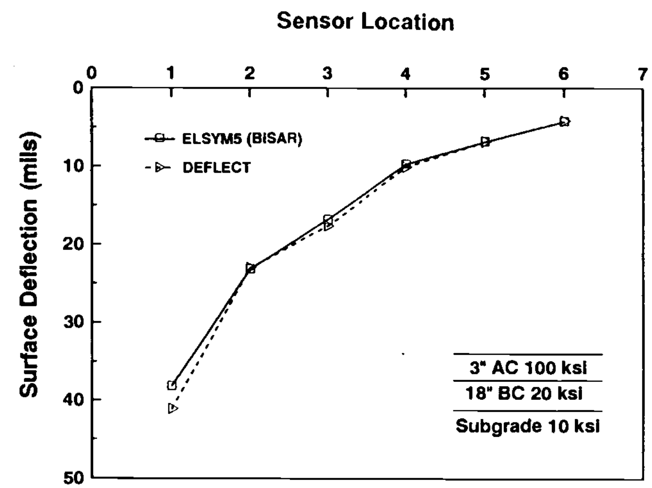


d) Structure 1 with AC Modulus of 1,000 ksi

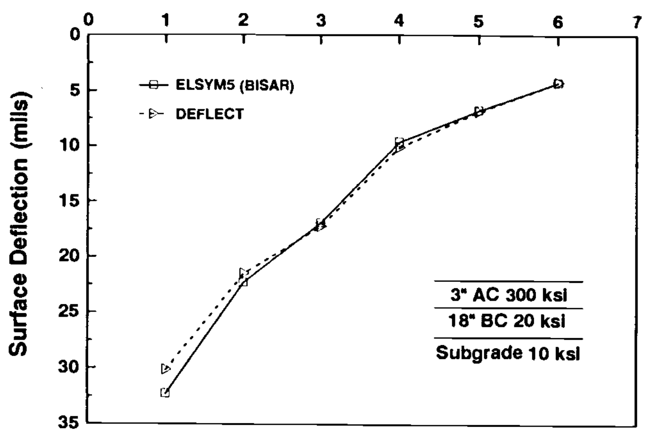
Figure 2.6 Deflection Comparison for Three-Layer Conventional Flexible Pavements



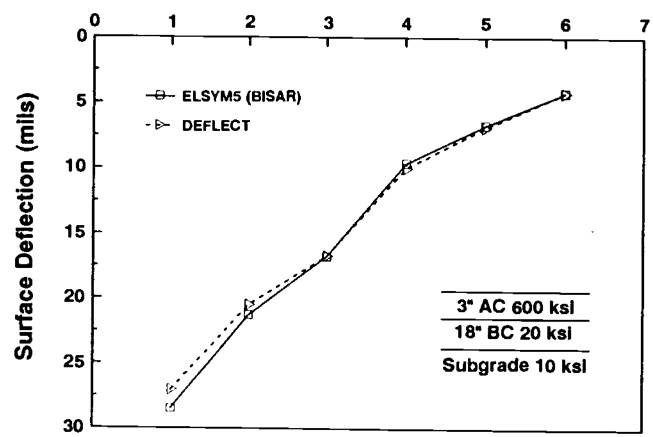
e) Structure 1 with AC Modulus of 1,500 ksi



f) Structure 2 with AC Modulus of 100 ksi

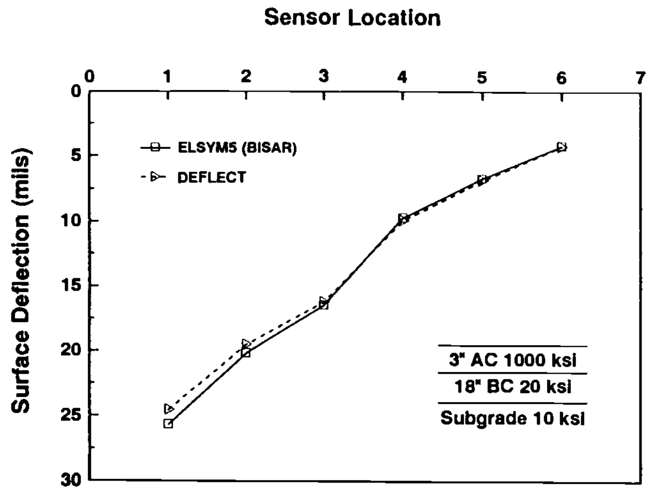


g) Structure 2 with AC Modulus of 300 ksi

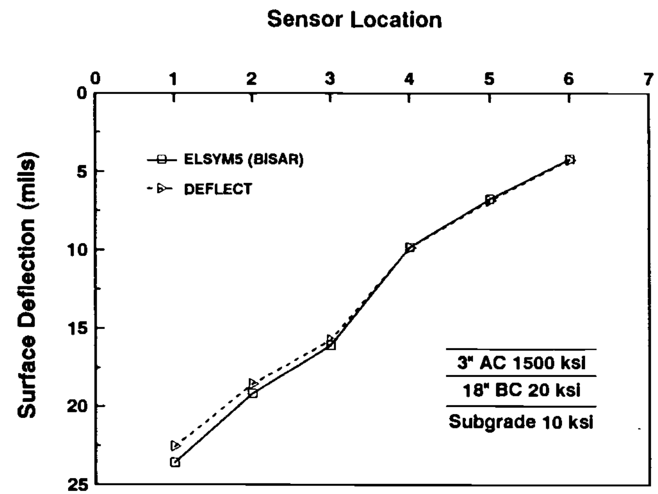


h) Structure 2 with AC Modulus of 600 ksi

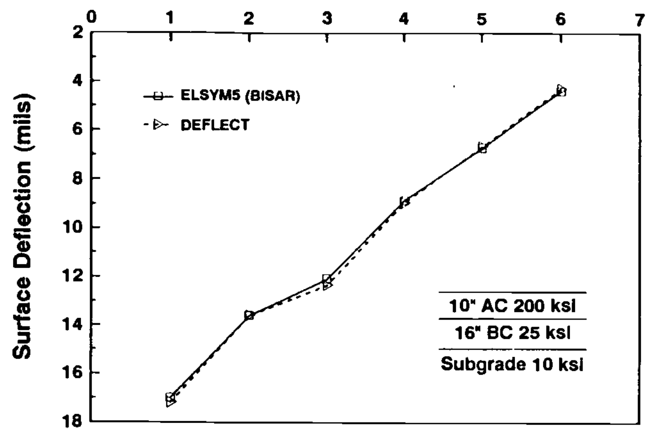
Figure 2.6 Deflection Comparison for Three-Layer Conventional Flexible Pavements (cont.)



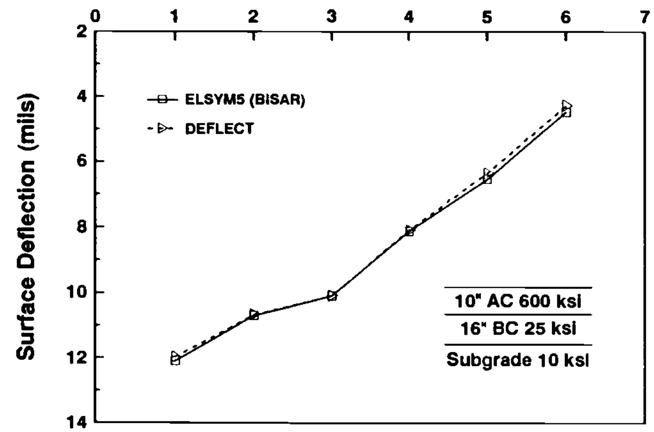
i) Structure 2 with AC Modulus of 1,000 ksi



j) Structure 2 with AC Modulus of 1,500 ksi

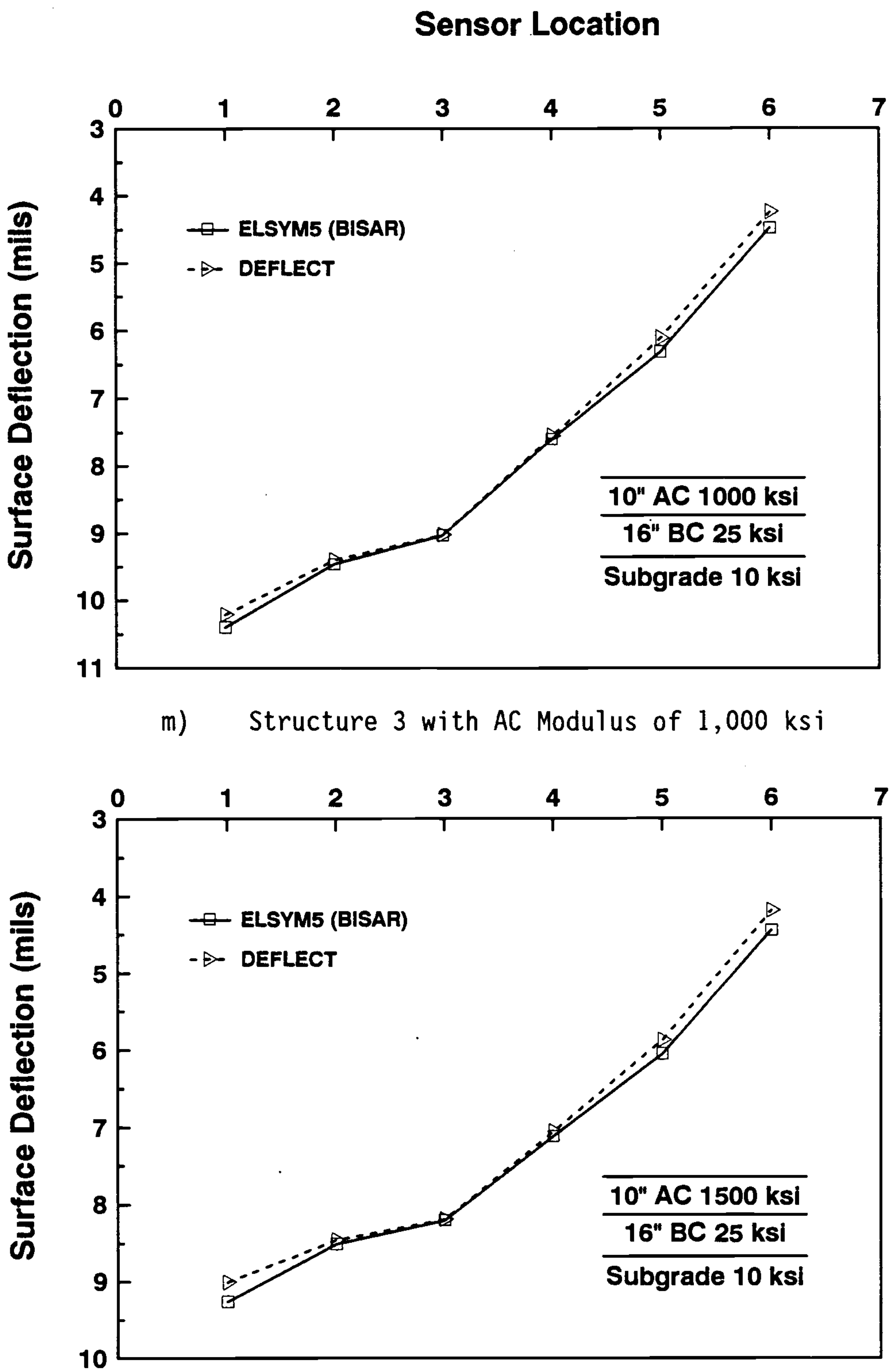


k) Structure 3 with AC Modulus of 200 ksi



l) Structure 3 with AC Modulus of 600 ksi

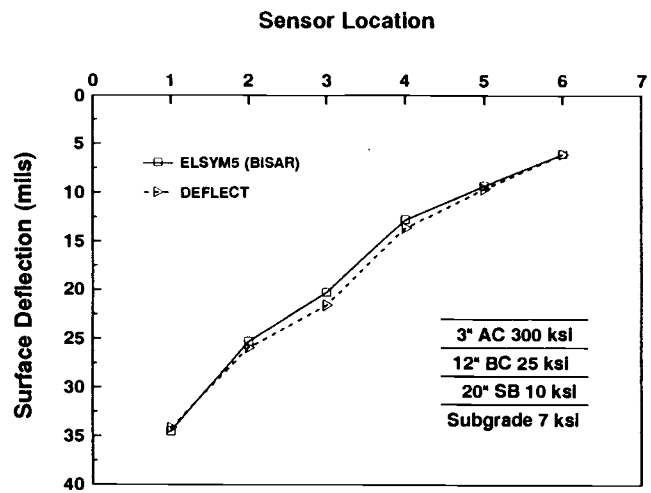
Figure 2.6 Deflection Comparison for Three-Layer Conventional Flexible Pavements (cont.)



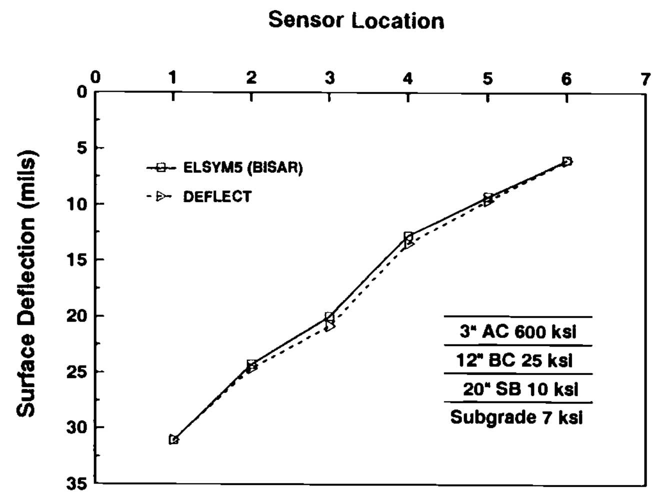
m) Structure 3 with AC Modulus of 1,000 ksi

n) Structure 3 with AC Modulus of 1,500 ksi

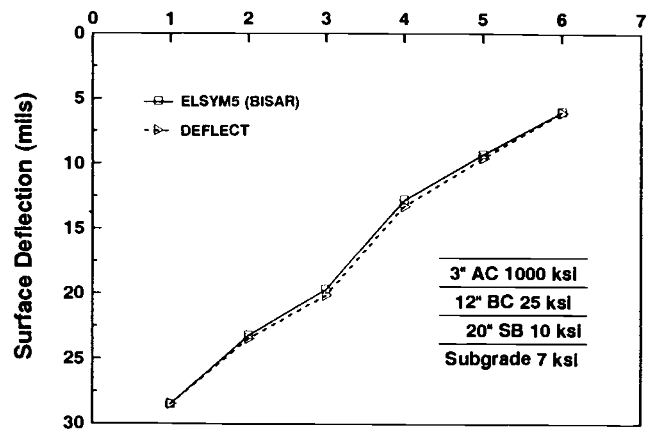
Figure 2.6 Deflection Comparison for Three-Layer Conventional Flexible Pavements (cont.)



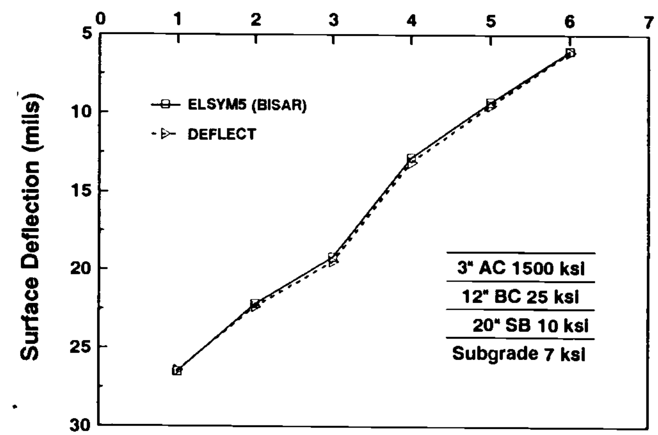
a) Structure 4 with AC Modulus of 300 ksi



b) Structure 4 with AC Modulus of 600 ksi

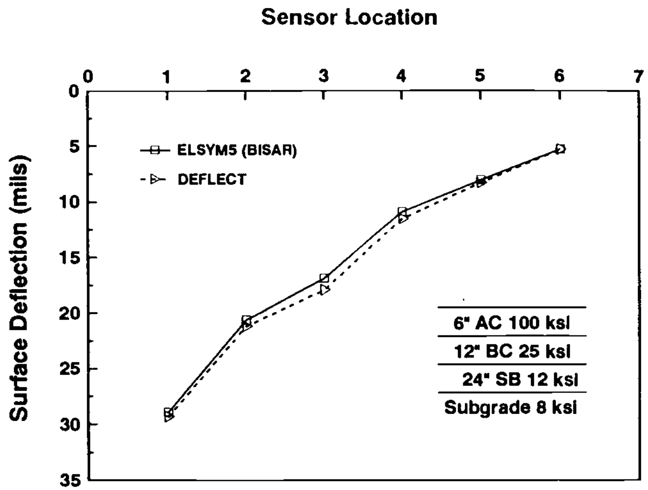


c) Structure 4 with AC Modulus of 1,000 ksi

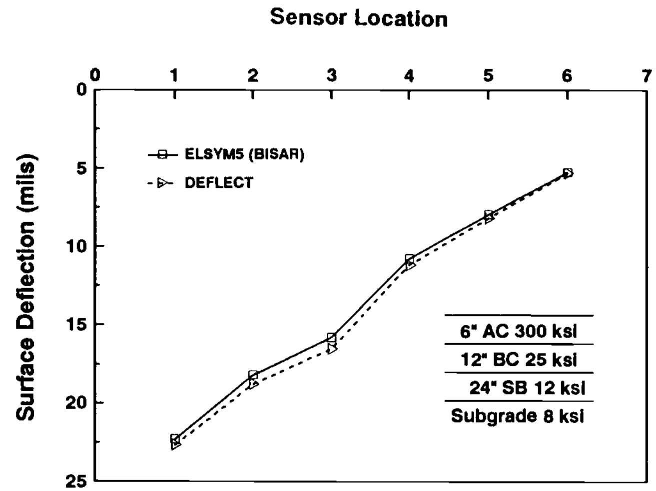


d) Structure 4 with AC Modulus of 1,500 ksi

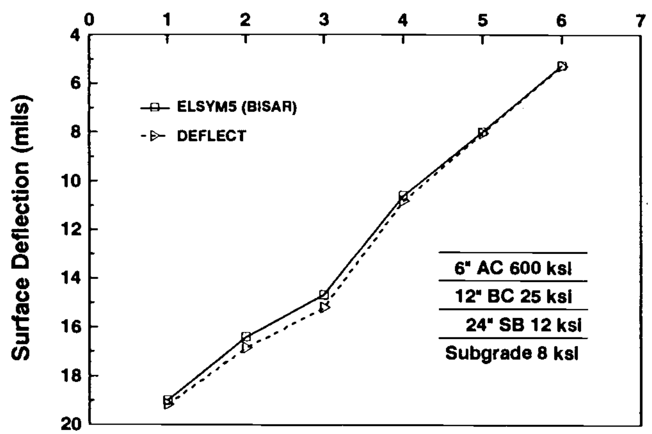
Figure 2.7 Deflection Comparison for Four-Layer Conventional Flexible Pavements



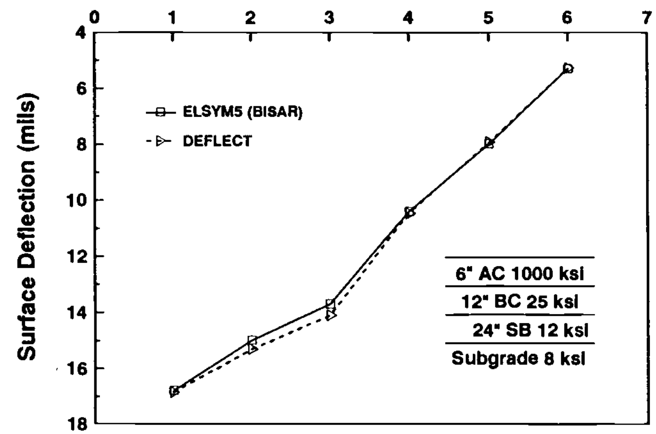
e) Structure 5 with AC Modulus of 100 ksi



f) Structure 5 with AC Modulus of 300 ksi

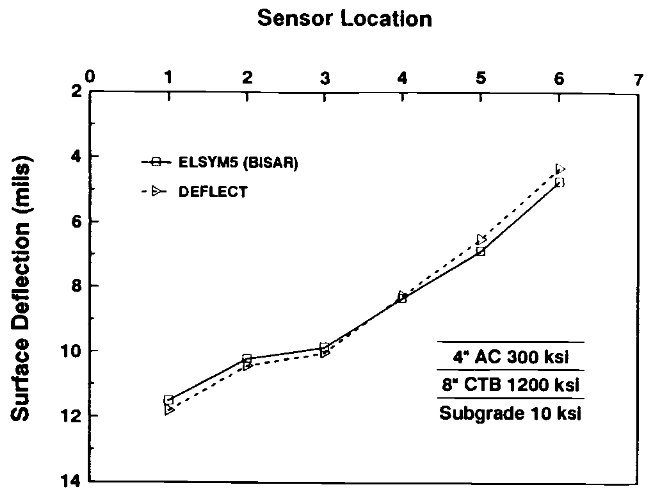


g) Structure 5 with AC Modulus of 600 ksi

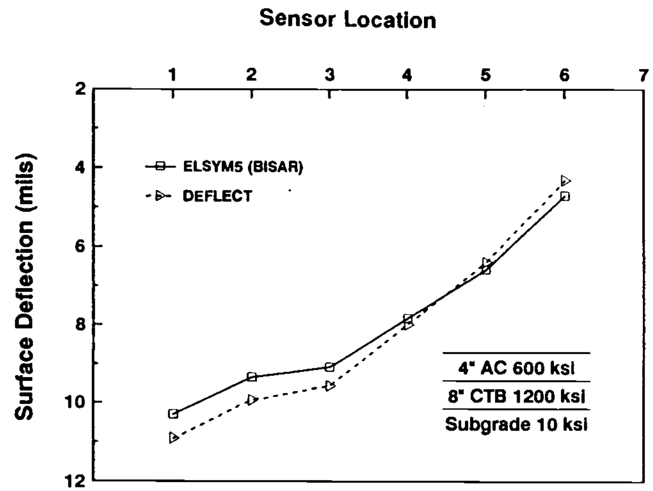


h) Structure 5 with AC Modulus of 1,000 ksi

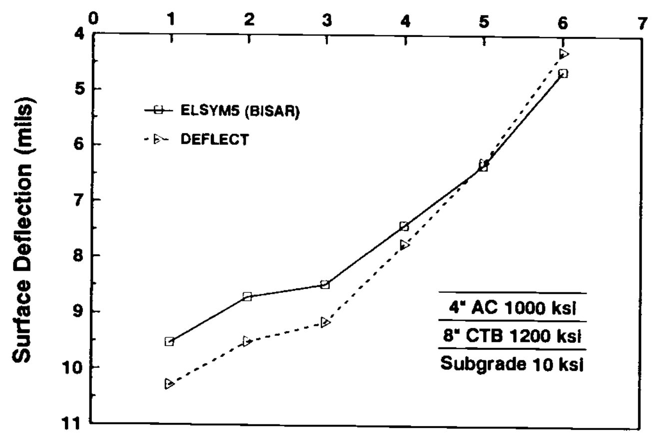
Figure 2.7 Deflection Comparison for Four-Layer Conventional Flexible Pavements (cont.)



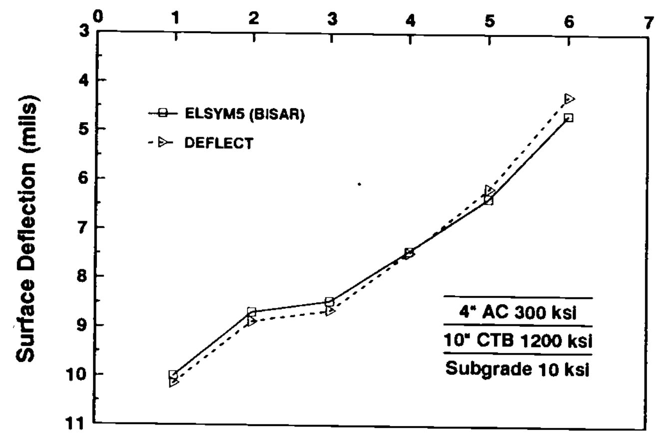
a) Structure 6 with AC Modulus of 300 ksi



b) Structure 6 with AC Modulus of 600 ksi

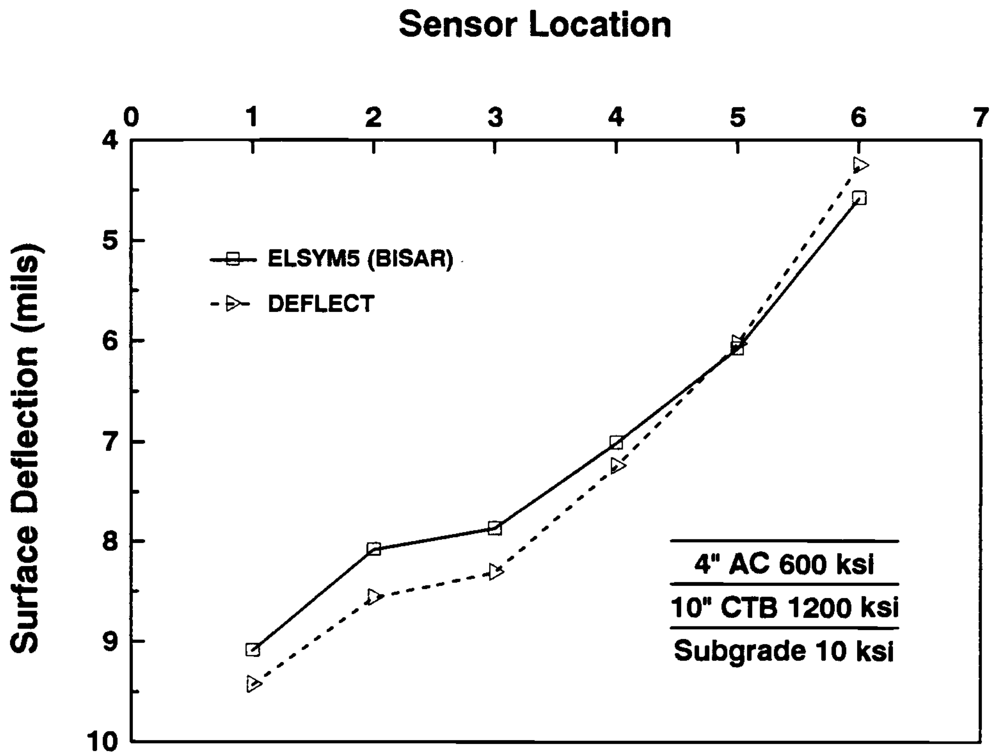


c) Structure 6 with AC Modulus of 1,000 ksi

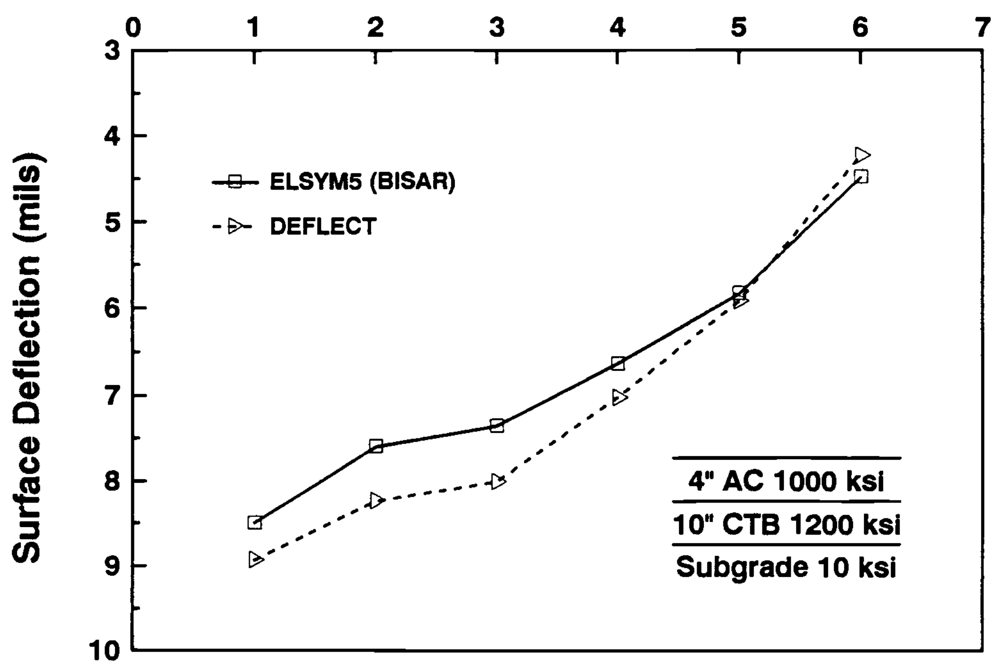


d) Structure 7 with AC Modulus of 300 ksi

Figure 2.8 Deflection Comparison for Pavements with Cement Treated Base

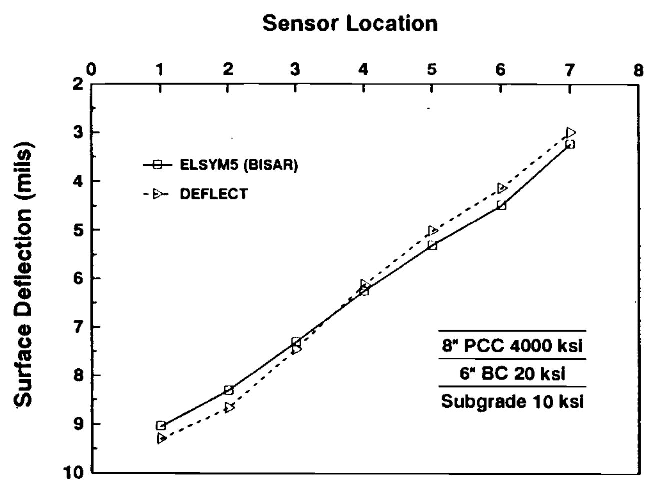


e) Structure 7 with AC Modulus of 600 ksi

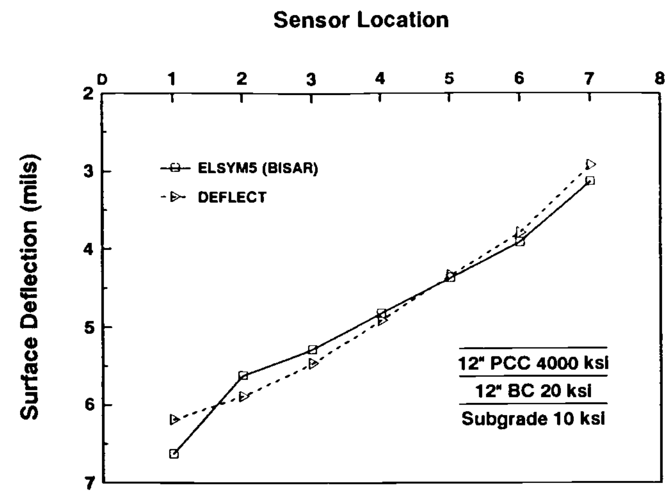


f) Structure 7 with AC Modulus of 1,000 ksi

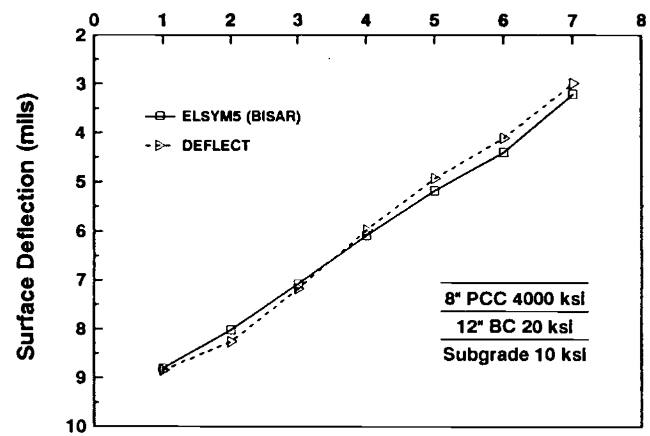
Figure 2.8 Deflection Comparison for Pavements with Cement Treated Base (cont.)



a) Structure 8: PCC with 6" Base



b) Structure 9: PCC with 12" Base



c) Structure 10: PCC with 12" Base

Figure 2.9 Deflection Comparison for Portland Cement Concrete Pavements conventional and PCC pavements. However, for pavements containing a cement treated base, greater differences are also observed.

2.2 Non-linearity of Pavement Materials

The theory of elasticity provides an exact solution for an elastic body. It gives, at least, an approximation to the real behavior of pavement structures. This is because when a real pavement material is subjected to a load, the deformations are not only elastic but also plastic, viscous and/or visco-elastic. The stress-strain relationship, or stress-strain rate relationship, is usually not linear (Ullidtz, 1987). Many materials are anisotropic, often as a result of the stress condition, and none of the materials are homogeneous, many even consist of discrete particles.

Many researchers (Hicks, 1970; Dunlap, 1966; Seed et al, 1967; Thompson, 1969; and Biarez, 1962) have shown that the resilient properties of pavement materials, especially those coarse-grained and fine-grained, are stress dependent. The resilient modulus of the these materials vary according to stress states within the layers. Numerous researchers indicate that modulus of these materials can be approximated by the following relationships;

for coarse-grained materials (Figure 2.10):

$$M_R = k_1 \, \theta^{k_2} \qquad (2\text{-}24a)$$

for fine-grained materials (Figure 2.11):

$$M_R = k_1 \, \sigma_d^{k_2} \qquad (2\text{-}24b)$$

where:

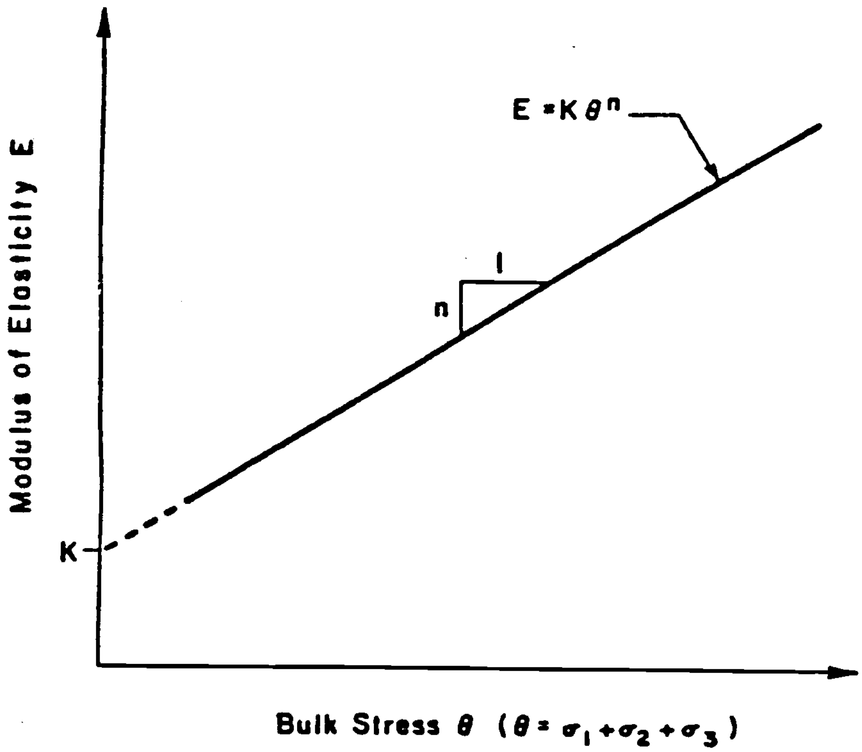


Figure 2.10 Modulus-Bulk Stress Relationship for Coarse-Grained Materials (Mahoney et al, 1983)

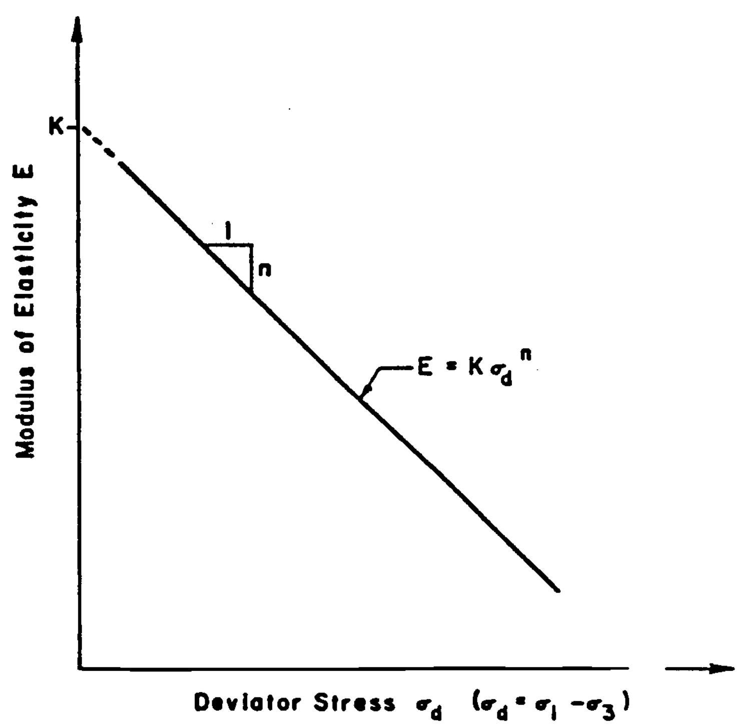


Figure 2.11 Modulus-Bulk Stress Relationship for Fine-Grained Materials (Mahoney et al, 1983)

M_R = Resilient modulus (psi),

θ = Bulk stresses (psi),

σ_d = Deviator stress (psi), and

k_1, k_2 = Regression coefficients depending on materials properties.

Most often, these coefficients are determined through laboratory tests.

2.3 Consideration of Overburden Stresses

Actual stresses in a pavement structure consist of two parts: load induced and overburden stresses. For vertical stresses, the overburden pressure is calculated by multiplying the layer thicknesses by their respective densities and summing these to the desired depth. The total vertical stress, σ_{vt}, is the sum of the load induced stress, σ_{vl}, plus overburden pressure:

$$\sigma_{vt} = \sigma_{vl} + \sum_{i=1}^{n} h_i \gamma_i \tag{2-25}$$

where:

h_i = thickness of i-th layer, and

γ_i = density of i-th layer.

The total horizontal stress, σ_{ht}, is a function of the load induced horizontal stress, σ_{hl}, plus horizontal stress due to overburden pressure:

$$\sigma_{ht} = \sigma_{hl} + K_o \sum_{i=1}^{n} h_i \gamma_i \tag{2-26}$$

where:

K_o = coefficient of at-rest earth pressure.

It should be noted that these expressions do not include a term for pore water pressure. This is because pore water pressure is a function of ground water table depth. The assumption is made that the ground water table is at depth below the top of the subgrade and therefore does not affect the results.

The coefficient of at-rest earth pressure, K_o, is a function of the angle of friction, ϕ, for a given soil as determined by a triaxial compression test. For granular soils:

$$K_o = 1 - \sin\phi \tag{2-27a}$$

and for fine grained soils (Brooker and Ireland, 1965):

$$K_o = 0.95 - \sin\phi \tag{2-27b}$$

Das (1984) reported an approximate range of ϕ from 25 to 38° for normally consolidated clays and from 26 to 46° for sands. Overall, this represents a range of K_o from 0.28 to 0.56. For most geotechnical work, when triaxial compression test data are not available, a value of 0.5 is assumed for K_o (Newcomb, 1986).

2.4 Summary

This chapter reviews some background on mechanistic analysis for flexible pavements, including the use of Boussinesq theory, the method of equivalent thicknesses, and layered elastic theory. Nonlinearity of pavement materials, in particular the granular and fine material, and the stresses induced by the static load, are also briefly described.

Deflections calculated using Boussinesq equations together with the method of equivalent thicknesses and layered theory are compared. The comparison shows that both Boussinesq equations and elastic layer theory produce similar deflection results for the conventional and PCC pavements. This would indicate that using Boussinesq equations to calculate the surface deflection is a valid approach for these two types of pavements. This comparison also provide theoretical support for the development of an improved backcalculation procedure as is described in Chapter Four. Greater difference in computing surface deflections is also observed for pavements with a cement treated base. This appears to be one of the limitations in using the method of equivalent thicknesses to calculate surface deflections for the pavement structure with a very stiff base layer.

Nonlinearity of coarse grained materials and stresses from overburden materials are also discussed. As is seen in Chapter 4, these discussions are used in an improved backcalculation procedure.

3.0 DETERMINATION OF PAVEMENT MODULI USING NDT METHODS

In mechanistic pavement analysis and evaluation procedures, as discussed in Chapter 2, there are three material parameters involved: modulus of elasticity, Poisson's ratio, and layer thickness. To perform the analysis, the modulus of elasticity must be known. For a pavement structure with multi-layers, the modulus value for each pavement layer must be determined. Two other material parameters must also be known; the Poisson's ratio may be assumed, typical values as given in Table 3.1 may be used and the thickness of each pavement layer may be obtained from construction records or coring pavement samples. Among the three material parameters, two can be easily obtained. However, determination of modulus values for pavement materials requires much more effort. Over the years, tremendous effort has been put in developing methods that are efficient and economical in determining modulus of pavement materials from destructive tests to nondestructive testing. This chapter reviews some of these developments, focusing on determination of pavement layer moduli using nondestructive testing methods.

3.1 Background

Highway and transportation agencies have an increasing responsibility for the maintenance, rehabilitation, and management of highways, particularly with regard to asphaltic concrete pavements. Efficient and economical methods are required for determining the structural properties of existing flexible pavements.

Pavement structural properties may be generally stated in terms

Table 3.1 Typical Poisson's Ratio Values (AASHTO, 1986)

Material	General	Remarks	Typical
Portland cement concrete	0.10-0.20		0.15
Asphalt concrete/ Asphalt treated bases	0.15-0.45	Highly dependent upon temperature; use low value (0.15) for cold temperatures (less than 30°F) and high value (0.45) for warm pavement (120°F plus)	0.35
Cement stabilized bases	0.15-0.30	Degree of cracking in stabilized layer tends to increase value towards 0.30 from sound (crack free) value of 0.15	0.20
Granular base/ subbase	0.30-0.40	Use lower value for crushed material and high value for unprocessed rounded gravel/ sands	0.35
Subgrade	0.30-0.50	Value dependent upon type of subgrade soil. For cohesionless soil, use value near 0.30. A value of 0.50 is approached for very plastic clays (cohesive soils)	0.40

of resilient modulus which is a key element in mechanistic pavement analysis and evaluation procedures. For a multi-layer pavement structure, resilient modulus of each pavement layer may be determined by two possible methods: destructive testing and nondestructive testing. Destructive testing is generally done by obtaining cores from an existing pavement and testing them using laboratory equipment. Nondestructive tests, on the other hand, use deflection basin data generated from a non-destructive testing (NDT) device to quantify the response of a pavement structure due to a known load.

Among the different load responses, only surface deflections are easily measurable. Deflection is a basic response of the whole system to the applied load. It is frequently used as an indicator of the load carrying capacity of the pavement. Also, surface deflection measurements are rapid, relatively cheap, and nondestructive.

Nondestructive test results can be used directly with a minimum of analysis, in designing overlay thickness, or they can be used to "backcalculate" material properties using mechanical analyses. Backcalculation is, to an extent, an inverted design process. If the cross section and properties of the paving materials and support system are known, it is possible to compute the pavement response (stresses, strains, and displacements) for a given loading condition. In the evaluation process, the response of the pavement is observed and the material properties are backcalculated.

Nondestructive testing of asphalt concrete pavements is one of the most useful and cost-effective methods that has been developed by engineers to assist in the management of pavements. With the increased responsibility that highway agencies have for effectively apportioning funds and efficiently designing major rehabilitation projects, the use of nondestructive testing methods has become, or in some cases, can become, an invaluable aid in determining the actual condition of pavement sections in a highway network (Lytton, 1986). The emphasis in the 1986 AASHTO Guide for Design of Pavement Structures (AASHTO, 1986) on the use of the resilient moduli of pavement materials in pavement design and on the use of nondestructive testing in overlay design also suggests that these methods will have increased usage in the future.

The analysis of nondestructive test data to determine pavement layer properties requires the use of mechanistic methods. The principal objective of the mechanistic analysis of nondestructive test data is to produce moduli of the pavement layers for in-service temperatures, and at various load levels. These mechanistic methods assume that the stresses, strains, and deformations in pavements can be modeled as multilayered linear or non-linear elastic structures, as shown in Figure 2.3, resting on linear or non-linear elastic foundations. This capability makes it possible to use a trial-and-error procedure to assume the layer properties, calculate the surface deflection, compare these with the measured deflections as illustrated in Figure 3.1, and repeat the procedure until the calculated and measured deflections are acceptably close. Several such backcalculation methods of analysis have been developed using different assumptions or algorithms concerning the layer material properties, all of which have a trial-and-error procedure as their basis.

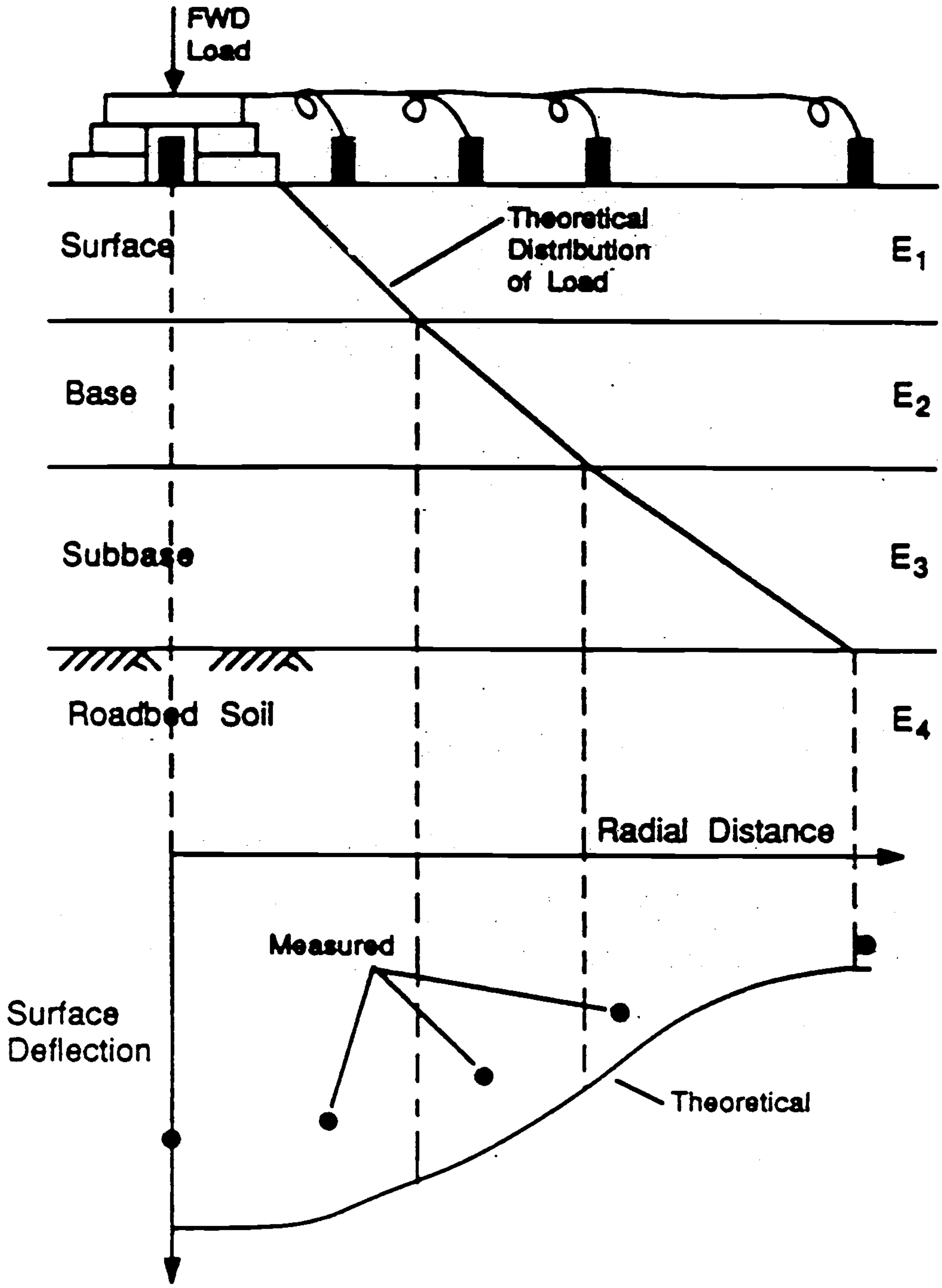


Figure 3.1 Conceptual Illustration of Backcalculation Approach (Mahoney, 1987)

3.2 Some Existing Approaches

There are a number of different analysis methods that can be used to determine the moduli of pavement layers using the deflection data measured with an NDT device. They fall broadly into three categories namely; 1) equivalent thickness methods, 2) layered elastic methods, and 3) finite element methods. Most of the procedures currently in use fall in one of the above categories. Table 3.2 shows some of the methods that can be used to determine the modulus automatically from NDT deflection data.

3.2.1 Equivalent Thickness Methods

This group of methods is based on Odemark's assumption as described in the previous sections. The advantage of the equivalent thickness method is that it greatly simplifies the layered structure so that rapid trial and error calculations of layer moduli can be obtained. The following describes two such programs; ELMOD and SEARCH.

3.2.1.1 ELMOD

The ELMOD program (Evaluation of Layer Moduli and Overlay Design) is a proprietary program of Dynatest Consulting, Inc (Dynatest, Undated). In this program, the method of equivalent thicknesses is used together with Boussinesq's equations (Ullidtz and Stubstad, 1986) to calculate the layer moduli of a pavement structure using load deflection data generated by a FWD. Once the deflection basin has been input, the ELMOD program automatically calculates the modulus for each layer and will also carry out an overlay design for given loading and climatic conditions.

Table 3.2 Summary of Self-Iterative Procedures for Evaluation of Layer Moduli from Deflection Basins for Flexible Pavements

Procedure Title	Source	Pavement Model[1]	Layered Theory Program for Analysis	Number of Deflection Readings[2]	Output Layer Modulus
BISDEF	Bush-WES	4-layers	BISAR	Up to 7	E_1 to E_4
CHEVDEF	Bush-WES	4-layers	CHEVRON	Up to 4	E_1 to E_4
ELMOD	Dynatest	4-layers	MET	Variable	E_1 to E_4
ELSDEF	Lytton, Roberts & Stoeffels, 1986	4-layers	ELSYM5	Variable	E_1 to E_4
EVERCALC	Mahoney, 1987	4-layers	CHEVRON	Variable	E_1 to E_4
FPEDDI	Uddin et al 1985	3 or 4-layers	ELSYM5	Variable	Up to E_4
ISSEM4	Sharma & Stubstad, 1980	4-layers	ELSYM5	Variable	E_1 to E_4
MODCOMP2	Irwin, 1983	8-layers	CHEVRON	Variable	E_1 to E_8
MODULUS	Lytton, Roberts & Stoeffels, 1986	3-layers	BISAR, ELSYM5 or CRANLAY	Up to 3	E_1 to E_3
OAF	Majidzadeh & Ilves, 1981	3 or 4-layers	ELSYM5	Variable	Up to E_4
SEARCH	Lytton, Roberts & Stoeffels, 1986	3-layers	MET	Up to 4	E_1 to E_3

1 Subgrade assumed in input.

2 Other input include thickness, Poisson's ratio, and/or initial, range of modulus.

Two empirical relationships are used in ELMOD, one for predicting cracking of bound layers and one for predicting permanent deformations, and they are of the exponential form:

$$N = KS^a \qquad (3\text{-}1)$$

where:

N = the number of loads to cause a certain deterioration at a stress or strain level,

S = stress or strain level at the critically loaded position in the layer, and

K,a = user-controlled input parameters.

Seasonal variation of the critical stresses and strains are also considered. As many as 12 "seasons" may be specified in the program, and the moduli of all layers (including the subgrade) may be varied with season. The damage caused in each season is calculated and summed using Miner's Hypothesis. If the remaining life of a pavement is insufficient, the program will determine the needed overlay thickness of a given material to satisfy the empirical equation above as specified for each layer in the structure. In addition, the program uses the following model to predict the future functional condition of the pavement (Ullidtz and Stubstad, 1986):

$$N = K * S^a * E^b * (P_I - P_T)^c \qquad (3\text{-}2)$$

where:

N = the number of load repetitions to cause the performance measure to change from P_I to P_T,

P_I = the initial level,

P_T = the terminal level, and

S = critical stress or strain,

E = the modulus of the material, and

K,a,b,c = constants.

For bedrock or frozen layers close to the surface, the ELMOD program also contains a subprogram called ELROC which calculates the (equivalent) depth to any hard layer, along with the requisite E-values of the materials above this layer.

In summary, it may be said that ELMOD could be useful for the maintenance and rehabilitation of a road network because of its simplicity. For more complex structures, particularly where the non-linear elastic properties of granular materials are important, Dynatest recommends that other programs be used.

3.2.1.2 SEARCH

The SEARCH program was developed at the Texas Transportation Institute by Lytton and Michalak (1979). This program uses a pattern search technique to fit deflection basins with elliptic integral function-shaped curves. These curves are solutions to the differential equations used in elastic layered theory. The deflection equation used in SEARCH is based on work that was done by two Russians, Vlasov and Leont'ev (1966), who were interested in the behavior of an elastic layer resting on a rigid incompressible layer. In addition, a generalized form of Odemark's assumption is used.

The non-linearity of the response of pavement materials to a load is accounted for by letting the coefficients of vertical displacement distribution with depth and radius depend upon the geometry of the pavement. These coefficients were determined by non-linear regression analysis upon displacements that were measured at the Texas Transportation Institute's Pavement Test Facility. The program searches for the elastic moduli that fits the measured deflection basin to the calculated deflection basin with the least average error. The outputs of the program include the calculated moduli, computed and measured deflections, force applied and the squared error of the fitted basin.

3.2.2 Elastic Layer Methods

In the elastic layer approach, the pavement is usually represented by elastic layers of known thicknesses, as shown in Figure 2.3. The subgrade is assumed to have an infinite depth. When a load of known intensity is applied over a known area, deflections are created at some distance from the center of the loaded area. It is normally assumed that the load is distributed through the pavement system by a truncated zone represented by the dashed line as shown in Figure 3.2. Based on this concept, the deflection d_4 at a distance r_4 from the center of the load can only be due to the elastic compression of layer 4 since layers 1, 2 and 3 are outside the influence zone created by the load as illustrated in Figure 3.2. Likewise, the deflection, d_3, at distance r_3 is due to compression of layers 3 and 4; the deflection at distance r_2 is due to compression in layers 2, 3 and 4 and the deflection, d_1 is due to the compression of all layers. This general approach is used to backcalculate properties of pavement layers. Examples of some developed backcalculation programs using elastic layer theory are described in the following sections.

3.2.2.1 CHEVDEF/BISDEF

These two programs were developed by the U.S. Army Corps of

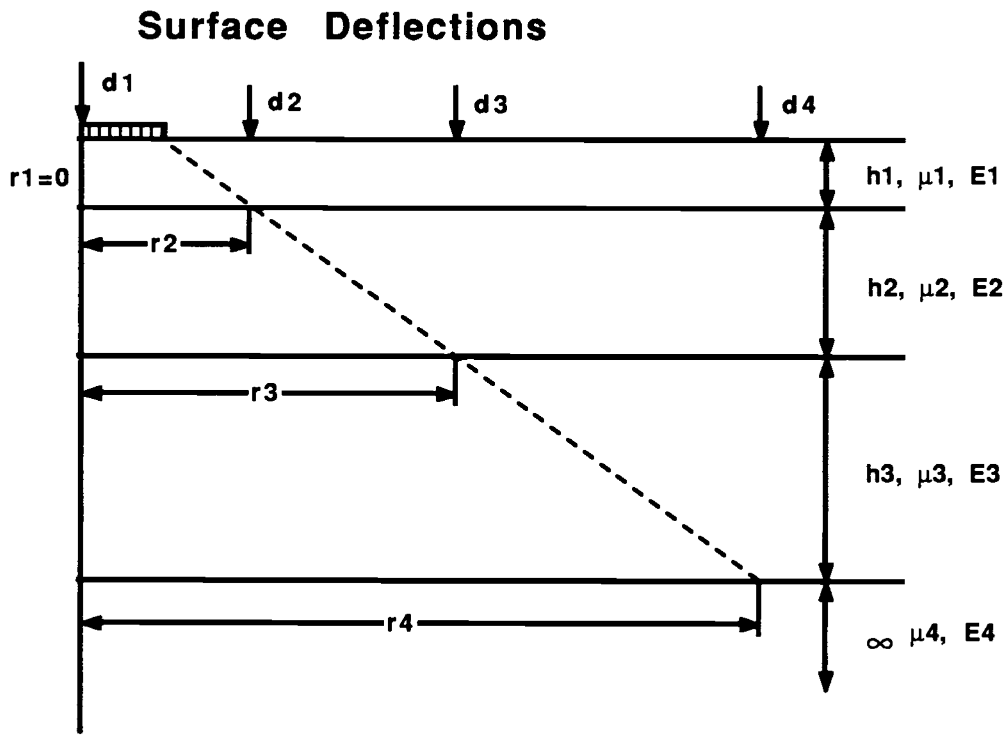


Figure 3.2 Four Layer Elastic Representation of a Pavement System (Lytton and Smith, 1985)

Engineers, Waterways Experiment Station (Bush, 1980). They use a deflection basin from nondestructive testing (NDT) results to predict the elastic moduli of up to four pavement layers. This is accomplished by matching the calculated deflection basin to the measured deflection basin. The basic assumption of the method is that dynamic deflections correspond to those from the layered elastic theory. The CHEVDEF program uses the Chevron (Michelow, 1963) layered elastic program to compute the deflections, stresses and strains of the structure under investigation. While the BISDEF program uses the BISAR program to calculate the surface deflections. The procedures were verified using the Model 2008 Road Rater.

To test the applicability of the deflection basin to the layered elastic analysis, analyses were carried out on test sections using both the BISAR (SHELL, 1972) and CHEVIT (Chevron program with iteration) programs. It was found that there was good agreement between computed and measured deflections when a rigid layer 20 ft from the surface was assumed.

The inputs required for determining layer moduli include the elastic layer pavement characteristics as well as deflection basin data, as described below:

1. Poisson's ratio,
2. Thickness of each layer,
3. Range of allowable modulus,
4. Initial estimate of modulus,
5. Deflection at a number of sensor locations (ND),
6. Maximum acceptable error in deflections, and
7. Number of iterations.

The programs, by an iterative process, provide the best fit between measured deflection and computed deflection basins. This is done by determining the set of E's that will minimize the error sum between the computed deflection and measured deflections. A flowchart of the two programs is given in Figure 3.3.

The basic steps in the analysis are described in the following:

1. A set of initial modulus values (E_i) is assumed and the deflection (Δ) is computed corresponding to the measured deflection (RRD_j).
2. Each unknown modulus is varied, and a new set of deflections is computed for each variation.
3. Using the two computed deflections and the two values of each E, a relationship is determined for each deflection as a function of slope and intercept of the log Modulus versus Deflection curve. Figure 3.4 is an illustration for one deflection and one layer. An equation is developed that defines the slope and intercept for each deflection and each variable layer as follows:

$$\Delta_j = A_{ji} + S_{ji} (\log E_i) \qquad (3\text{-}3)$$

where:

Δ_j = surface deflection at position for E_i,

E_i = modulus of layer i,

A_{ji} = intercept,

S_{ji} = slope,

j = 1 to number of deflections, and

i = 1 to number of variable layers.

4. For multiple deflections and layers, the solution is obtained

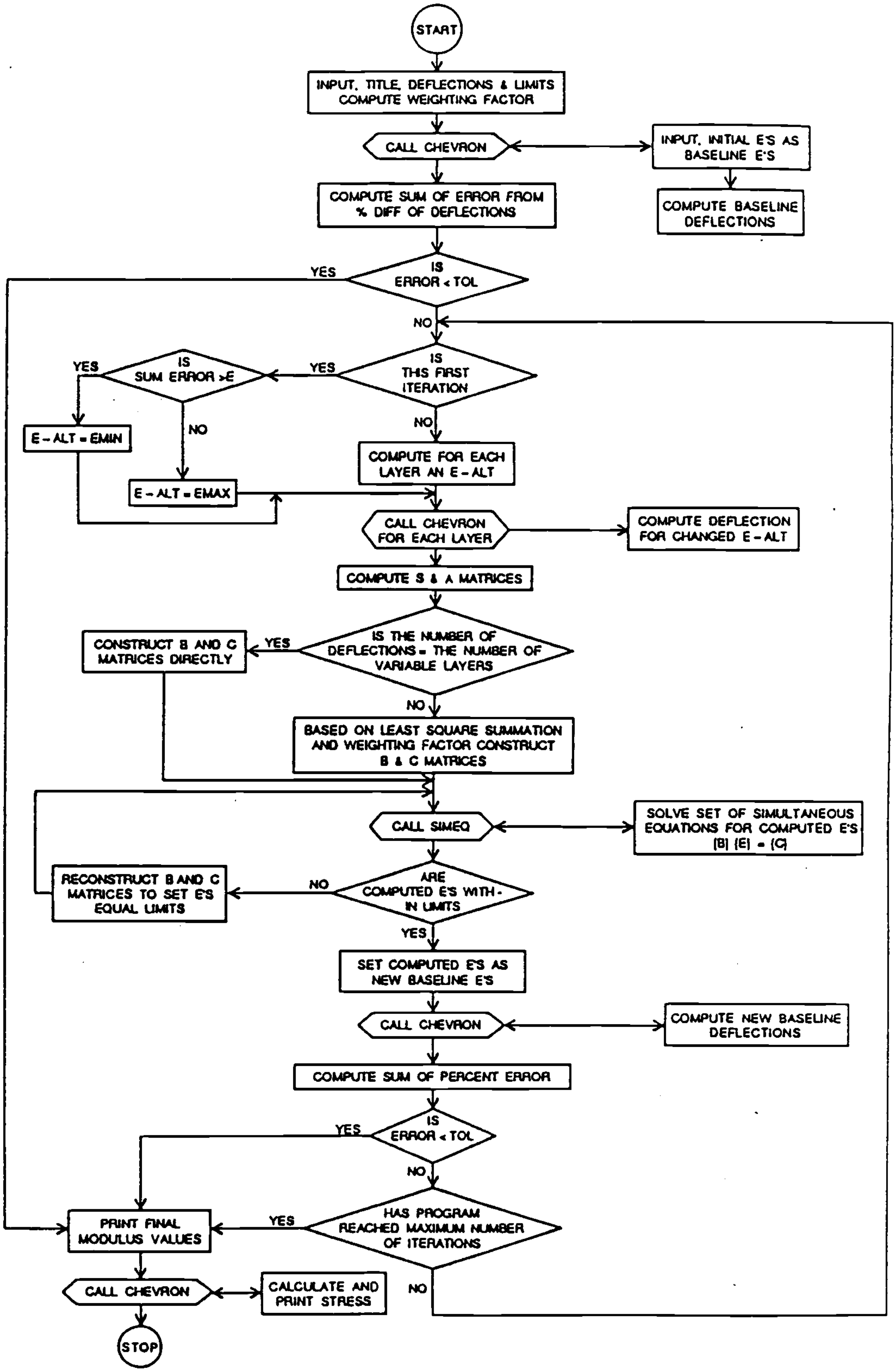


Figure 3.3 CHEVDEF/BISDEF Program Flowchart (Bush, 1980)

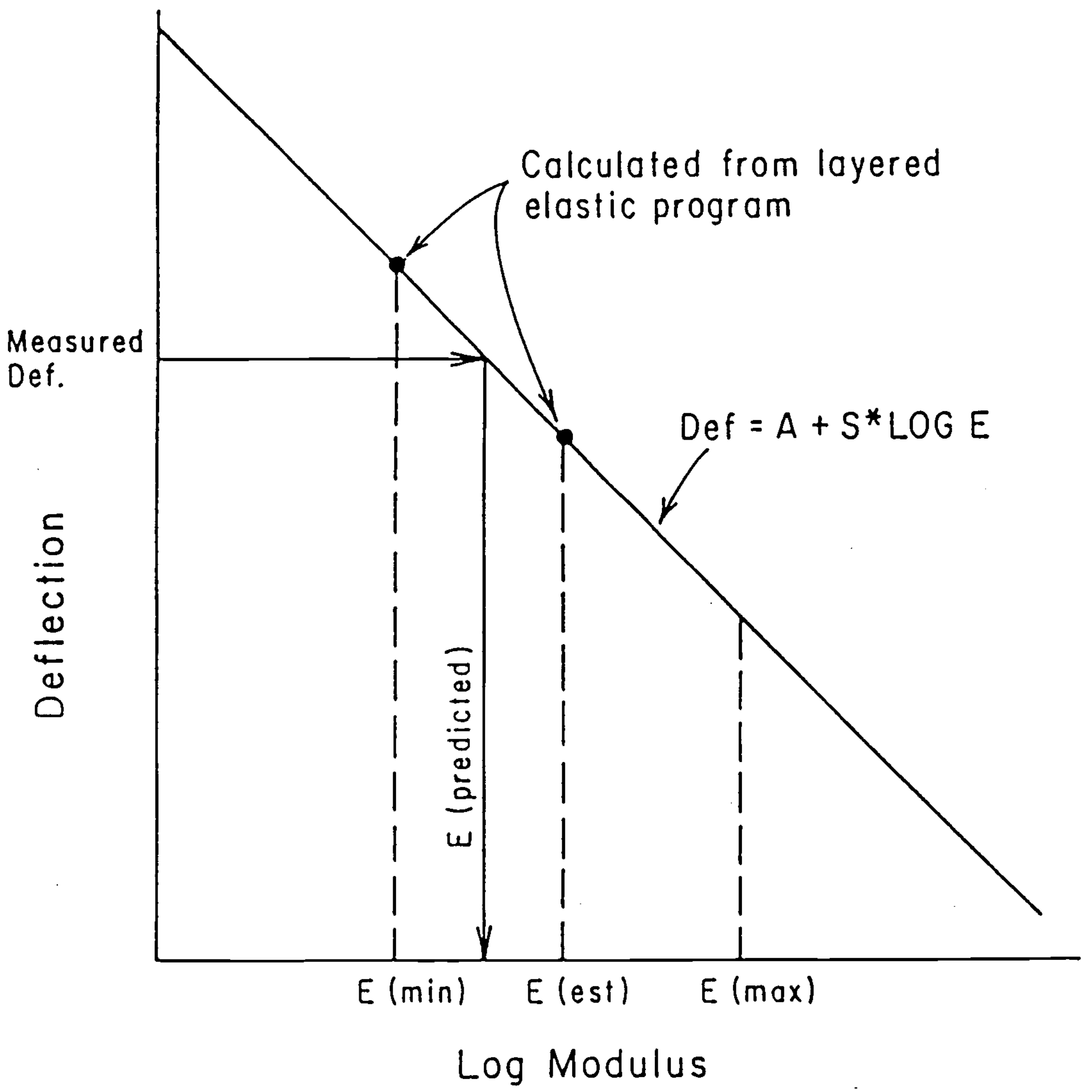


Figure 3.4 Simplified Description of the Deflection Matching Procedure (Bush, 1980)

by developing a set of equations similar to the above:

$$\Delta_j = \overset{\circ}{\Delta}_j + \sum_{i=1}^{NL} S_{ji} \, (\log E_i - \log \overset{\circ}{E}_i) \qquad (3\text{-}4)$$

where:

$\overset{\circ}{\Delta}_j$ = computed deflection at position j for $\overset{\circ}{E}_i$, and

NL = number of variable layers.

5. Next the error between the calculated and measured value is determined:

$$RRD_j - \Delta_j = RRD_j - [\overset{\circ}{\Delta}_j + \sum_{i=1}^{NL} S_{ji}(\log E_i - \log \overset{\circ}{E}_i)] \qquad (3\text{-}5)$$

where:

RRD_j = measured deflection value.

6. If the equations derived are put in a matrix form, then the following is obtained:

$$[B][E] = [D] \qquad (3\text{-}6)$$

where:

D = the constant part of the equation, and

B = a function of S_{ij} and measured deflection RRD_j.

7. Solution of the above equations for minimum error cases yields the values of E's. Errors are minimized by weighing deflections so that the smaller deflections away from the applied load contribute equally to those near the load. Normally, three iterations within the program produce a set of modulus values that yield a deflection basin within an average of three percent difference of the measured

deflections. This accuracy appears to be well within the accuracy of most NDT deflection measuring sensors.

The modulus of any surface layer may be assigned or computed. If assigned, the resilient modulus value of the material at the time of testing may be used. The number of layers with unknown modulus values cannot exceed the number of measured deflections. Best results are obtained when not more than three layers are allowed to vary.

The limitations of this approach are mostly related to the use of the elastic layer theory. First, the elastic layer theory assumes a uniform pressure applied to the surface of the pavement. With some deflection test equipment, the load is applied through a rigid circular plate with the center deflection measured on top of that plate. Therefore, a difference does exist in the measured center deflection and the deflection computed from layer elastic procedures at the center of the load area. Use of the linear elastic layer theory also limits the approach in that it cannot directly characterize the non-linear behavior of granular and subgrade materials. The final limitation of this procedure and all deflection curve fitting procedures is that the modulus derived is not unique. It is generally sensitive to the initial assumed seed moduli, especially if these values are drastically different from actual moduli. For gravel roads, the program has difficulty matching the computed to measured deflections even after more than five iterations (Rwebangira, 1987).

A microcomputer version of the programs is available for use on personal computers. Running time for a three layer pavement system with four deflection readings takes about five minutes, on an IBM AT computer with a math-coprocessor. The running time will be substantially increased with more pavement layers and deflections used in backcalculation analysis.

3.2.2.2 <u>ELSDEF</u>

The ELSDEF program (Lytton et al., 1986) was modified from the program BISDEF. The modification was performed by Brent Rauhut Engineers and instead of using the BISAR subroutine in BISDEF, ELSYM5 was substituted. The Elastic Layered System computer program (ELSYM5) which was developed at the University of California at Berkeley is used to determine the various component stresses, strains and displacements along with principal values in a three-dimensional ideal elastic-layered system. ELSDEF has been compiled with the Microsoft Fortran Compiler to run on IBM-compatible microcomputers. Two versions are available, the standard version and an 8087 math coprocessor chip version. Running time for a three layer pavement system with four deflection readings takes about eight minutes, on an IBM AT computer with a math-coprocessor. The running time will be significantly increased with more pavement layers and deflections used in backcalculation analysis.

3.2.2.3 <u>MODCOMP2</u>

The MODCOMP2 (Irwin, 1983) program was developed at Cornell University. As with BISDEF and ELSDEF, the purpose of this program is to determine the moduli for pavement layers from surface deflection data. The program specifications include:

1. The program is capable of accepting data from several typical non-destructive testing devices such as the Falling Weight Deflectometer, the Road Rater, and the Dynaflect.

2. The program can take up to eight surface deflections for each load level, measured at various radial distances from the center of the load.
3. The combination of the layers may be linearly elastic or non-linearly stress-strain dependent. For the non-linear case the program presumes an exponential constitutive relationship of the form:

$$E = k1*S^{k2} \tag{3-7}$$

where:

E = modulus of elasticity,

S = stress-strain parameter,

k_1 = a coefficient, and

k_2 = an exponent.

4. The program is capable of accepting up to six load levels.
5. Given three or more different load levels the program is capable of deriving the k_1 and k_2 parameters when they are unknown.
6. The program can deal with up to eight layers in a pavement system, including the bottom layer which is assumed having an infinite depth. However, good results are obtained for pavement systems having four unknown variables.
7. To determine the moduli of deep layers, surface deflections must be measured at relatively large radial distances from the load. Generally the program will be able to determine the moduli for layers which lie at a depth that is no more than two thirds of the distance from the load to the outermost measured deflection.

8. The computed results of the program are sensitive to variations in the layer thickness. The layer thicknesses should be determined to a degree of precision of five percent or better.

MODCOMP2 utilizes the Chevron elastic layer computer program for determining the stresses, strains and deformations in the pavement system. Since there is no closed-form solution for determining layer moduli from surface deflection data, an iterative approach is used in the computations. The procedure is as follows:

1. Input a set of "seed" moduli from which surface deflections are computed using the Chevron program.
2. The computed deflections are compared to the measured deflections and the seed moduli adjusted as a function of the magnitude of the difference in deflections.
3. The modulus for the layer is interpolated to obtain one which agrees with the measured deflection (Figure 3.5).
4. This process is repeated for each layer until the agreement between the calculated and measured deflection is within the specified tolerance or until the specified number of iterations has been reached.

Where unknown nonlinear models are to be determined, the program evaluates a modulus for the layer for each of several load levels. The moduli and associated stresses in the layer are then passed to a subroutine which performs a regression analysis to determine the k_1 and k_2 parameters. A hypothesis test is performed to assure that the nonlinear model is significant. If the model is not found to be significant, the layer is treated as being linearly elastic for the

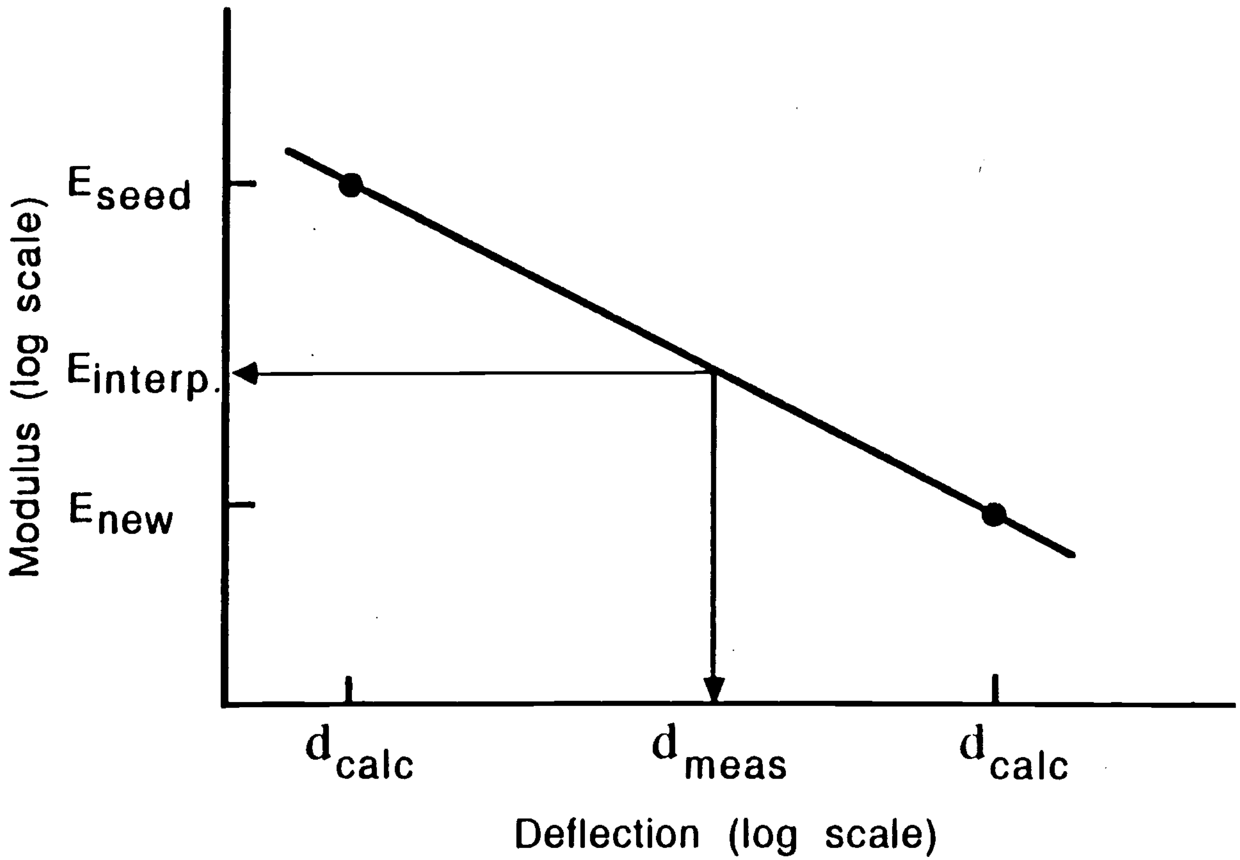


Figure 3.5 Interpolation of Modulus Using Calculated and Measured Deflections in MODCOMP2 Program (Irwin, 1983)

rest of the iteration. If the model is significant, it is used for the remainder of the calculations in the iteration. One of four non-linear model types can be specified.

Figure 3.6 shows the depth beneath which 95% of the surface deflection occurs. The actual shape and position of this line is a function of the moduli and thicknesses of the pavement layers. Most of the registered surface deflection is attributable to compression that occurs in the layers that are below this line. While the actual location of the line is unknown for a particular problem, in MODCOMP2 its position is approximated by a 34° line. Deflections are assigned to given layers from the set of input data using this line. The deflection that falls closest to the intersection between the upper layer interface and 34° line will generally be used.

Sensitivity analyses with the MODCOMP2 program have found that an extremely small tolerance must be specified in order to get accurate results. In general, a deflection tolerance on the order of 0.5 percent is required. This is recommended to avoid compounding measurement uncertainties with calculation uncertainties. This means a large number of iterations is required to converge to a solution. The actual number varies depending on the number of variable layers and whether a linear or non-linear solution is required.

An initial run of this program was performed to backcalculate pavement layer moduli from FWD deflection basin data. Many difficulties were encountered. Unknown errors appeared for some deflection data for no apparent reason. The procedure for determining the nonlinearity of materials did not work properly, errors or no solutions often occurred.

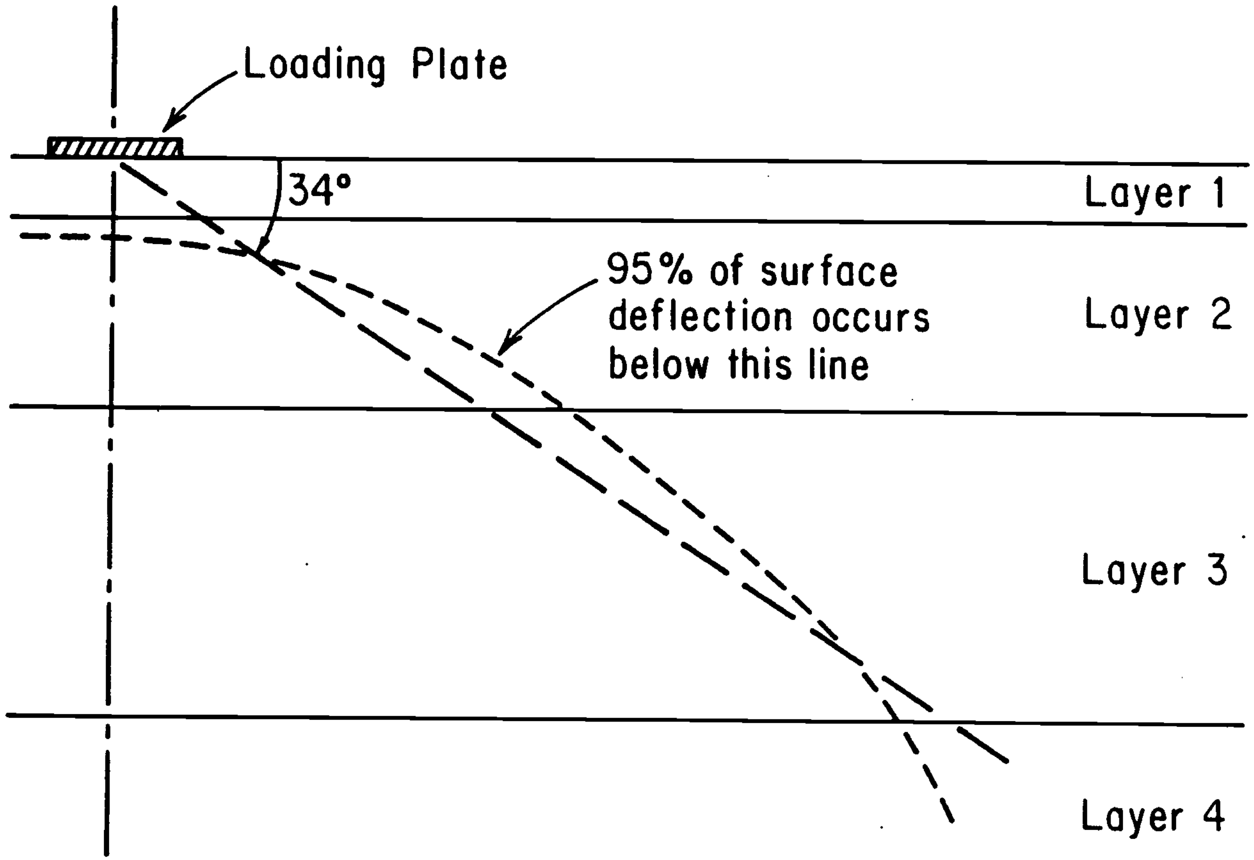


Figure 3.6 Pavement Model Showing Line of 95% Deflection (Irwin, 1983)

3.2.2.4 FPEDDI

FPEDDI (Uddin et al., 1985, Uddin, 1984) is a flexible pavement structural evaluation system using dynamic deflections. It evaluates NDT data to determine in situ pavement moduli and applies relevant corrections for the temperature dependency of the asphalt concrete layer and the nonlinear stress-dependent behavior of granular layers and subgrade. An option for determining the remaining life is also provided. The system utilizes the ELSYM5 computer program for calculating theoretical response of a pavement structure. FPEDDI is designed to handle a three or four layer flexible pavement. Currently, the program is capable of analyzing 50 deflection basins in one run.

The input data required for running the program include the following:

1. Number of total deflection basins for analyses.
2. Test site and date.
3. Station (test location) and name of NDT device.
4. Switch for NDT device, number of deflection sensors, peak force, peak stress of NDT device, and radius of loading.
5. Options for:
   a) summary output of basin fitting subroutine,
   b) remaining life analysis,
   c) default procedure for creating a rigid layer at a finite depth of subgrade,
   d) type of base material,
   e) average unit weight of subgrade soil, and
   f) surface condition of pavement.

6. Measured deflections in mils.
7. Number of layers including subgrade layer, pavement test temperature (°F), and design temperature (°F).
8. Information about each layer, starting from the top layer. Layer number, thickness, Poisson's ratio, initial seed modulus, maximum allowable modulus, and minimum permissible value of modulus.
9. Maximum allowable number of iterations and five types of tolerances for use in the self-iterative basin fitting procedure.
10. Indicator for user specified design load configuration, design load per tire, tire pressure, and past traffic in cumulative 18-kip ESAL.

A simplified flow chart of FPEDDI is presented in Figure 3.7. The principal analysis models and methodology are briefly described herein.

The following assumptions are made in order to validate the application of layered elastic theory for use in determining in situ moduli. These are listed below:

1. The existing pavement is considered to be a layered elastic system. Therefore, the principle of superposition is valid for calculating response due to more than one load.
2. The peak to peak dynamic force of the Dynaflect is modeled as two pseudo-static loads of 500 lb, each uniformly distributed on circular areas (3 in^2). The peak dynamic force of the FWD is assumed to equal the static load uniformly distributed on a circular area representing the FWD loading plate.

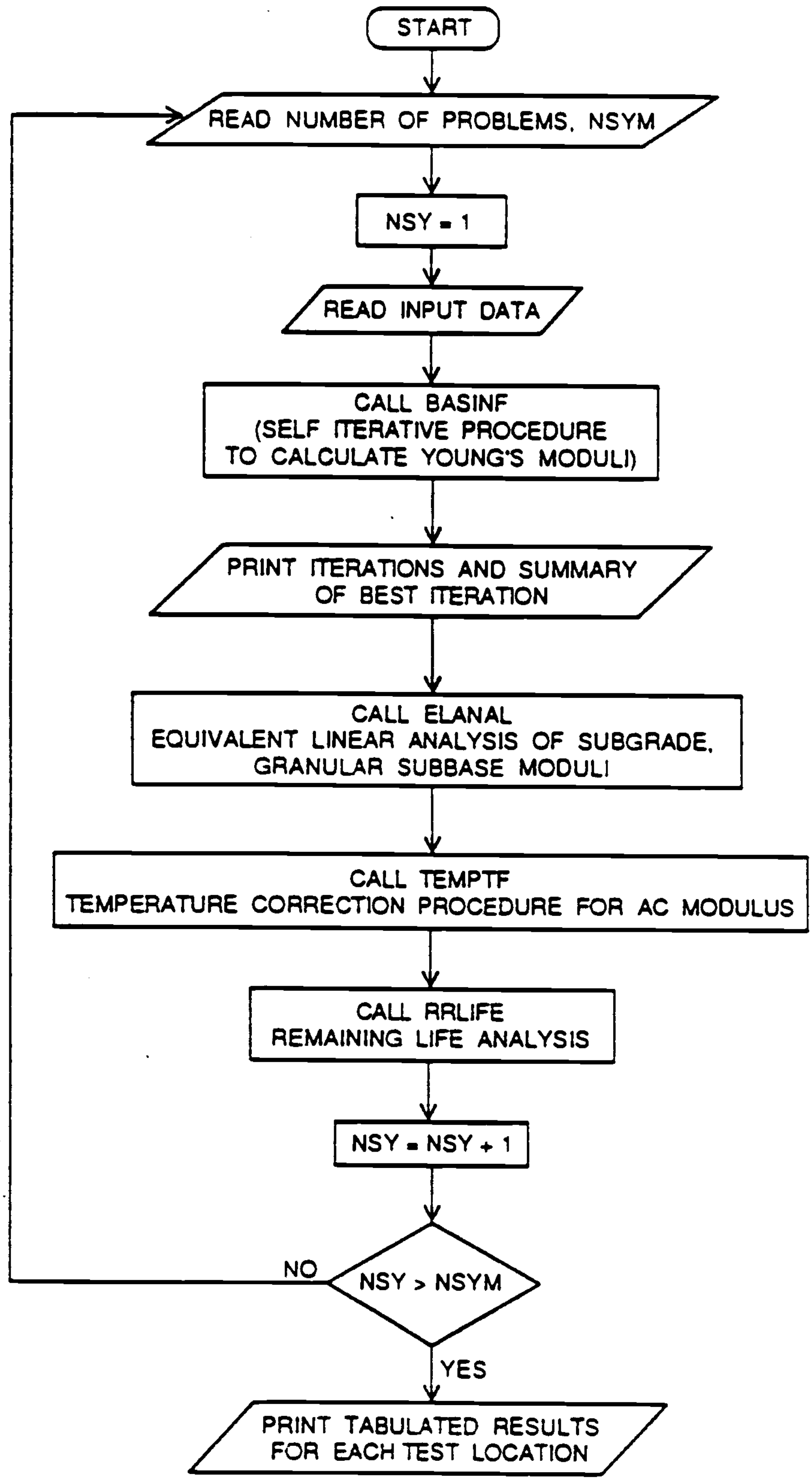


Figure 3.7 Simplified Flowchart of FPEDDI (Uddin, 1984)

3. Thickness of each layer is assumed to be known.
4. Subgrade is characterized by assigning an average value to its modulus of elasticity.

The methodology of determining the in situ moduli relies on generating theoretical deflection basins with ELSYM5 and changing the initial values of assumed moduli through a procedure of successive corrections until a best fit of the measured basin is obtained. A conceptual treatment of the procedure of successive corrections is presented in the following paragraph.

To start with, deflections are calculated from the initial input or default values of moduli. In the first cycle, the number of iterations is equal to the number of layers in the pavement. In each cycle, the first iteration is made to correct the subgrade modulus. ELSYM5 is then called to calculate theoretical deflections. Corrections are then applied to the modulus of the next upper layer and ELSYM5 is again called to calculate theoretical deflections. This procedure of successive corrections is continued until the moduli of all layers have been checked for corrections. Then, another cycle of iterations begins anew from the subgrade layer. The generalized form of the relationship used in the procedure of successive corrections is given as:

$$ENEW_i = E_i\ (1.0 - CORR_i * ERRP_k * 0.5) \qquad (3\text{-}8)$$

where:

$ENEW_i$ = corrected value of Young's modulus of ith layer,

E_i = value of Young's modulus of ith layer in the previous iteration.

$CORR_i$ = correction factor for the ith layer, and

$ERRP_k$ = discrepancy in measured deflection and predicted deflection as percent error.

The discrepancy in measured and theoretical deflections at the furthest sensor can be used to correct the subgrade modulus. The moduli of intermediate layers are related to discrepancies in the deflection of one or more of the intermediate sensors. Finally, the surface layer modulus can be corrected using the discrepancy at the first sensor and Equation (3-8). Only half of the discrepancy is removed in each iteration. A set of three factors is used in the self-iterative procedure; one is for the subgrade modulus, the second is for the intermediate layers, and the third is associated with the surface layer. Iterations are stopped when one of the following criteria is reached: 1) the maximum absolute discrepancy among calculated and measured deflections is equal to or less than the permissible tolerance, 2) any further correction in the modulus value causes the discrepancies in calculated and measured deflections to increase, and 3) the specified number of iterations is achieved.

3.2.2.5 MODULUS

The MODULUS program is an interpolation program that was written by Uzan (Lytton, Roberts & Stoeffels, 1985). It is based on data calculated using an elastic layered program such as BISAR and ELSYM5. Numerous elastic layered problems must be run for the specific layer thicknesses and loading radii for the pavement sections in question. Therefore, MODULUS is recommended for use when a large number of pavements with similar cross-sections are to be run or when an appropriate data base is already available. MODULUS is written in FORTRAN and compiled with the Microsoft FORTRAN compiler for use on an IBM microcomputer. Two versions are available, one utilizing the presence of an 8087 math-coprocessor chip and the other without. A maximum of three pavement layers, including subgrade, and four sensor locations can be defined in the program.

3.2.2.6 ISSEM4

The ISSEM4 (In Situ Stress-dependent Elastic Moduli, 4 layers maximum) program was developed for use on data generated with the Dynatest FWD by Sharma and Stubstad (1979, 1980). The original concepts used in the program were first published by Ullidtz (1977).

The ISSEM4 program backcalculates resilient modulus values for a layered, non-linear elastic system from the surface deflections generated by a FWD (Dynatest, 1986). The process is iterative, and a set of seed moduli values is used to initiate each program run.

From the deflection basin, a deflection reading which reflects the contribution of the subgrade alone is picked. A minimum of seven deflection readings is advised to obtain a full deflection basin profile. Using the ELSYM5 subprogram, the subgrade modulus value is then obtained when the calculated deflection basin fits the measured deflection basin. This process is then repeated with another deflection reading that is farther away from the load, and another subgrade modulus value obtained. The two moduli are then combined to obtain a composite modulus which can be related to the major principal stress level at or near the surface of the subgrade. Similarly, two modulus values can be found for layer i and so on. The modulus and stress relationship is of the general form:

$$E_i = k1_i * S(1)_i^{k2_i} \tag{3-9}$$

where:

E_i = modulus of the ith layer,

$S(1)_i$ = principal stress at or near surface of layer i, and

$k1_i$, $k2_i$ = constants for layer i.

The underlying layer moduli represented by the above equation are appropriately adjusted to reflect their actual moduli at the deflection position being processed. Finally, the above modulus relationships for each layer below the surface layer are used to calculate the corresponding centerline E-values, and the E-value under the load for the surface layer (E_1) is derived.

The above process describes the first iteration to arrive at a set of modulus versus stress levels relationships for layers 2 to the subgrade, and a set of centerline modulus values for all layers. Next, the ISSEM4 program uses the matrix of E-values obtained from the first iteration loop to re-initiate the next iteration. The relationships and modulus values derived from the second iteration are then compared with those from the first iteration and if the percentage tolerance is less than the user-specified amount, a satisfactory solution has been obtained for the given deflection basin and structural cross section. If not, a new iteration loop is initiated until the percentage tolerance is met. The better the initial seeded modulus values, the quicker the convergence to a solution.

All values of stress used in the above equation are calculated based on the linear elastic theory. However, the non-linearity of a material will not significantly affect the major principal stress magnitudes in a layered, non-linear elastic system, although the strains may be affected markedly (Dynatest, 1986).

As with all backcalculation programs, ISSEM4 is not perfect. In particular, there are a few points to look out for:

1. If the AC layer is less than 3 in. (75 mm), the modulus value for that layer may be quite unreliable.
2. The thickness of layer 2 should be greater than layer 1, or the results may likewise be unreliable.
3. Each layer in the pavement should have a decreasing modulus from the top on downwards, unless E_1 is fixed, in which case E_1 may be less than E_2.
4. If a four-layer system is to be analyzed, the results for layer 3 may be inaccurate unless it is constrained. ISSEM4 functions most reliably in two or three-layered systems.
5. A unique solution may not always be possible, due to the fact that the models used in the layered-elastic programs are merely an approximation of actual pavement layers conditions.

3.2.3 Finite Element Method

Linear elastic layer assumptions do not consider the stress dependent nature of the modulus of most pavement materials. It has been shown that the modulus of granular materials is a function of the bulk stress and also that the modulus of fine material is a function of the deviator stress. The advantage of using a finite element program is that non-linear stress-strain properties of each pavement layer may be used, and these properties can be changed with stress levels. However, the computing time required to reach a solution using a finite element program is much greater than that using the linear elastic layer programs.

There are no known automated methods which use a finite element program to calculate layer moduli to match a measured deflection basin. Instead, the approach that is commonly followed is to select a typical pavement type and NDT loading device and make a series of computer runs to determine the surface deflections of that type of pavement as the layer thicknesses and material properties of the layer materials change. An experimental design is used to set the high, low and medium levels of the pavement properties that vary. The surface deflections are then related to thickness and material properties by linear regression analysis. A widely known method utilizing this approach is the set of equations developed by Hoffman and Thompson (1982), as described below.

3.2.3.1 ILLI-CALC

ILLI-CALC (Hoffman & Thompson, 1981, 1982) is a method developed at the University of Illinois and is used to evaluate nonlinear resilient moduli based on the interpretation of the measured surface deflection basin. The method is not a true backcalculation procedure in the sense of the methods mentioned earlier. Instead it utilizes regression equations and nomographs developed from selected pavement types and materials. The regression equations and nomographs are based on the results of the stress-dependent finite element model ILLI-PAVE. Solutions are possible for conventional flexible pavements composed of an asphalt concrete layer with a typical crushed stone base layer and a fine grained subgrade soil.

The method is based on a deflection basin measured with either the Road Rater or the Falling Weight Deflectometer. The Road Rater deflection values are converted to FWD values using the correlations developed during the Illinois study (Hoffman & Thompson, 1981). The deflection basin is characterized as follows;

1. D_0 = The maximum deflection at the center of the applied load.
2. D_1, D_2, D_3 = Deflections at 1, 2 and 3 ft. from the center of the load plate.
3. The deflection basin "area" is defined as follows:

   Area (in^2) = $6 * (1 + 2D_1/D_0 + 2D_2/D_0 + D_3/D_0)$
4. The deflection basin shape factors, F1 and F2, are defined as:

   $F1 = (D_0 - D_2)/D_1$ and $F2 = (D_1 - D_3)/D_2$

In the evaluation procedure, Road Rater center deflections (D_0) at 8 kips and 15 Hz are converted to equivalent FWD deflections by using the given correlations between the two devices.

The greatest advantage of this procedure is its ability to characterize the non-linear stress-strain relationships exhibited by most pavement materials. The ILLI-PAVE model is an axisymmetric solid of revolution based on the finite-element method. The model incorporates nonlinear stress-dependent material models and failure criteria for granular materials and fine grained soils. The principal stresses in the granular base and subgrade layers are modified at the end of each iteration so that they do not exceed the strength of the materials as defined by the Mohr-Coulomb theory of failure. Raad and Figueroa (1980) in their study showed that measured and ILLI-PAVE predicted load deformation responses yielded favorable results.

Material characterizations for the ILLI-PAVE model are shown in Table 3.3. The asphalt concrete (AC) material is assumed to be linear elastic with a modulus ranging from 100 to 1400 ksi. Two material models are used to characterize the granular base materials. The general model is of the form:

$$E_r = k\theta^n \qquad (3\text{-}10)$$

where:

E_r = resilient modulus (psi),

θ = first stress invariant or bulk stress (psi), and

k,n = material constants determined in repetitive triaxial tests.

Four different fine-grained subgrade soil models were used. These models are given in Figure 3.8. The "breaking point" of the curves at a deviator stress of 6 psi corresponds to a resilient modulus denoted E_{ri}. For each of the subgrade chosen, E_{ri} is the main parameter characterizing the nonlinear subgrade soil.

By using the material properties and cross-sections summarized in Table 3.3, ILLI-PAVE deflection basin data were generated for a total of 144 combinations. Using multiple-regression techniques, deflection-basin predictive equations were developed as a function of the four ILLI-PAVE inputs (E_{ac}, E_{ri}, T_{ac}, T_{gr}) for conventional flexible pavements, where;

E_{ac} = Modulus of asphalt concrete layer,

E_{ri} = Breaking point of subgrade moduli (Figure 3.8),

T_{ac} = Thickness of asphalt concrete layer, and

T_{gr} = Thickness of granular layer.

The crushed stone material model is kept constant. The regression

Table 3.3 Material Characterization for ILLI-PAVE Program (Thompson, 1982)

a) Summary of Material Properties

	Asphalt Concrete			Crushed		Subgrade			
	40°F	70°F	100°F	Stone	Gravel	Stiff	Medium	Soft	V. Soft
Unit Weight (psf)	145.00	145.00	145.00	135.00	135.00	125.00	120.00	115.00	110.0
Lateral Pressure Coeff. at Rest	0.37	0.67	0.85	0.60	0.60	0.82	0.82	0.82	0.82
Poisson's Ratio	0.27	0.40	0.46	0.38	0.38	0.45	0.45	0.45	0.45
Unconfined Compress. Strength (psi)	-	-	-	-	-	32.80	22.85	12.90	6.21
Deviator Stress									
Upper limit (psi)	-	-	-	-	-	32.80	22.85	12.90	6.21
Lower limit (psi)	-	-	-	-	-	2.00	2.00	2.00	2.00
σ_{di} (psi)	-	-	-	-	-	6.20	6.20	6.20	6.20
E_{ri} (ksi)	-	-	-	-	-	12.34	7.68	3.02	1.00
$E_{failure}$ (ksi)	-	-	-	4.00	4.00	7.605	4.716	1.827	1.00
$E_{const.\ mod.}$ (ksi)	1400.00	500.00	100.00	-	-	-	-	-	-
$E_{r\text{-}model}$ (psi)	-	-	-	$9000\theta^{0.33}$	$6500\theta^{0.30}$	-	-	-	-
Friction angle (°)	-	-	-	40.0	40.0	0.0	0.0	0.0	0.0
Cohesion (psi)	-	-	-	0.0	0.0	16.4	11.425	6.45	3.105

b) Layer Thickness (inches)

Asphalt Concrete Layer	Granular Base
0.0	4.0
1.5	6.0
3.0	9.0
	12.0

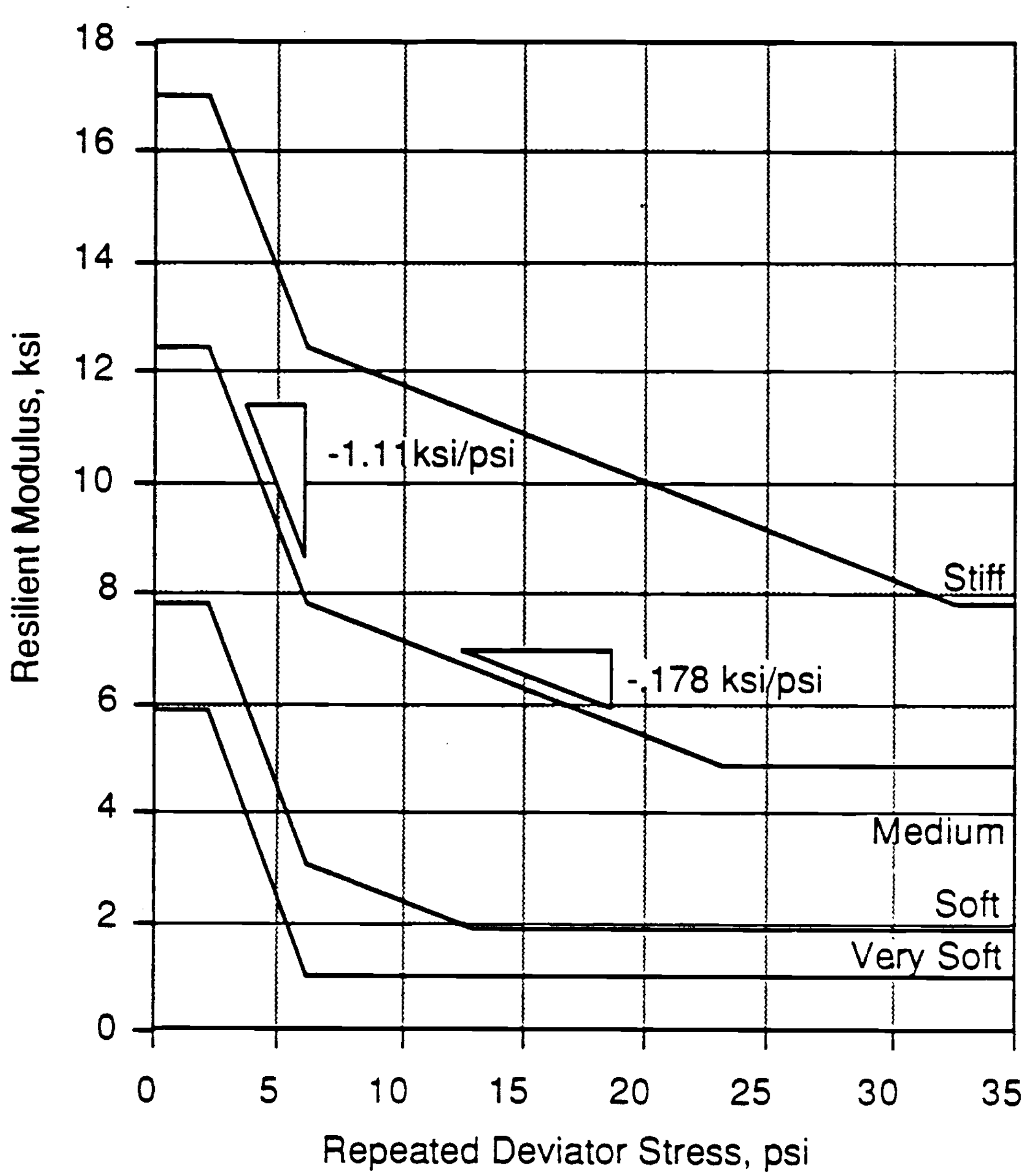


Figure 3.8 Subgrade Soil Material Models for ILLI-PAVE Analysis (Hoffman and Thompson, 1981)

equations show that it is possible to predict ILLI-PAVE deflection-basin parameters with reasonable accuracy. (R^2 ranges from 0.90 to 0.95)

The backcalculation procedure, given that T_{gr} and T_{ac} are known, is as follows:

1. Determine the mean RR (Road Rater) maximum deflection D_0.
2. Determine mean RR area (in^2).
3. Determine mean RR shape factors F1 and F2.
4. Determine the predicted FWD values for steps 1-3.
5. Determine D_0 for ILLI-PAVE interpretation.
6. Using nomograph with T_{ac} and T_{gr}, determine E_{ri} and E_{ac}.
7. Check the ratio of measured and computed F1 and F2

The advantages of this method are:

1. The deflection-basin predictive models can be used in lieu of expensive and frequently unavailable computer runs.
2. The model used to generate the equations takes into account the non-linear behavior of base and subgrade material.

The limitations of this method are:

1. The method lacks universality in that it requires the use of specific testing devices, one of which is owned by the Illinois DOT and the other (FWD) which is still to be used on a large scale in the United States.
2. The method assumes a subgrade material relationship which might not be typical of subgrade soils in other areas.
3. The method assumes one relationship for the unbound aggregate layer, which might not apply to all aggregate materials.
4. The model used is only capable of one loading configuration.

5. Because of its reliance on regression equations, this method cannot be transferred to another area without having to go through the development of new regression models.

3.3 Summary

This chapter reviews some of the existing backcalculation procedures for determining pavement layer moduli using NDT methods. The existing procedures can be broadly categorized into three classes: 1) equivalent thicknesses methods, 2) elastic layer methods, and 3) finite element method. Two programs in the category of method of equivalent thicknesses are reviewed. They are ELMOD and SEARCH. Several programs in the group of elastic layer method are also looked into. These programs are CHEVDEF/BISDEF, ELSDEF, MODCOMP2, MODULUS, PFEDDI, and ISSEM4. A backcalculation procedure ILLI-CALC which uses finite element method is also reviewed.

It is difficult to conclude which program is more superior than others. In general, the programs which use the method of equivalent thicknesses take less computing time than both elastic layer theory and finite element method.

A severe limitation in any deflection basin fitting method is the non-uniqueness of the backcalculated moduli. In general, the subgrade modulus can be uniquely related to the farthest sensor deflection readings. However, for a multi-layered pavement structure, more than one combination of moduli which match calculated deflection basin with the measured deflection basin with reasonable error tolerance could be obtained. In addition, a basin matching procedure is generally sensitive to the initial or seed moduli, especially if these values are drastically different from actual moduli.

4.0 DEVELOPMENT OF AN IMPROVED BACKCALCULATION PROGRAM

It has been seen in Chapter 3 that the nondestructive testing of asphalt concrete pavement has become one of the most useful and cost-effective methods for pavement structural evaluation and that the use of deflection measurements for the estimation of pavement layer moduli is rapidly gaining popularity and application.

For these reasons, considerable effort has been applied to develop computer programs that would allow engineers to determine pavement material characteristics from the use of the deflection testing data. Many such computer programs have been developed using different assumptions or algorithms as described in the previous chapter. After reviewing the available programs, one major drawback of each program is its computing efficiency. In the evaluation of a large quantity of deflection data, the requisite of too much computing time could seriously impact the use of these programs in routine design work.

This chapter presents an improved backcalculation program (BOUSDEF). The major advantage of this improved program is its computing speed, which allows engineers to make a quick and initial evaluation of the deflection testing data for the determination of pavement layer moduli. The BOUSDEF program uses the method of equivalent thicknesses and modified Boussinesq equations to compute the surface deflections. The validation of using Boussinesq equations together with the MET to calculate surface deflections is presented in Chapter 2.

4.1 Program Development and Description

4.1.1 Program Flowchart

The BOUSDEF program was developed for determining in-situ moduli of a pavement structure using deflection data through a backcalculation technique. Figure 4.1 shows a flow diagram of the program, while the user's guide can be found in Appendix A.

To start with, the program first reads input data sets which include: 1) NDT load force and load radius, 2) pavement layer thicknesses, 3) Poisson's ratio, 4) minimum, maximum, and initial modulus, 5) density of pavement materials, 6) deflection data (up to seven sensor readings), 7) percent of tolerance to stop the deflection matching process and 8) number of iterations. By calling a subroutine DEFLECTION, the initial modulus and layer thickness information are used to determine the equivalent thicknesses. Deflections for the given NDT load and load radius are then calculated. The calculated deflections are compared to measured deflections. If the sum of the differences is greater than the tolerance specified by the user, the program will start an iteration by changing the moduli to compute a new set of deflections.

A simplified description of the deflection matching procedure is illustrated in Figure 3.4. This process repeats until the sum of the differences is less than the tolerance or the maximum number of iterations has been reached. This procedure is repeated for each load level until all deflection data are used.

The moduli determined from each set of deflection basin data are used to calculate normal stresses induced by load. Stresses under the deadload of the upper pavement materials are also determined. For the

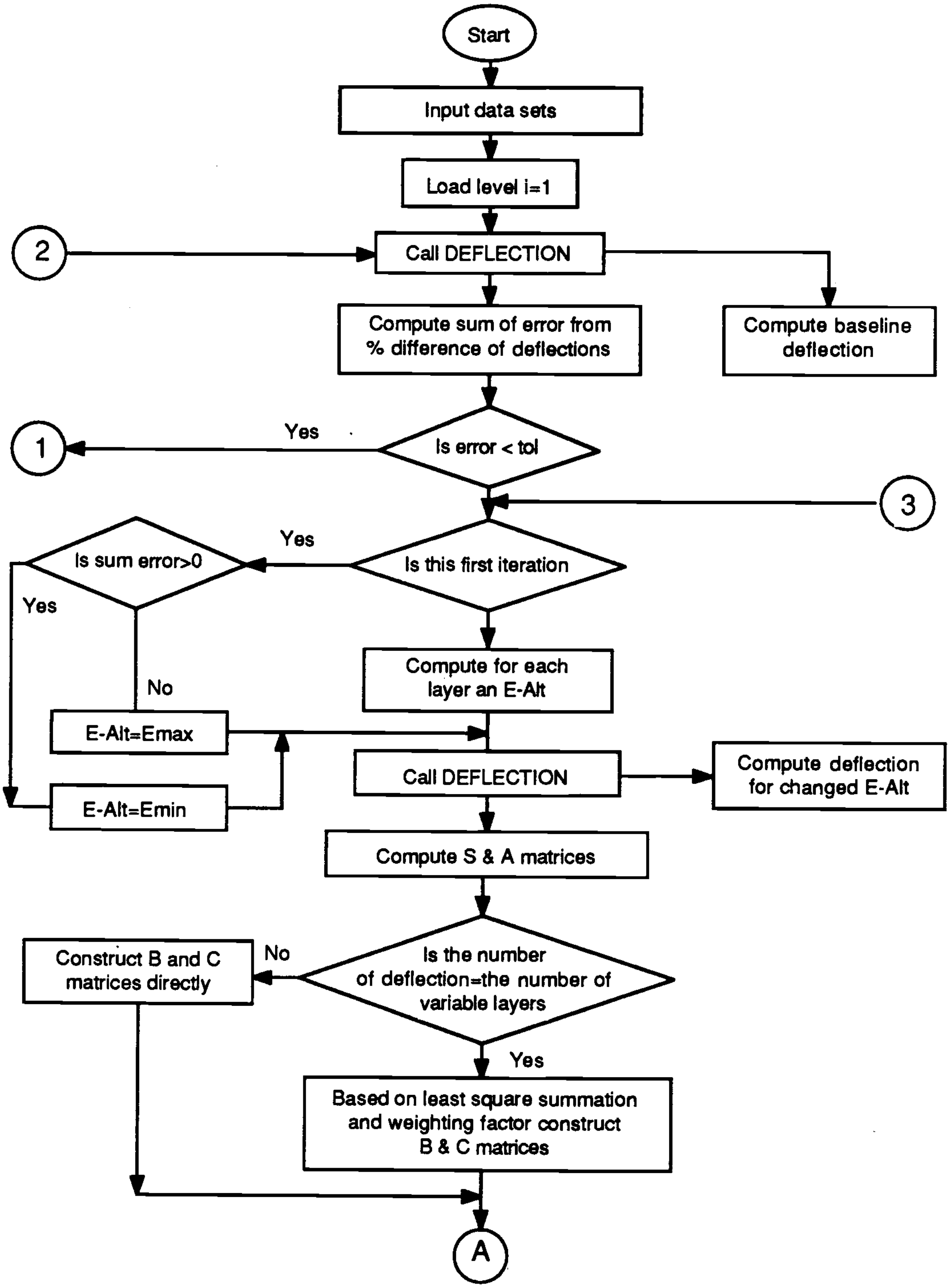


Figure 4.1 Flowchart of the BOUSDEF Program

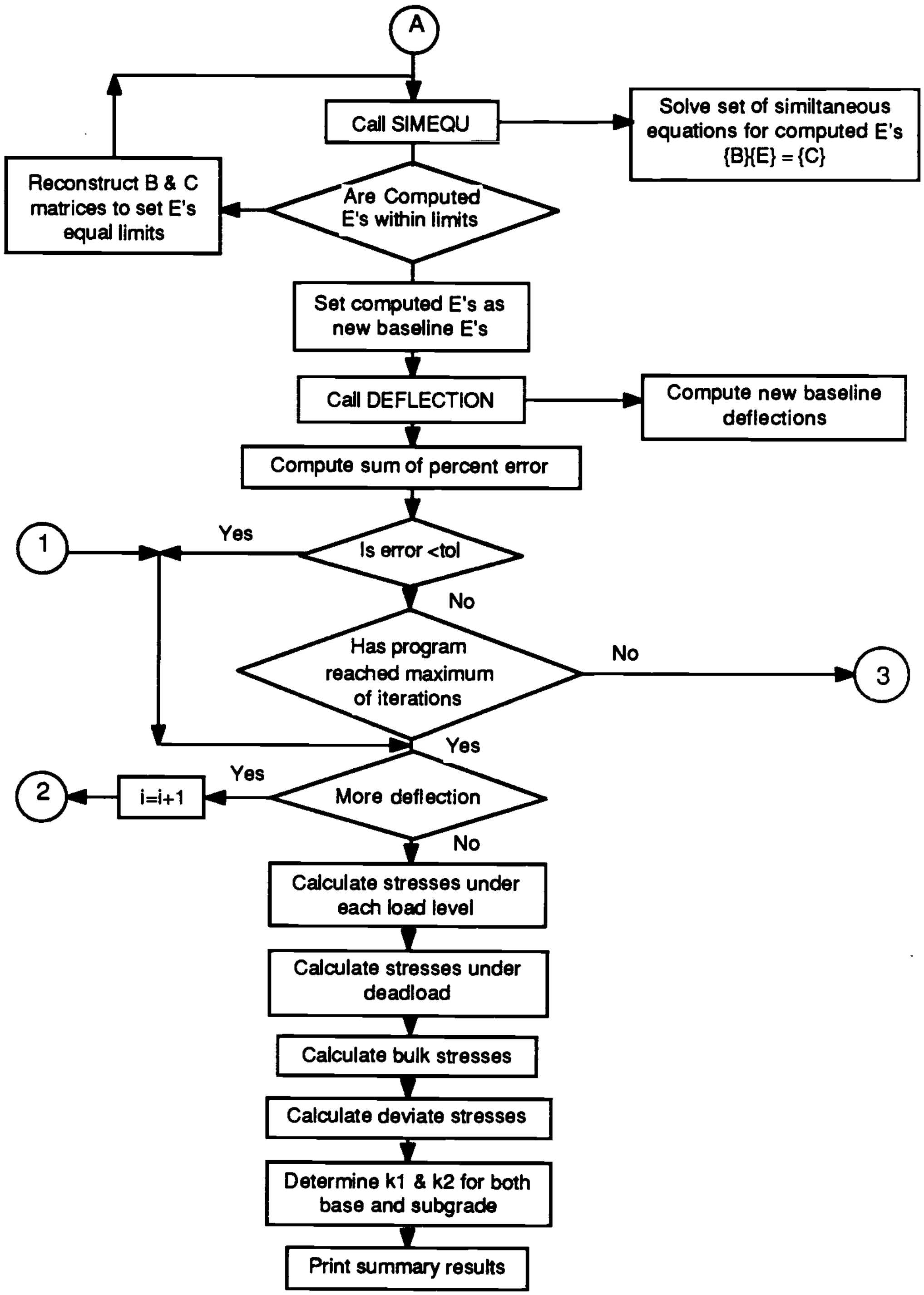


Figure 4.1 Flowchart of the BOUSDEF Program (cont.)

base layer, bulk stresses in the middle of the layer are calculated. For the subgrade, deviator stresses on the top of subgrade are determined. These stress values and moduli are then regressed to find coefficients k_1 and k_2 for both base layer and subgrade.

It should be noted that the backcalculated modulus corresponds to an average condition in the pavement material while the bulk and deviator stresses are calculated under the load at the middle of the base layer and top of the subgrade rather than the entire body of the base and subgrade. Therefore, the nonlinear analysis is limited to the stress condition at a specific location rather than at different depth of base and subgrade. Also, the method of equivalent thicknesses/Boussinesq approach is least reliable in predicting horizontal stresses (Ullidtz, 1980).

4.1.2 Program Output

The program has the capability of determining the following:

1. Resilient modulus for each pavement layer.
2. Bulk stresses and deviator stresses induced by both load and deadload of upper layer pavement materials.
3. Coefficients k_1 and k_2 for base and subgrade materials with a form of relationship shown below:

   for coarse-grained materials,

$$M_R = k_1 \theta^{k_2} \tag{4-1a}$$

or for fine-grained materials

$$M_R = k_1 \sigma_d^{k_2} \tag{4-1b}$$

where:

M_R = Resilient modulus (psi),

θ = Bulk stresses (psi),

σ_d = Deviator stress (psi), and

k_1, k_2 = Regression coefficients of material properties.

4.1.3 Example

An example is provided to illustrate the use of the program. Table 4.1 summarizes the pavement and deflection test data for the example. The pavement is a conventional flexible structure with an eight-inch asphalt concrete surface, twelve-inch aggregate base and infinite depth of subgrade. Deflection testing was performed using a falling weight deflectometer (FWD) on one short section of a road. Various load levels were applied in order to obtain pavement responses under different stress conditions. At least two load levels of FWD should be used to define the modulus versus stress relationship. However, it is preferable to have several stress conditions so that a more representative relation can be better defined.

By using the BOUSDEF program, resilient modulus for each pavement layer is determined and presented in Table 4.2. Bulk stresses in the middle of the base layer and deviator stresses on the top of subgrade are calculated. Regression coefficients k_1 and k_2 for both base and subgrade are also determined. As can be seen in Table 4.2, both base and subgrade materials appear to have a non-linear property with k_2 = 0.58 for base and -0.13 for subgrade. The results are plotted in Figure 4.2.

4.1.4 Sensitivity to the User Input

The initial moduli specified by the user should have a minor effect on the final backcalculated moduli. This feature would minimize the variation in the final moduli because of the user's input and would result in a more reliable solution. An initial

Table 4.1 Pavement and Deflection Data for the Example

Pavement Data

Layer	Thickness (inch)	Poisson's ratio	Density (pcf)
AC	8	0.35	144
Agg. Base	12	0.40	120
Subgrade	∞	0.40	100

Deflection Data

Load (lbs)	Distance to sensor (inch): 0	8	18	36	58
	Deflection Readings (mils)				
2789	6.07	4.04	2.41	1.25	0.91
3035	6.59	4.02	2.41	1.37	0.94
3055	6.55	3.89	2.28	1.50	0.94
6521	12.92	8.26	6.47	3.19	1.82
6644	13.18	8.81	7.23	3.53	1.82
6562	13.82	9.57	6.47	3.88	1.72
6521	13.31	8.26	7.10	3.53	1.94
6480	13.05	8.48	5.58	3.65	1.93
6480	13.44	12.72	7.48	5.59	3.50
11442	22.09	14.35	11.92	5.81	3.76
11770	22.48	15.44	13.19	6.38	3.96
11606	23.77	16.74	11.79	6.84	3.83
11442	22.99	14.78	12.68	6.84	3.97
11770	22.35	14.78	10.65	6.84	3.91

Note: Load radius is 5.9 inches

Table 4.2 Summary of Backcalculation Results for the Example

Summary of Non-linear Characteristics of Lower Layers

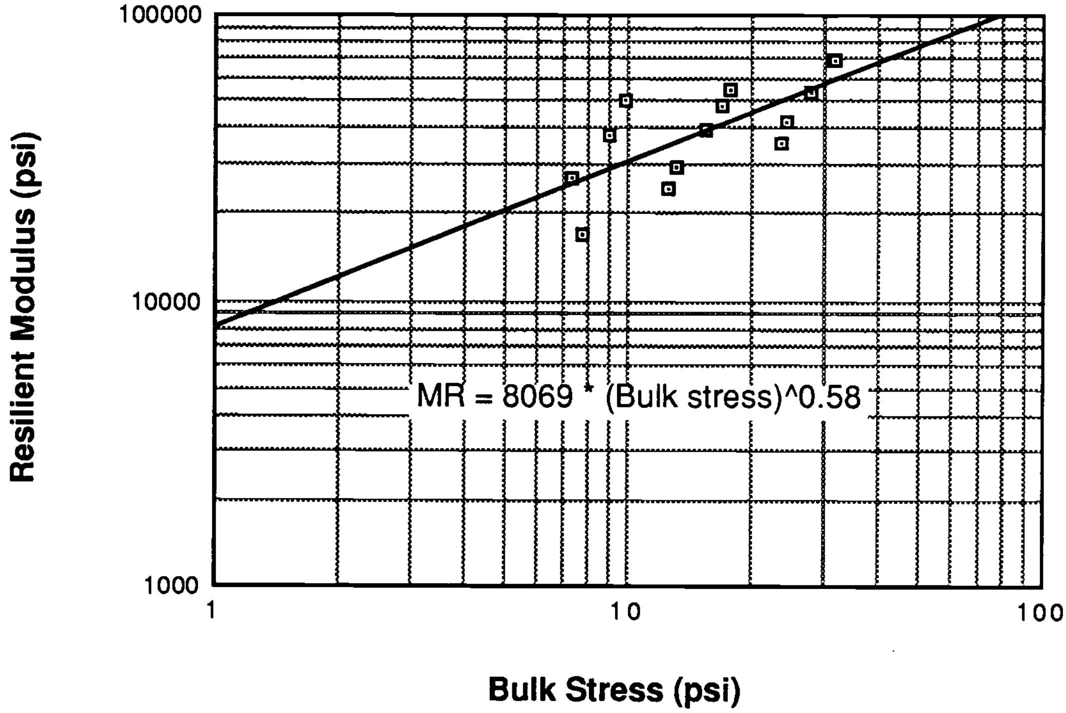
For base layer: kl= 8069 k2= 0.58 $(M_R = k_1\ \theta^{k_2})$

For subgrade: kl= 18687 k2= -0.13 $(M_R = k_1\ \sigma_d^{k_2})$

Summary of Moduli and Stresses *

Load (lb)	E(1)	E(2)	E(3)	BSTRS	DSTRS
2,789	106,432	26,911	16,377	7.29	5.59
3,035	83,362	38,107	16,870	8.99	5.76
3,055	74,978	49,985	16,606	9.88	5.59
6,480	104,087	48,343	14,961	16.81	7.75
6,480	399,359	17,074	9,462	7.74	5.96
6,521	117,982	39,666	15,393	15.41	8.01
6,521	99,314	54,258	13,863	17,67	7.44
6,562	142,581	24,546	15,015	12.58	8.40
6,644	158,740	29,287	14,770	13.00	7.96
11,442	117,180	53,092	14,045	27.83	10.55
11,442	100,939	69,773	12,518	31.35	9.65
11,606	136,673	35,135	13,533	23.61	11.16
11,770	156,599	41,680	13,376	24.18	10.46
11,770	105,657	69,787	13,774	31.79	10.18
Average	135,994	42,689	14,326		

* Moduli and stresses are in psi.



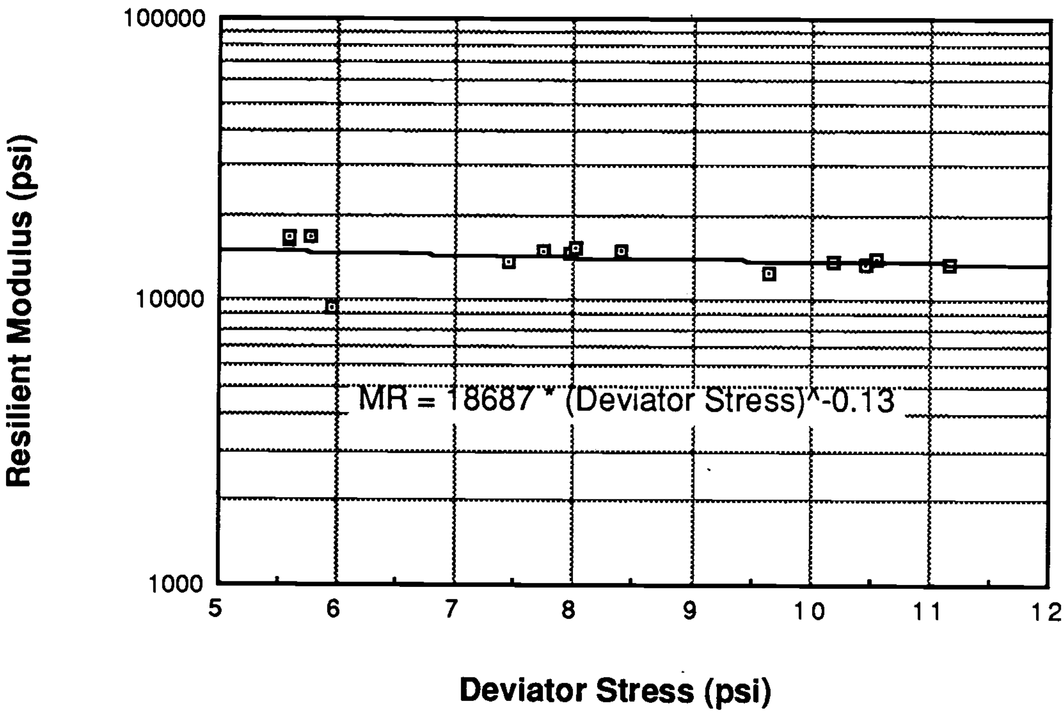


Figure 4.2 Plot of the Example Output

evaluation on the sensitivity to input modulus was performed using data in Table 4.3. The results are summarized in Table 4.4. As indicated, the program provides very similar results regardless of what initial modulus values would be.

4.2 Evaluation of the BOUSDEF Program

To evaluate the BOUSDEF program, three approaches were used: 1) comparing backcalculated moduli with preassumed theoretical values, 2) comparing backcalculated moduli with results from other developed programs, and 3) comparing backcalculated moduli with the laboratory test results. The following discusses the process.

4.2.1 Comparison With Theoretical Values

The BOUSDEF program was evaluated by comparing the backcalculated results with hypothesized theoretical values. This is done by assuming a set of pavement structures with different combination of layer thicknesses and different resilient modulus. Ten pavement structures, as described in Section 2.1.4, are used for the comparison.

Table 4.5 summarizes calculation results. The backcalculated moduli for all structures are very close to those of theoretical values. This would indicate the BOUSDEF program has the capability of backcalculating the layer moduli from known deflections and layer thicknesses and load data. However, it should be noted that the MET is not recommended for pavements with base layers that are very stiff compared to the surface (Ullidtz, 1987) as mentioned earlier. The pavements with CTB layers were included here to illustrate that BOUSDEF is capable of providing an initial evaluation for such pavements. Alternative means of backcalculation should also be carried out to improve this evaluation.

Table 4.3 Data Used for Evaluating Sensitivity on Initial Modulus

LAYER	THICKNESS	POISSON'S RATIO
1	11.0"	0.30
2	15.0"	0.35
3	∞	0.45

MEASURED DEFLECTIONS

DISTANCE FROM LOAD (IN)	0.0	18.0	36.0	60.0
DEFLECTION (MILS)	6.47	4.27	2.34	1.47

LOAD = 14696 pounds

LOADING RADIUS = 9.0 inches

DEVICE = WES Vibrator

(Lytton, 1986)

Table 4.4 Effect of Initial Moduli on Calculated Moduli Using BOUSDEF

Initial Moduli (psi)			Calculated Moduli (psi)		
Surface	Base	Subgrade	Surface	Base	Subgrade
Variation of surface modulus					
200,000	50,000	25,000	768,422	57,228	46,810
300,000	50,000	25,000	768,455	57,248	46,803
400,000	50,000	25,000	768,485	57,248	46,803
500,000	50,000	25,000	764,142	57,702	46,766
600,000	50,000	25,000	764,203	57,693	46,768
700,000	50,000	25,000	764,250	57,689	46,769
800,000	50,000	25,000	772,642	56,432	46,914
900,000	50,000	25,000	769,176	56,987	46,835
1,000,000	50,000	25,000	764,989	57,592	46,791
Variation of base modulus					
500,000	10,000	10,000	728,648	56,086	46,783
500,000	20,000	10,000	739,009	54,808	46,863
500,000	30,000	10,000	738,916	54,843	46,837
500,000	40,000	10,000	738,827	54,860	46,830
500,000	50,000	10,000	738,859	54,845	46,842
500,000	60,000	10,000	738,985	54,813	46,861
500,000	70,000	10,000	728,289	56,131	46,770
500,000	80,000	10,000	735,888	54,997	47,021
500,000	90,000	10,000	740,119	54,560	47,021
500,000	100,000	10,000	739,447	54,540	46,980
Variation of subgrade modulus					
500,000	30,000	10,000	738,916	54,843	46,837
500,000	30,000	20,000	735,079	55,446	46,847
500,000	30,000	30,000	728,013	56,166	46,759
500,000	30,000	40,000	743,267	54,092	46,998
500,000	30,000	50,000	733,450	55,287	47,091
500,000	30,000	60,000	736,109	53,809	48,243
500,000	30,000	70,000	735,286	54,468	47,642
500,000	30,000	80,000	735,390	54,333	47,767
500,000	30,000	90,000	735,356	54,292	47,814
500,000	30,000	100,000	739,984	53,871	47,754

Table 4.5 Comparison Between Theoretical and Backcalculated Modulus Values *

Pavement Structure	Theoretical Values 1	2	3	4	5	Backcalculated Values 1	2	3	4	5
Three-Layer Conventional										
7" AC	100.0	300.0	600.0	1000.0	1500.0	101.9	289.9	602.7	1022.1	1551.1
12" Agg.	25.0	25.0	25.0	25.0	25.0	24.7	25.0	25.1	24.6	24.4
Subgrade	10.0	10.0	10.0	10.0	10.0	10.0	10.1	9.9	9.9	9.9
3" AC	100.0	300.0	600.0	1000.0	1500.0	100.7	310.1	594.3	1017.2	1538.2
18" Agg.	20.0	20.0	20.0	20.0	20.0	20.0	19.8	20.1	19.9	19.8
Subgrade	10.0	10.0	10.0	10.0	10.0	10.0	9.9	9.9	9.9	9.9
10" AC	200.0	600.0	1000.0	1500.0		202.6	615.5	1017.5	1566.5	
16" Agg.	25.0	25.0	25.0	25.0		31.1	31.9	31.6	30.8	
Subgrade	10.0	10.0	10.0	10.0		10.0	9.9	10.1	9.9	
Four-Layer Conventional										
3" AC	300.0	600.0	1000.0	1500.0		357.3	638.8	1024.9	1493.5	
12" Base	25.0	25.0	25.0	25.0		23.6	24.3	24.6	25.0	
20" Subbs	10.0	10.0	10.0	10.0		9.7	10.0	10.0	10.0	
Subgrade	7.0	7.0	7.0	7.0		7.2	7.0	7.0	7.0	
6" AC	100.0	300.0	600.0	1000.0		101.3	298.5	615.6	1027.3	
12" Base	25.0	25.0	25.0	25.0		24.9	25.1	24.0	23.9	
24" Subbs	12.0	12.0	12.0	12.0		12.0	12.0	12.1	12.1	
Subgrade	8.0	8.0	8.0	8.0		8.0	8.0	8.0	8.0	
Cement Treated Base										
4" AC	300.0	600.0	1000.0			294.8	588.3	1158.5		
8" CTB	1200.0	1200.0	1200.0			1216.1	1205.4	1107.7		
Subgrade	10.0	10.0	10.0			10.0	10.0	10.0		
4" AC	300.0	600.0	1000.0			292.7	584.0	1081.8		
10" CTB	1200.0	1200.0	1200.0			1215.0	1225.8	1081.8		
Subgrade	10.0	10.0	10.0			10.0	10.0	10.0		
PCC										
8" PCC	4000.0					4172.8				
6" Base	20.0					21.2				
Subgrade	10.0					9.9				
8" PCC	4000.0					4028.6				
12" Base	20.0					19.8				
Subgrade	10.0					9.9				
12" PCC	4000.0					4015.5				
12" Base	20.0					20.0				
Subgrade	10.0					10.0				

* Moduli are in ksi.

4.2.2 Comparison With Other Developed Programs

The BOUSDEF program was compared with four developed programs. The programs used are: BISDEF (Bush, 1985), CHEVDEF (Bush, 1980), ELSDEF (Lytton, 1986), and MODCOMP2 (Irwin, 1983). Pavement data and deflection test data used for the comparison are presented in Tables 4.6 and 4.7, respectively. The computed layer moduli for the various programs are presented in Table 4.8. Results from BOUSDEF seem to be very compatible with those from the other developed programs.

One major advantage of the BOUSDEF program over the other programs is its computation speed. In using a deflection data set presented in Table 4.3, the BOUSDEF program takes only three seconds to find the solution, using an IBM-AT microcomputer with a math-coprocessor. The same data would take significantly longer time using other programs, as can be seen in Table 4.9. This feature makes use of the program to evaluate a large amount of deflection data easy and possible.

BOUSDEF is a user-friendly program. The program has a built-in data file creating and editing routine. This significantly eases the data input and edit process and avoids possible calculation errors due to improper data entry.

4.2.3 Comparison With Laboratory Test Results

The BOUSDEF program was also evaluated by comparing the backcalculated results with the resilient modulus tested in the laboratory. This was accomplished by selecting actual projects in the state of Oregon. The general procedures followed are described below:

1. Select project sites for evaluation.

Table 4.6 Pavement Data Used for Backcalculation

Pavement Layer	Material	Thickness (inch)	Poisson's Ratio
1	Asphalt Concrete	9.0	0.35
2	Aggregate Base	16.0	0.40
3	Soil Subgrade	∞	0.40

Table 4.7 Deflection Data Used for Backcalculation

Test Site	FWD Load (lb)	Deflection @ Sensor Location 0"	8"	18"	30"	60"
1	11,729	22.99	16.74	12.81	9.81	4.57
2	11,647	27.39	21.68	14.96	11.06	5.33
3	11,442	20.54	17.28	12.30	9.69	4.90
4	11,073	24.16	20.33	14.08	10.83	5.77
5	11,688	16.28	13.70	8.88	6.95	3.92

Note: FWD Load Radius is 5.9 inches.

Table 4.8 Summary of Backcalculation Results *

Test Site	Program	AC Surface	Aggregate Base	Subgrade
1	BISDEF	194.0	25.1	11.5
	BOUSDEF	163.0	25.7	11.2
	CHEVDEF	175.8	24.7	12.1
	ELSDEF	200.0	23.6	11.7
	MODCOMP2	162.8	33.4	10.5
2	BISDEF	173.7	15.4	10.5
	BOUSDEF	157.7	15.2	9.9
	CHEVDEF	150.7	16.6	10.5
	ELSDEF	174.0	15.2	10.4
	MODCOMP2	131.5	27.1	9.3
3	BISDEF	288.3	20.1	11.2
	BOUSDEF	262.2	19.3	10.9
	CHEVDEF	257.8	23.3	11.3
	ELSDEF	286.9	20.0	11.3
	MODCOMP2	184.0	50.6	9.3
4	BISDEF	206.4	19.0	9.4
	BOUSDEF	196.5	17.0	9.2
	CHEVDEF	182.3	21.7	9.2
	ELSDEF	205.7	18.9	9.4
	MODCOMP2	431.8	1.0	N/S**
5	BISDEF	259.1	37.7	14.8
	BOUSDEF	266.0	30.5	14.8
	CHEVDEF	260.9	36.4	15.0
	ELSDEF	258.2	37.2	14.8
	MODCOMP2	165.8	89.7	12.9

* Moduli are in ksi.

** N/S = No Solution.

Table 4.9 Comparison on Computing Time and Backcalculated Results

PROGRAM	COMPUTED LAYER MODULI (KSI)			COMPUTING TIME (SECONDS)
	LAYER 1	LAYER 2	LAYER 3	
BISDEF*	685.7	55.4	48.8	285
BOUSDEF	764.1	57.7	46.8	3
CHEVDEF	527.8	28.6	29.9	327
ELSDEF	632.1	84.7	34.2	485
MODCOMP2	772.5	35.9	53.0	495

*Contains proprietary BISAR program

2. For selected sites, perform deflection test using FWD.
3. Obtain samples from same road section where deflections were measured.
4. Backcalculate pavement layer moduli from deflection basin data using the BOUSDEF program.
5. Perform laboratory tests on samples.
6. Compare results from backcalculated and laboratory tests.

The following paragraphs discuss this process in more detail.

4.2.3.1 Selection of Project Sites

Two project sites in the state of Oregon were selected for evaluating the BOUSDEF program. These two projects are typical conventional pavement structures consisting of an asphalt concrete surface layer over an aggregate base and subgrade. Figure 4.3 shows the location of the two projects. Table 4.10 summarizes the pavement parameters of the two projects.

4.2.3.2 Deflection Test

Deflection tests were performed on selected project sites using KUAB Falling Weight Deflectometer (FWD). For the Rufus-Quinton project, the deflection tests were conducted using the FWD owned by the Oregon State Highway Division. For the Centennial Boulevard project, the FWD tests were performed using equipment (KUAB FWD) owned by Pavement Services Inc. of Portland.

The KUAB FWD is trailer-mounted and towed by a 3/4-ton van. The impulse force is created by dropping a set of two weights from different heights. By varying the drop height, the load at the pavement surface was varied from approximately 3,000 to 15,000 lbs. A smooth load pulse similar to that created by a moving wheel load is

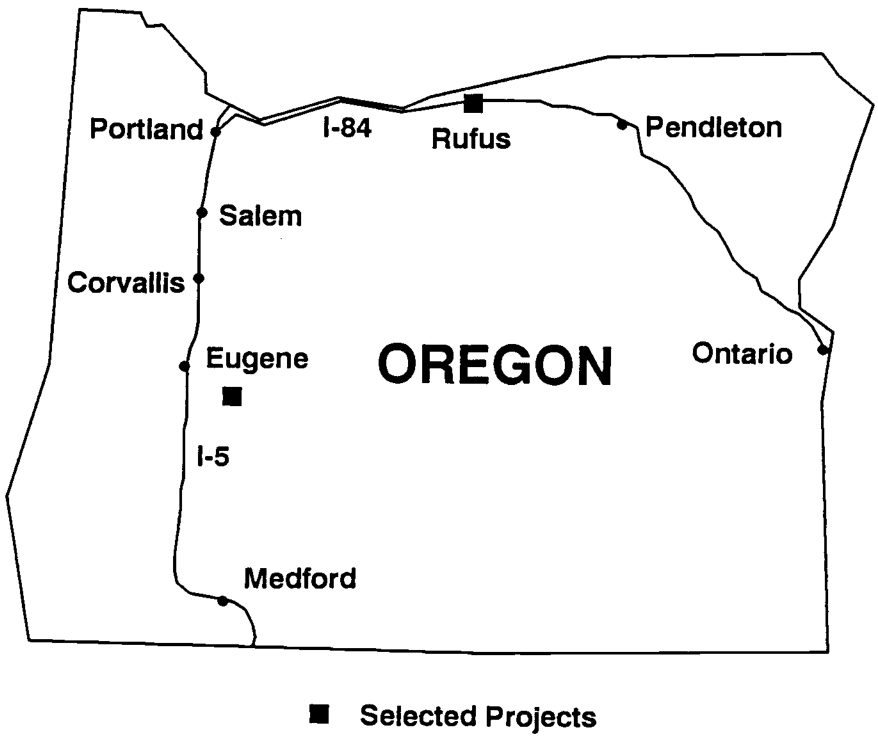


Figure 4.3 Location of Selected Project Sites

Table 4.10 Summary of Selected Project Sites

Project Location	Pavement Structure	Layer Thickness *
Rufus-Quinton Section Columbia River Hwy No.2 MP110.8 - MP124.0	AC Aggregate	6.8" 18.0"
Centennial Boulevard Coburg - I-5 Eugene	AC Aggregate	4.0" 16.0

* Average thickness

generated by using the two-mass system (Tholen, 1980; Tholen et al, 1985). Surface deflections were measured with seismic transducers that are lowered automatically with the loading plate. The sensor locations may be adjusted for the job requirement. For the Rufus-Quinton project, the sensors were set at 0", 8", 12", 24", 36", and 58". For the Centennial Boulevard project, the sensors were set at 0", 12", 24", 36", 60", and 99". There is no standard procedure for where the sensors should be located. However, it is important to have one sensor which is located far enough away from the load to obtain the pavement response from the subgrade.

The actual Rufus-Quinton project is thirteen-mile long. For the purpose of comparing the results between backcalculated results and the laboratory test, an one-mile long section was selected. The deflections were measured at 250-ft intervals. Three FWD load levels, ranging from approximately 3,000 to 12,000 lbs, were applied at each test spot. Deflections were recorded with a personal computer. Pavement temperatures at time of testing were also recorded. The detailed output may be found in Appendix B-1.

The Centennial Boulevard project is approximately 1.3 mile long. The deflections were measured at 200-ft intervals. Two load levels at each test location were applied ranging from 8,000 to 14,000 lbs. Recorded data included test locations, pavement temperature, load applied and deflections at each sensor location. The detailed output may be found in Appendix B-2.

4.2.3.3 Materials Sampling

Best efforts were made to acquire material samples from the project sites. Pavement materials sampled at both sites included asphalt concrete cores and base aggregates. Subgrade soil were not obtained because of difficulties in obtaining undisturbed soil samples.

Eight four-inch diameter asphalt concrete cores and two bags of aggregates were obtained for the Rufus-Quinton project. The same amount of asphalt concrete cores and four bags of aggregates were received from the Centennial Boulevard project.

4.2.3.4 Backcalculation of Layer Moduli

The BOUSDEF program was used to backcalculate the moduli for each pavement layer from the deflection data. Raw data, without correcting for temperature, were used calculate the pavement moduli at time of testing. Table 4.11 summarizes the backcalculated results for the Rufus-Quinton project. Table 4.12 presents the results for the Centennial Boulevard project. Figures 4.4 and 4.5 illustrate the backcalculated results for Rufus-Quinton, both eastbound and westbound directions. Figures 4.6 to 4.9 present the backcalculation results for Centennial Boulevard project.

4.2.3.5 Laboratory Tests on Samples

Laboratory tests were performed on the actual pavement samples for modulus. For the AC cores, the diametral test (ASTM D-4123) was followed. For the aggregate base, the triaxial test (AASHTO T-274) was used. For the purpose of testing, the AC core samples were trimmed to a height of approximately 1.5 to 2.5 inches, depending on the thickness of the top lift.

The AC cores were tested at three temperatures: 42°F, 73°F, and 95°F, to determine the influence of the temperature on the modulus of the asphalt concrete. An H&V diametral testing system (H&V Materials

Table 4.11 Backcalculated MR for the Rufus-Quinton Project (EB)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk stress	Deviator stress
1	3,199	302,658	87,337	14,847	8.42	4.27
1	6,398	1,257,591	14,555	23,882	6.07	7.03
1	11,934	1,268,846	30,659	22,929	12.67	9.21
2	3,158	509,816	34,371	24,822	6.11	5.13
2	11,811	173,076	48,314	19,659	25.80	11.51
3	3,199	610,269	33,422	33,890	5.86	5.48
3	6,726	492,083	28,512	30,505	10.41	8.63
4	2,953	259,183	26,058	30,547	6.39	5.93
4	6,603	267,678	35,667	25,531	12.86	8.48
4	11,852	324,543	36,048	31,620	20.52	13.67
5	3,158	353,341	20,003	25,054	5.86	5.80
5	6,603	709,493	11,538	24,949	6.92	8.53
5	11,811	176,235	10,351	29,877	16.93	19.86
6	6,521	266,598	12,658	31,552	9.58	11.15
7	2,830	161,216	20,294	24,605	6.51	6.02
7	11,893	363,088	40,729	25,635	20.65	11.89
8	6,439	243,075	36,564	15,768	12.97	7.09
8	12,016	386,336	17,561	31,867	15.83	15.70
9	3,076	287,092	17,354	39,274	5.85	6.82
9	6,480	267,245	27,931	29,528	11.89	9.30
10	3,076	244,209	13,748	32,867	5.75	6.86
10	6,480	332,561	13,664	28,046	9.13	10.04
10	11,770	153,986	13,075	30,703	18.88	19.57
11	6,439	326,903	11,389	20,418	8.64	9.20
11	11,893	526,235	11,665	22,739	12.26	13.54
12	3,076	253,026	16,343	29,930	5.94	6.48
12	6,398	329,310	14,050	24,271	9.14	9.40
12	11,975	346,906	19,621	22,916	16.93	13.58
13	3,035	254,005	18,565	18,566	6.06	5.53
13	6,357	376,159	10,805	23,589	8.06	9.43
13	11,852	329,116	28,234	21,706	19.06	12.27
14	2,871	195,491	16,824	15,610	6.05	5.39
14	6,357	319,128	16,976	15,848	9.70	7.80
14	11,893	503,199	21,622	18,842	15.40	11.20
16	3,117	193,967	26,817	33,926	7.12	6.49
16	12,139	571,760	21,556	35,889	15.01	14.61
17	12,180	620,775	17,300	37,613	13.56	15.31
18	3,076	230,240	35,813	32,091	7.23	5.93
18	6,685	497,033	39,748	27,553	11.35	7.77
18	11,975	809,831	40,781	25,952	16.32	10.19
19	3,117	572,716	32,391	34,328	5.80	5.50
19	6,644	680,060	19,775	33,094	8.37	8.83
20	3,117	269,346	21,742	32,117	6.31	6.33
20	6,726	473,480	15,311	29,783	8.73	9.63
21	3,035	924,348	13,054	24,918	4.06	5.18
21	6,685	570,617	44,089	13,831	11.24	5.90
21	12,016	380,178	126,956	11,562	27.26	6.57
Average		424,767	27,060	26,278		
STD		248,301	20,108	6,585		

Table 4.11 Backcalculated MR for the Rufus-Quinton Project (WB) (cont.)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk stress	Deviator stress
1	3,240	340,993	12,043	31,568	4.94	6.51
1	6,521	666,413	13,607	24,690	6.59	7.68
1	12,057	882,720	18,052	24,040	10.29	9.94
2	3,158	399,510	15,647	25,811	4.98	5.83
2	6,685	359,843	22,021	20,414	9.06	7.49
2	11,975	450,584	25,414	21,510	14.10	10.12
3	3,199	491,324	22,562	25,731	5.19	5.49
3	6,480	657,531	19,015	23,906	7.23	7.23
3	12,385	885,645	26,625	24,856	11.92	9.54
4	3,076	396,075	21,830	22,061	5.27	5.38
4	6,808	377,011	27,770	19,762	9.64	7.14
4	12,262	516,346	29,416	21,705	14.42	9.76
5	3,199	365,477	31,656	32,607	5.91	5.72
5	6,808	601,823	21,182	32,505	7.90	8.17
5	12,057	706,802	25,741	33,820	12.39	11.13
6	6,767	810,309	63,150	28,590	9.73	6.29
6	12,303	869,746	77,331	26,934	16.46	7.98
7	3,199	401,272	20,879	39,374	5.32	6.25
7	6,849	546,094	18,504	36,591	7.85	8.87
7	12,303	691,963	21,264	39,325	11.94	12.53
8	6,644	467,614	11,154	20,492	6.97	8.00
8	12,221	569,319	14,296	20,966	11.12	10.88
9	3,199	464,359	20,343	20,264	5.14	5.31
9	6,767	617,598	16,485	18,818	7.29	7.09
9	12,098	806,569	15,690	22,057	10.14	10.06
12	3,076	244,263	18,082	19,262	5.59	5.59
12	6,726	428,882	13,792	21,249	7.64	8.00
12	12,262	637,104	13,400	27,265	10.52	11.97
13	3,117	209,438	28,711	19,979	6.37	5.42
13	6,808	351,754	23,308	21,679	9.38	7.65
13	12,344	426,199	33,843	22,354	15.99	9.94
14	3,199	366,653	29,561	32,745	5.83	5.77
14	6,767	503,474	21,672	35,231	8.32	8.58
14	12,344	652,950	25,325	40,620	12.89	12.43
19	3,158	419,703	31,587	34,765	5.70	5.70
21	3,158	400,430	37,071	27,611	5.95	5.34
21	6,685	594,077	23,851	28,384	8.09	7.61
21	12,139	785,417	28,260	30,241	12.41	10.28
22	3,158	643,400	15,778	25,774	4.52	5.52
22	6,726	513,236	20,965	25,605	8.16	7.72
22	11,852	674,652	21,580	28,103	11.73	10.68
23	3,117	588,250	19,544	27,662	4.78	5.51
23	6,726	555,988	17,631	28,134	7.61	8.08
23	12,139	690,632	19,644	29,886	11.52	11.28
24	3,117	257,551	28,055	28,818	6.09	5.78
24	6,685	374,314	19,633	31,491	8.69	8.75
Average		536,115	23,978	27,071		
STD		172,033	11,600	5,792		

Table 4.12 Backcalculated Modulus for Centennial Project
EASTBOUND FROM LOCATION 200 TO 4000

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
200	8,821	1,192,686	35,389	10,619	13.2	6.3
200	14,269	1,074,783	44,632	10,656	22.3	8.1
400	8,821	383,337	33,174	12,131	17.3	7.9
400	14,297	280,833	50,940	11,598	31.6	9.9
600	8,763	446,242	33,644	10,133	16.7	7.2
600	14,269	498,348	44,397	10,037	27.1	9.0
800	8,705	524,632	37,849	10,832	16.4	7.0
800	14,153	1,140,917	30,466	10,620	19.5	8.7
1000	8,849	677,562	21,917	10,991	13.6	7.7
1000	14,240	647,469	29,774	10,578	22.9	9.8
1200	8,763	339,800	29,463	12,337	17.2	8.3
1200	14,240	395,530	38,190	11,842	27.6	10.4
1400	8,792	576,179	23,206	13,901	14.3	8.5
1400	14,211	625,636	28,086	13,105	22.7	10.9
1600	8,734	364,318	24,634	11,208	16.2	8.2
1600	14,182	315,199	32,533	11,030	27.9	10.9
1800	8,734	429,492	28,801	9,912	16.2	7.4
1800	14,153	380,923	36,522	9,931	27.4	9.8
2000	8,763	898,118	32,653	10,838	13.9	6.7
2000	14,211	656,243	44,998	10,683	25.3	8.8
2200	8,676	476,446	20,870	9,959	14.4	7.8
2200	14,067	537,890	25,928	9,760	22.9	10.0
2400	8,763	676,194	20,354	12,914	13.2	8.3
2400	14,182	564,264	29,181	12,294	23.5	10.7
2600	8,734	666,228	25,826	23,487	14.1	9.9
2600	14,269	648,552	33,947	25,003	23.7	13.8
2800	8,705	383,872	16,507	17,944	14.4	10.8
2800	14,124	458,096	19,922	18,146	22.4	14.5
3000	8,676	641,011	33,459	23,180	15.1	9.3
3000	14,211	568,411	49,657	22,162	26.9	12.0
3200	8,648	982,052	31,485	32,579	13.3	10.0
3200	14,067	964,432	42,288	32,492	22.3	13.4
3400	8,648	583,606	30,334	17,083	15.1	8.5
3400	13,923	382,669	46,799	16,351	28.4	11.1
3600	8,705	666,593	26,030	25,630	14.1	10.2
3600	14,182	851,510	27,606	25,665	20.7	13.9
3800	8,676	502,722	47,255	19,749	17.4	8.3
3800	14,240	413,078	68,918	19,793	30.9	10.8
4000	8,705	904,828	40,382	24,621	14.6	8.6
4000	14,211	609,647	60,128	24,355	27.6	11.7
	AVERAGE	608,259	34,454	15,904		
	STD	229,872	11,032	6,581		

Table 4.12 Backcalculated Modulus for Centennial Project EASTBOUND FROM LOCATION 4200 TO 7000 (cont.)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
4200	8,648	733,522	44,104	19,073	15.6	7.9
4200	14,124	604,680	67,282	19,012	28.2	10.1
4400	8,648	578,668	45,958	17,889	16.7	7.9
4400	14,096	524,224	64,597	17,972	28.8	10.2
4600	8,532	676,229	42,831	10,781	15.6	6.5
4600	13,951	680,957	56,206	10,770	26.1	8.2
4800	8,561	858,319	47,075	18,196	15.1	7.4
4800	14,009	479,265	77,869	18,668	30.3	9.9
5000	8,561	1,054,069	45,675	15,151	14.3	6.8
5000	14,038	1,102,778	60,950	15,907	23.7	8.8
5200	8,619	1,154,214	48,720	15,489	14.2	6.7
5200	14,096	872,094	74,352	15,633	26.5	8.6
5400	8,792	1,185,558	26,500	13,516	12.1	7.2
5400	13,980	995,197	36,552	12,831	21.1	9.2
5600	8,676	918,746	35,486	15,219	14.0	7.4
5600	14,096	777,984	49,862	14,379	24.7	9.4
5800	8,590	623,626	54,045	9,928	16.9	6.1
5800	14,038	758,515	64,979	10,062	26.4	7.6
6000	8,561	1,287,120	34,744	10,354	12.5	6.1
6000	14,009	1,256,945	42,694	10,303	20.7	7.8
6200	8,705	274,332	57,679	13,491	20.5	7.4
6200	14,124	420,490	61,997	13,297	29.9	9.4
6400	8,648	917,159	34,679	12,716	13.9	6.9
6400	14,096	868,758	48,870	11,850	23.9	8.5
6600	8,619	648,294	46,532	8,220	16.2	5.9
6600	14,009	528,858	56,056	8,724	27.7	7.8
7000	8,734	633,344	36,933	13,752	15.6	7.5
7000	14,124	547,457	50,960	12,784	27.1	9.4
	AVERAGE	784,336	50,507	13,785		
	STD	259,845	12,384	3,177		

Table 4.12 Backcalculated Modulus for Centennial Project WESTBOUND FROM LOCATION 6900 TO 2700 (cont.)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
6900	8,705	549,293	86,849	16,120	19.4	6.6
6900	14,182	505,870	110,433	16,033	32.4	8.4
6700	8,705	311,068	82,928	13,055	21.3	6.6
6700	14,182	393,500	93,740	12,641	33.0	8.2
6500	8,648	604,949	32,495	16,002	15.2	8.1
6500	14,096	588,483	41,301	15,352	25.3	10.6
6300	8,676	567,289	33,848	23,922	15.6	9.5
6300	14,182	620,694	42,163	24,353	25.2	12.8
6100	8,676	361,100	34,291	20,897	17.4	9.6
6100	14,153	351,517	43,914	21,888	29.0	13.2
5900	8,648	720,605	28,884	16,867	14.1	8.3
5900	14,096	703,185	34,819	15,889	23.1	10.9
5700	8,590	484,190	48,198	14,289	17.4	7.3
5700	14,096	338,452	67,074	14,020	31.7	9.6
5500	8,648	874,525	48,054	21,573	15.3	7.9
5500	14,211	624,465	74,903	21,459	28.9	10.3
5100	8,676	774,804	57,989	16,033	16.5	6.9
5100	14,153	776,411	70,602	16,035	27.0	9.0
4900	8,648	706,615	47,964	16,225	16.1	7.3
4900	14,124	604,709	66,351	16,016	28.1	9.4
4700	8,619	795,417	61,138	15,027	16.5	6.6
4700	14,182	724,053	78,649	15,175	28.2	8.6
4500	8,619	902,274	25,244	12,929	12.7	7.4
4500	14,153	786,905	35,892	13,110	22.7	9.8
3700	8,619	530,502	44,536	20,145	16.8	8.4
3700	14,153	736,687	49,111	20,853	25.1	11.2
3500	8,619	1,263,788	22,439	26,557	11.1	9.4
3500	14,124	1,182,953	29,387	25,427	19.0	12.7
3300	8,561	920,650	18,988	15,307	11.6	8.3
3300	14,096	1,080,032	22,397	15,850	17.9	11.2
3100	8,532	1,277,277	16,303	17,317	10.0	8.4
3100	14,038	1,418,923	21,726	15,827	16.2	10.6
2900	8,561	1,202,374	22,991	10,836	11.3	6.8
2900	14,067	1,388,525	25,879	10,491	17.3	8.6
2700	8,590	983,678	25,082	14,033	12.3	7.5
2700	14,096	938,722	35,231	13,158	21.4	9.5
	AVERAGE	766,513	46,716	16,964		
	STD	298,557	23,418	4,008		

Table 4.12 Backcalculated Modulus for Centennial Project
WESTBOUND FROM LOCATION 2500 TO 100 (cont.)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
2500	8,561	696,691	30,281	17,457	14.3	8.3
2500	14,038	508,317	47,227	16,663	26.9	10.8
2100	8,532	485,466	34,521	11,670	16.1	7.3
2100	14,009	512,793	40,242	10,969	25.9	9.4
1900	8,676	1,070,951	27,632	13,658	12.5	7.3
1900	14,182	1,192,106	32,396	12,922	19.6	9.3
1700	8,561	640,110	37,988	10,675	15.4	6.7
1700	14,067	337,358	59,504	10,487	30.9	8.8
1500	8,619	525,731	39,137	14,395	16.4	7.6
1500	14,038	295,918	64,070	13,622	32.1	9.8
1300	8,648	201,822	38,022	13,687	19.9	8.5
1300	14,067	201,950	51,226	12,949	33.1	10.7
1100	8,590	618,645	28,924	15,765	14.6	8.3
1100	14,067	625,296	36,771	14,750	24.1	10.6
900	8,648	337,715	44,163	14,580	18.6	7.9
900	14,096	353,862	54,817	13,782	30.2	10.1
700	8,648	1,102,055	27,453	17,099	12.3	7.9
700	14,182	840,150	41,470	15,911	23.2	10.2
500	8,648	142,658	49,225	15,638	22.1	8.7
500	14,096	226,980	65,390	14,904	33.9	10.4
299	8,648	271,970	70,620	11,342	21.1	6.6
299	14,067	306,764	85,021	10,933	33.6	8.2
100	8,705	522,935	74,902	12,136	19.0	6.2
100	14,153	871,873	69,792	12,004	26.2	7.9
	AVERAGE	537,088	47,950	13,667		
	STD	293,206	16,195	2,061		

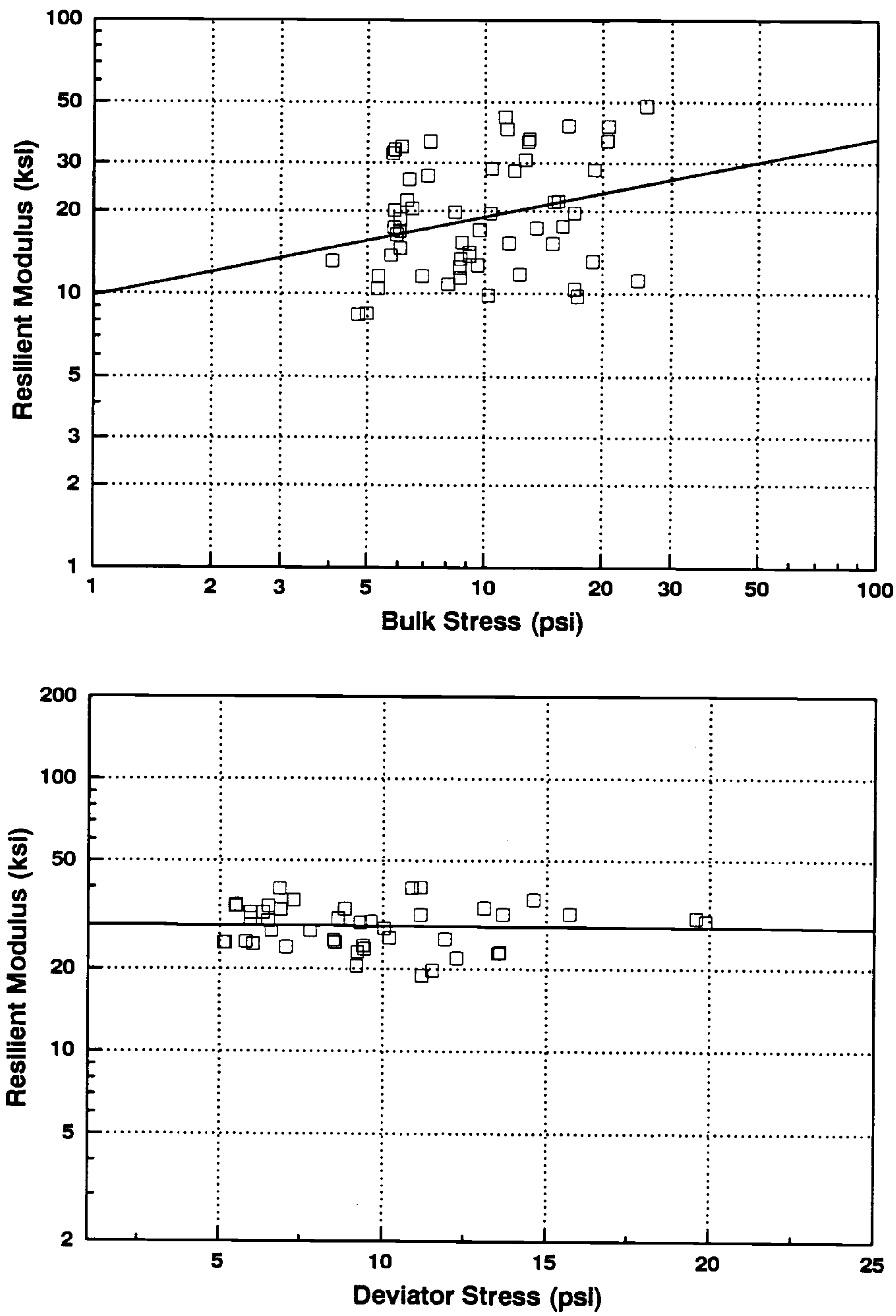
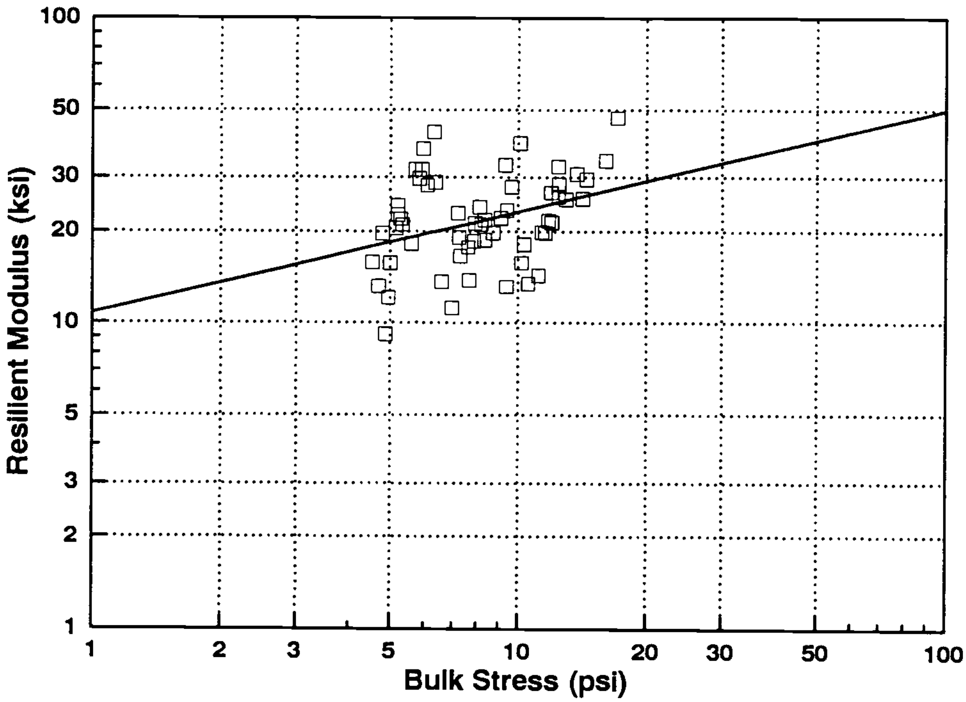


Figure 4.4 Backcalculated Base and Subgrade Moduli for the Rufus-Quinton Project (Eastbound)



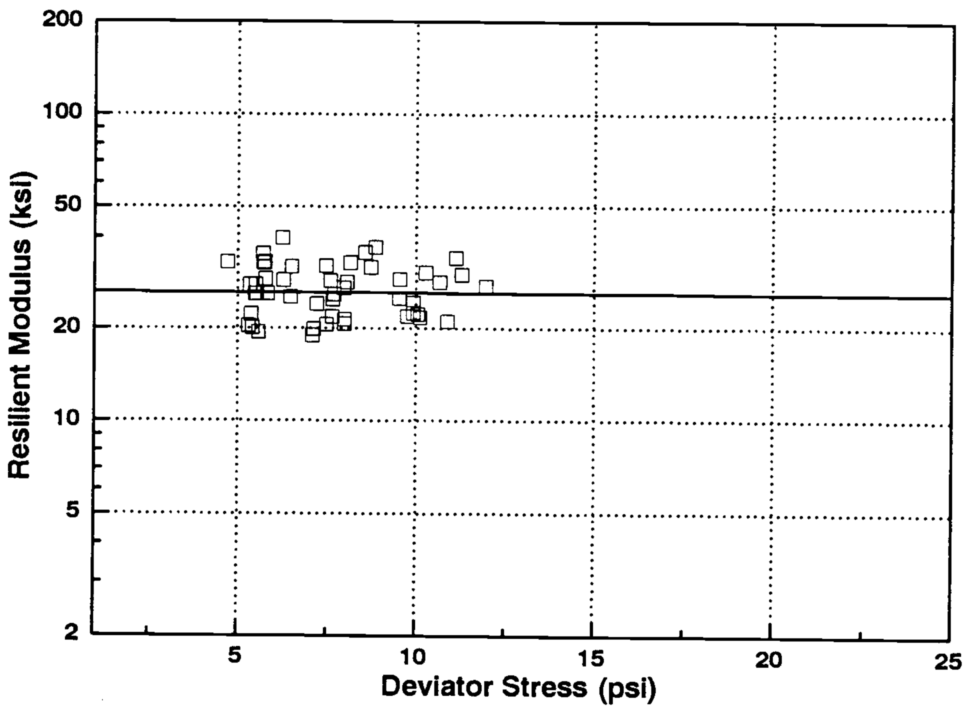
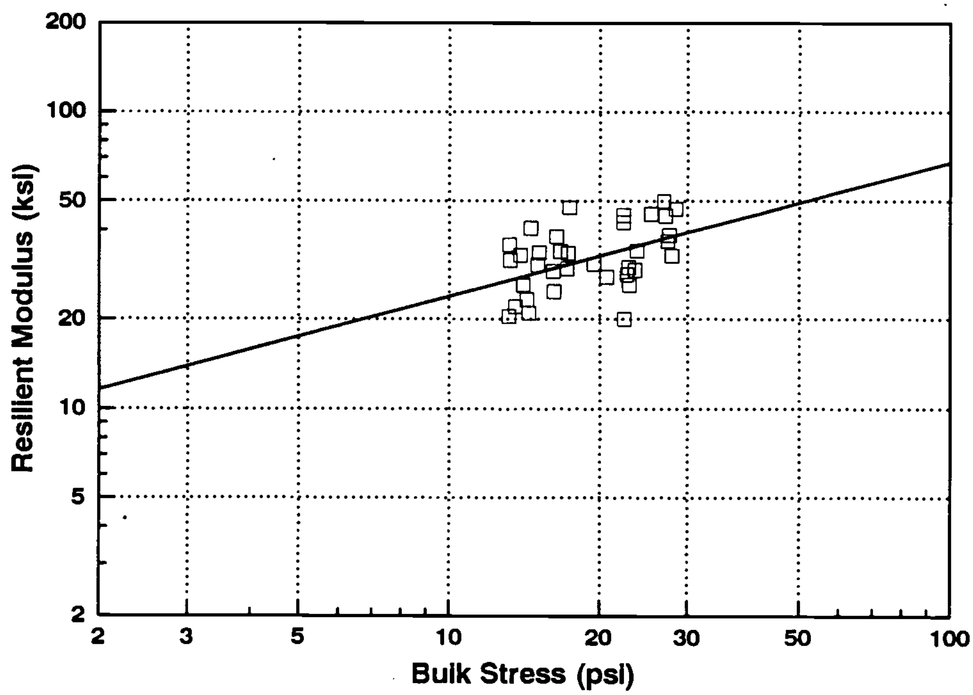


Figure 4.5 Backcalculated Base and Subgrade Moduli for the Rufus-Quinton Project (Westbound)



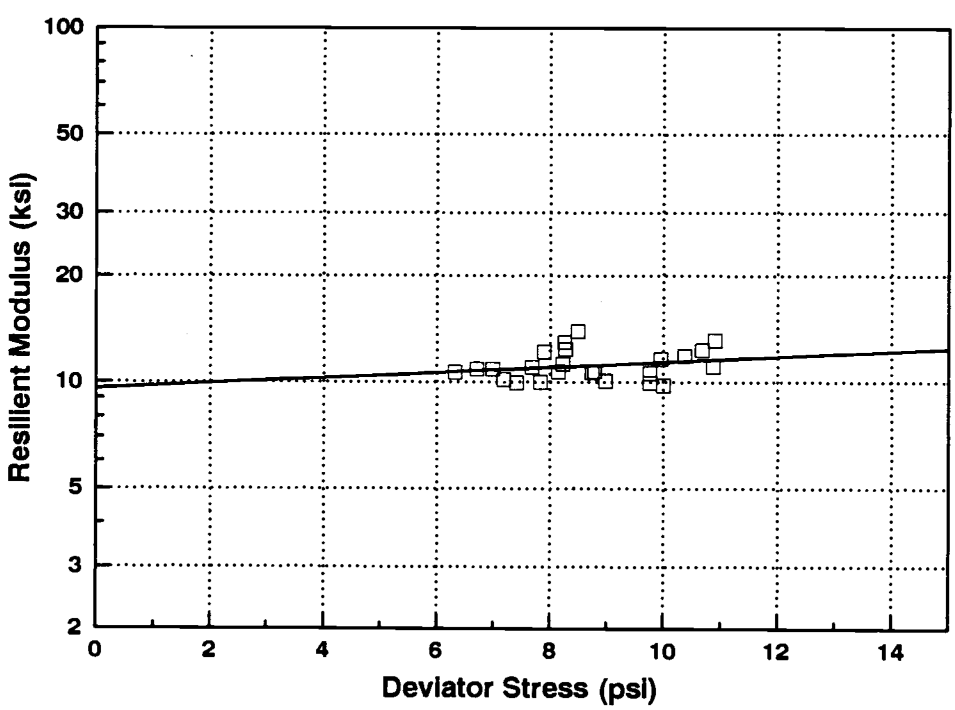


Figure 4.6 Backcalculated Base and Subgrade Moduli for the Centennial Blvd Project (Station 200 to 400, Eastbound)

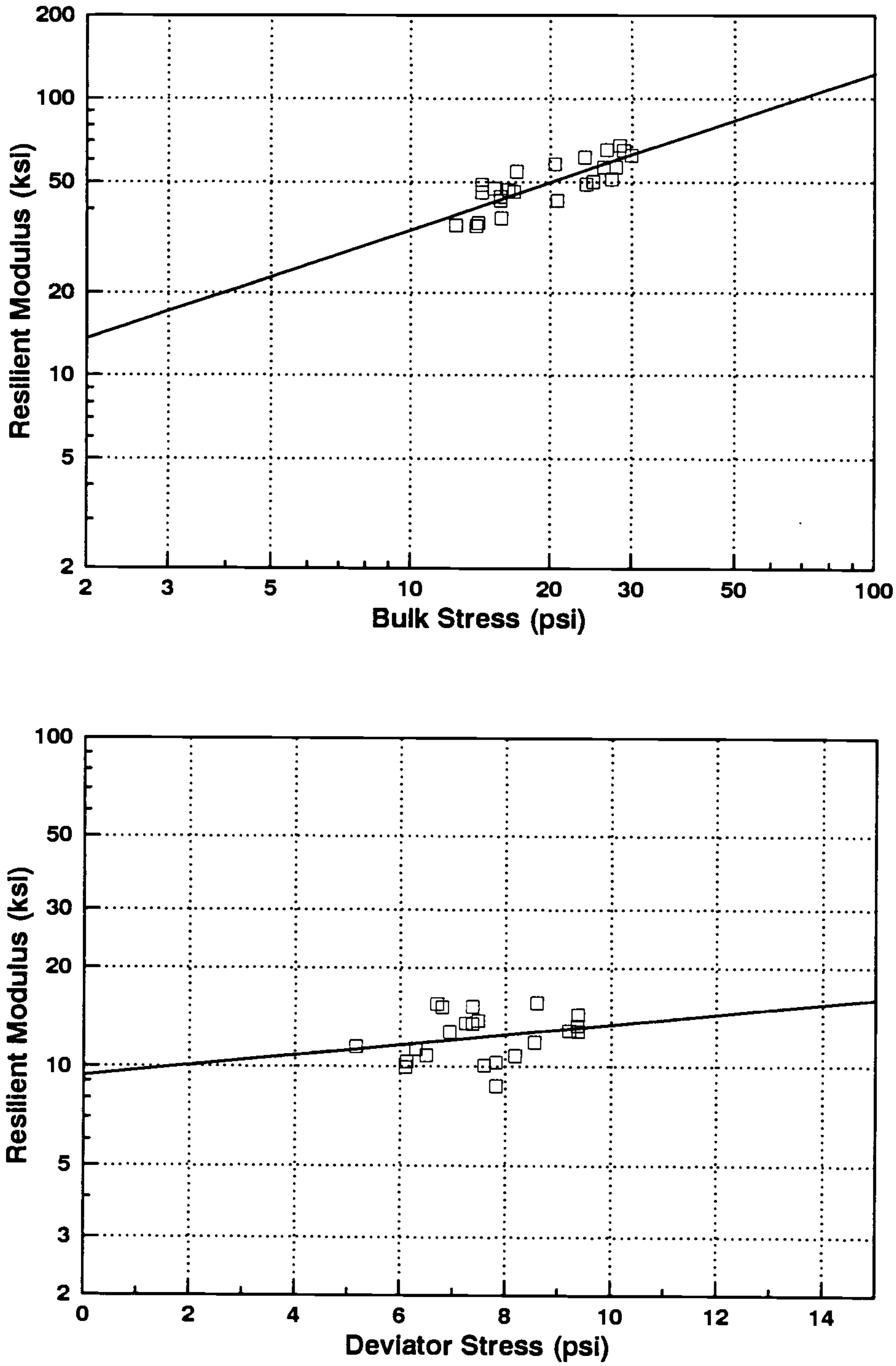
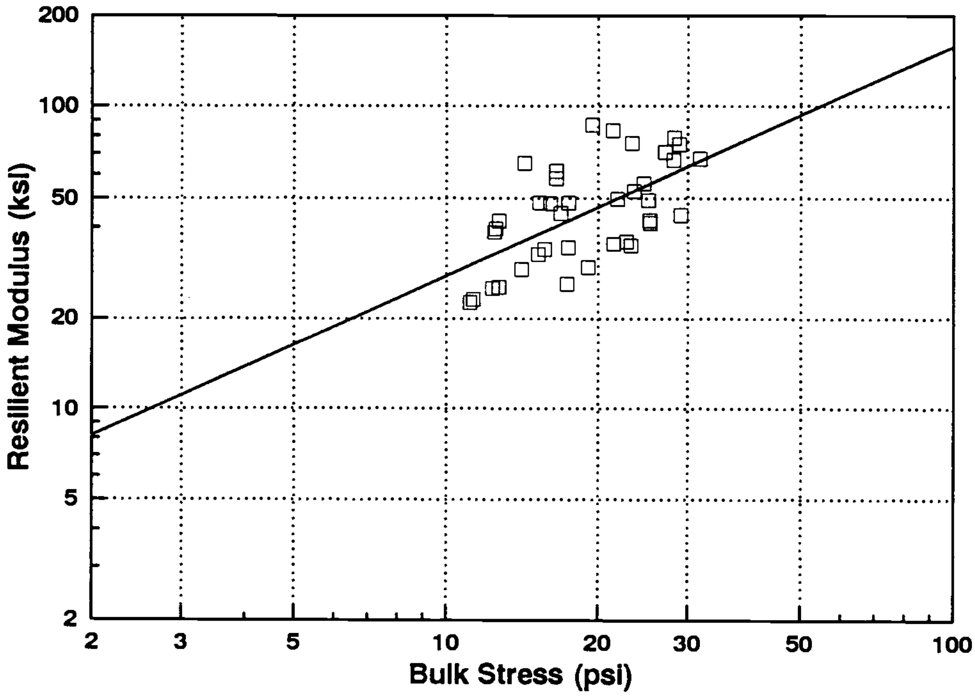


Figure 4.7 Backcalculated Base and Subgrade Moduli for the Centennial Blvd Project (Station 4200 to 7000, Eastbound)



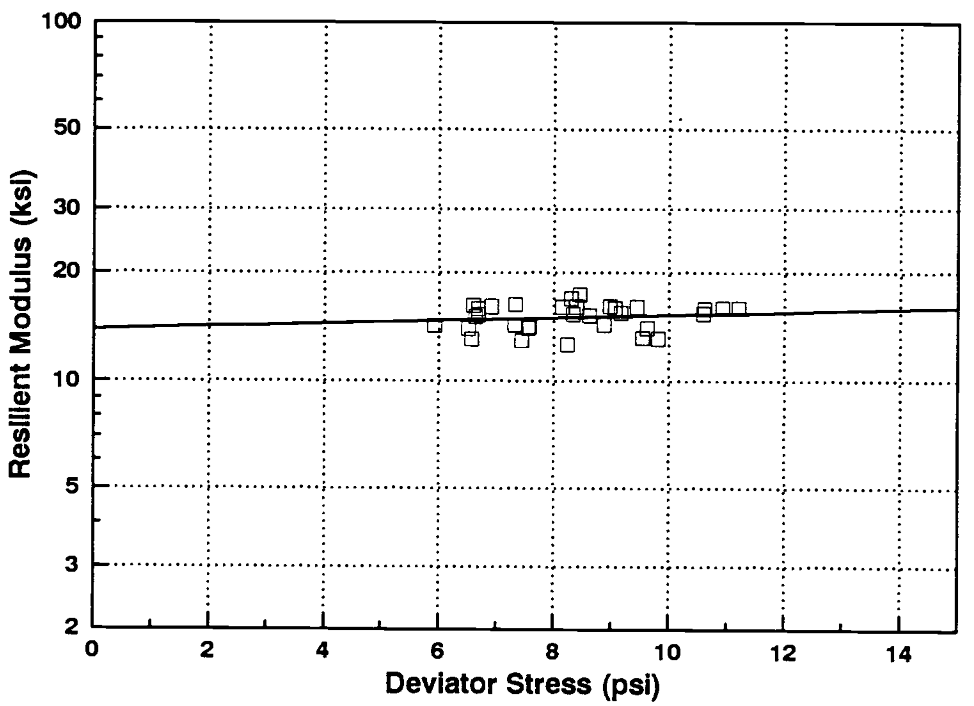
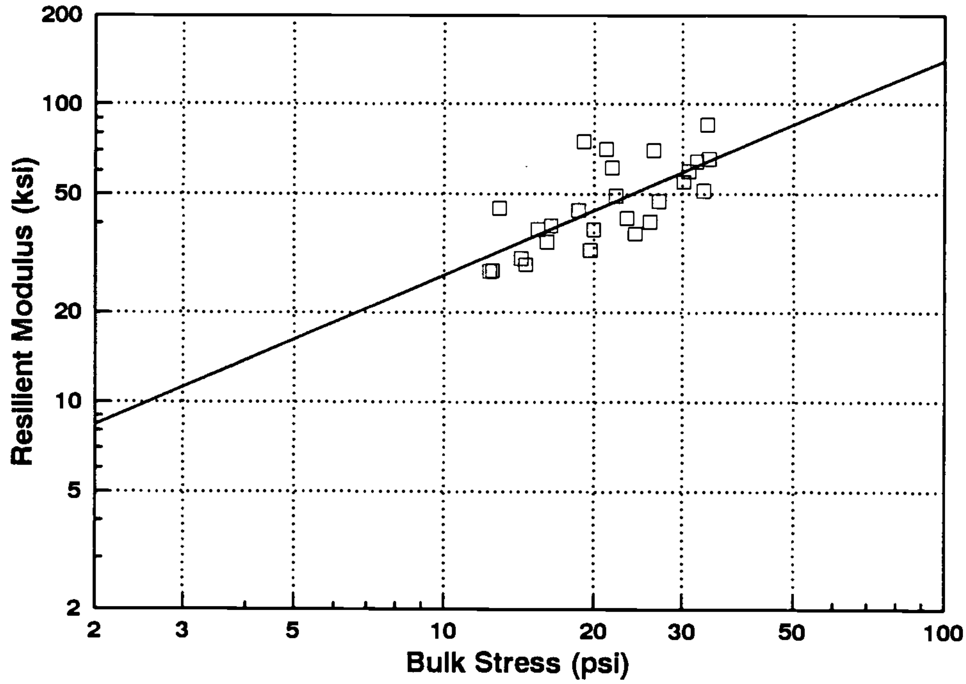


Figure 4.8 Backcalculated Base and Subgrade Moduli for the Centennial Blvd Project (Station 6900 to 2700, Westbound)



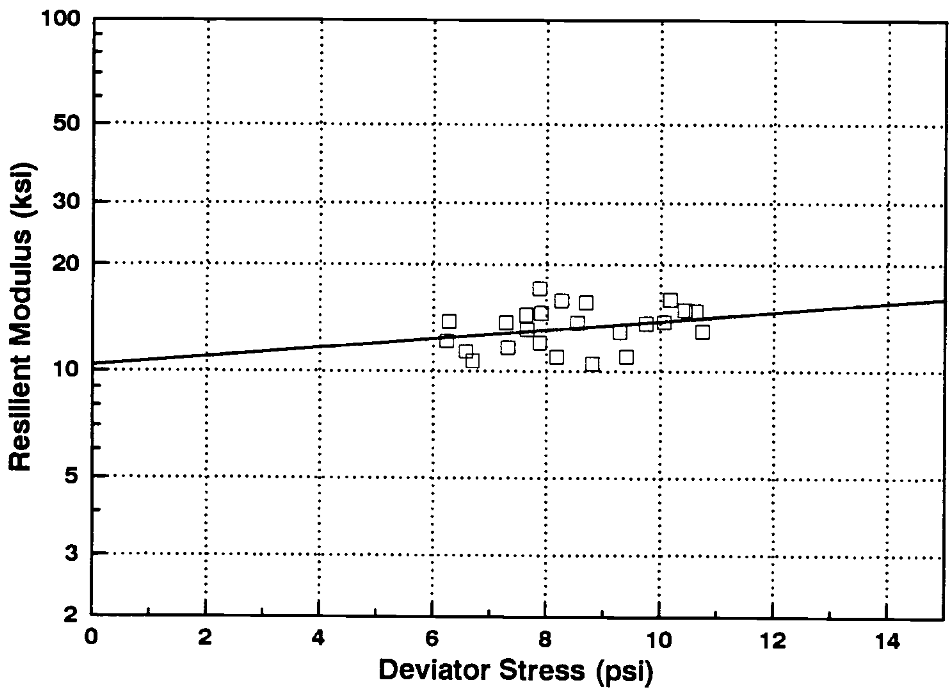


Figure 4.9 Backcalculated Base and Subgrade Moduli for the Centennial Blvd Project (Station 2500 to 100, Westbound)

Research and Development, Inc., 1989) was employed for the test. The H&V testing system can be used for both diametral and triaxial resilient modulus tests. For the diametral test, a temperature chamber was used for the control of the temperature. The set up of the system is illustrated in Figures 4.10 and 4.11. The data acquisition and modulus calculation were accomplished by a microcomputer.

Table 4.13 summarizes the test results for the Rufus-Quinton project, while results for the Centennial Boulevard project are presented in Table 4.14. Actual temperatures at time of testing were recorded.

The triaxial resilient modulus test on aggregate was performed by following AASHTO T-274. For the Rufus-Quinton project, the moisture-density relationship for the aggregate was determined by following the AASHTO T-99 method C. The results are summarized in Table 4.15, and plotted in Figure 4.12. The samples for the resilient modulus test were prepared according to the moisture-density relationship determined in the laboratory. Two samples were made. Both were prepared at optimum moisture content. The actual moisture content at time of testing was slightly less than the optimum. The actual moisture content and dry density were measured right after the triaxial test and are summarized in Table 4.16. Resilient modulus test results for both samples are presented in Table 4.17 and plotted in Figure 4.13. The test results from this project indicate an important fact that the resilient modulus values seem to be proportional to the sample density achieved in the process of sample preparation.

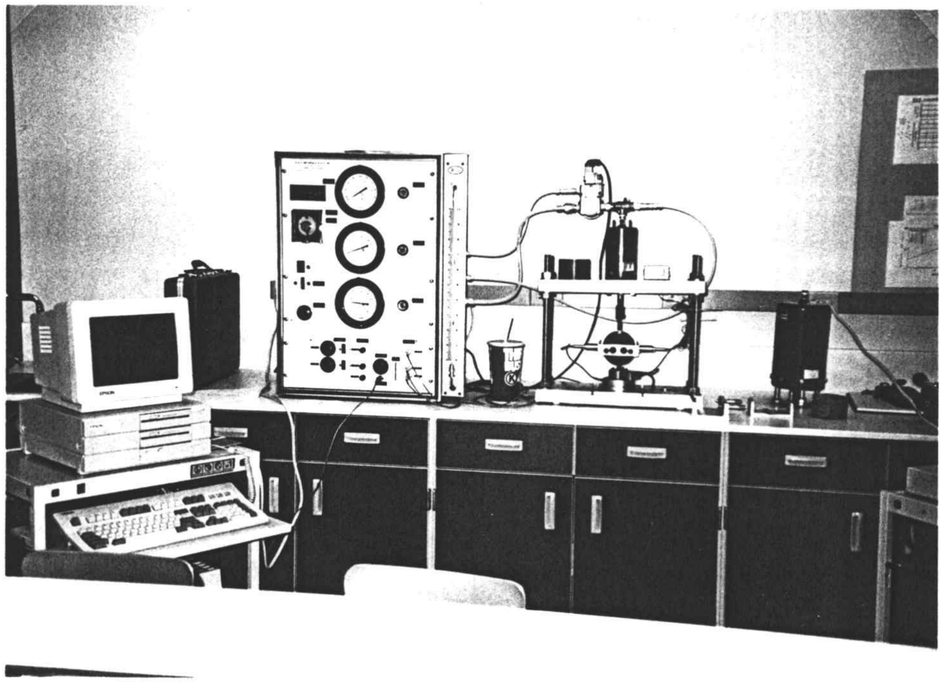


Figure 4.10 H&V Diametral Testing System

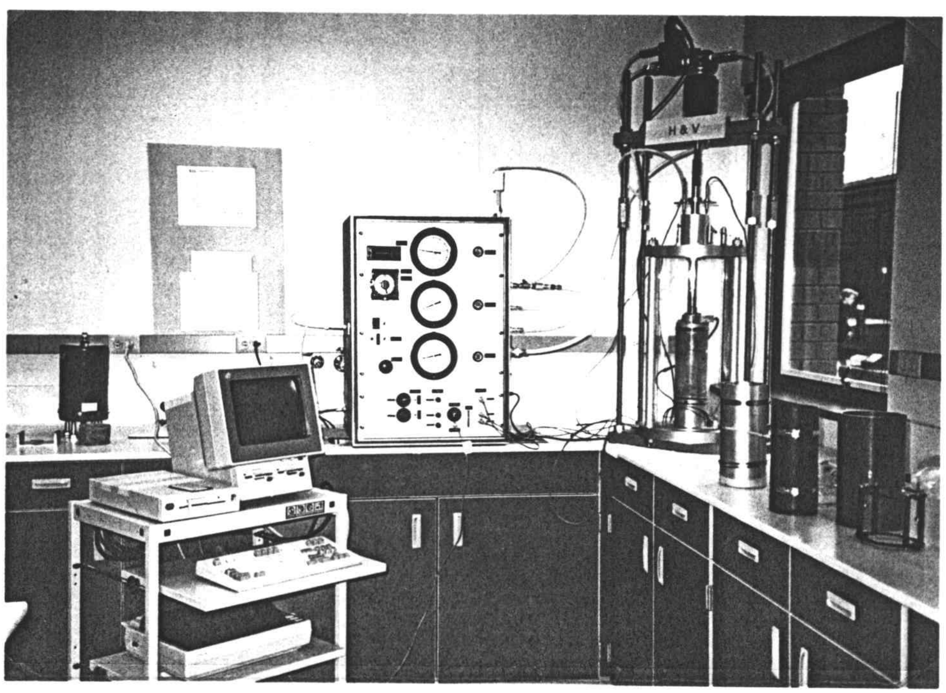


Figure 4.11 H&V Triaxial Testing System

Table 4.13 Summary of AC Resilient Modulus Test for Rufus-Quinton Project

Sample No.	Testing Temperature 42 °F	73 °F	95 °F
1	2,521,010	476,677	183,420
2	2,886,430	834,289	515,580
3	3,563,450	727,813	538,010
4	2,316,240	848,096	600,630
5	2,733,340	624,261	261,870
6	3,441,240	718,098	403,840
7	2,535,850	811,157	559,790
8	2,054,130	653,839	158,980
Average	2,756,461	711,779	402,765
Standard Dev.	491,013	117,289	166,666

Table 4.14 Summary of AC Resilient Modulus Test for Centennial Boulevard Project

Sample ID.	Testing Temperature 42 °F	73 °F	95 °F
C2	2,874,350	1,634,000	792,140
C4	2,673,370	1,295,980	469,040
C5	2,897,700	1,724,670	841,080
C6	2,262,320	1,372,710	515,250
C7	2,723,470	1,383,540	696,050
B1	2,369,490	1,482,210	602,180
B3	2,793,980	1,678,240	714,690
B4	2,794,100	1,754,010	752,380
Average	2,673,598	1,540,670	672,851
Standard Dev.	218,990	167,032	123,752

Table 4.15 Moisture-Density Relationship for the Rufus-Quinton Project

Water Content (%)	Wet Density (pcf)	Dry Density (pcf)
3.8	131.48	126.67
4.5	136.11	130.24
5.2	143.69	136.59
6.2	144.60	136.16

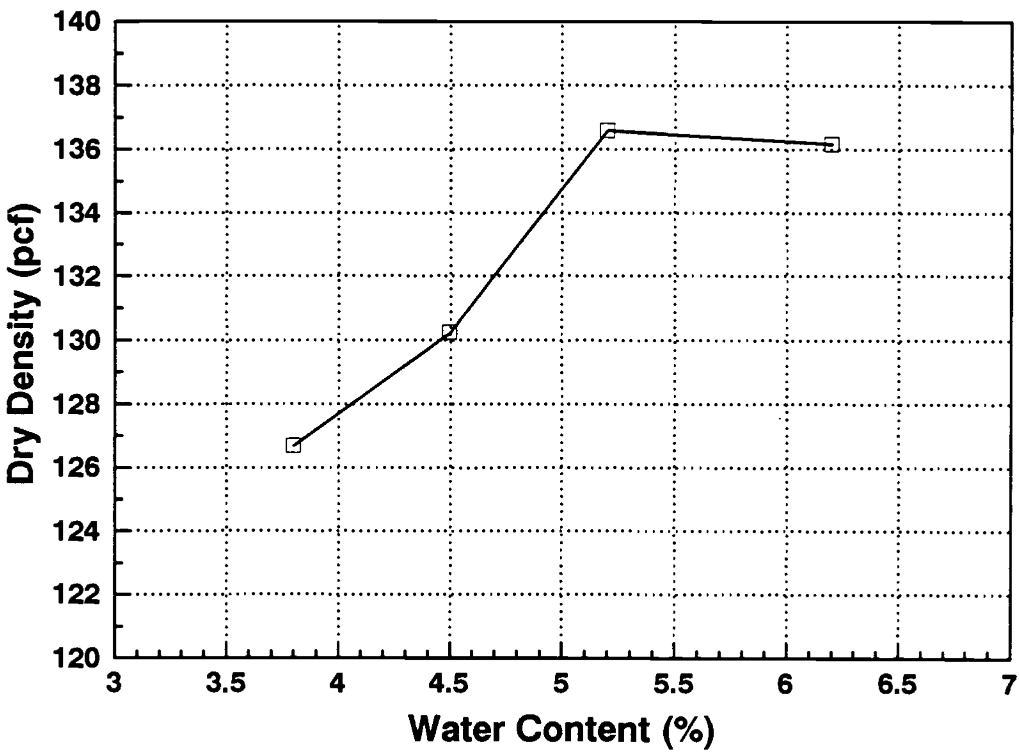


Figure 4.12 Moisture-Density Relationship for the Rufus-Quinton Project

Table 4.16 Density Results for the Rufus-Quinton Project

Sample ID	Optimum Moisture (%)	Maximum Dry Density (pcf)	Actual Moisture (%)	Actual Dry Density (pcf)	Relative to Max Density (%)
A	5.2	136.59	5.09	136.33	99.8
B	5.2	136.59	5.00	131.29	96.1

Table 4.17 Summary of Base Material Resilient Modulus Test for the Rufus Project

No.	Confining Stresses (psi)	Sample A Bulk S (psi)	Sample A Modulus (ksi)	Sample B Bulk S (psi)	Sample B Modulus (ksi)
1	20	61.7	23.6	61.2	18.0
2	20	62.5	28.4	62.1	18.4
3	20	64.7	32.8	65.3	19.7
4	20	69.6	37.9	70.3	20.5
5	20	74.7	40.7	74.4	21.5
6	20	80.0	42.9	79.6	22.4
7	15	46.8	26.2	46.5	16.2
8	15	47.3	29.5	47.3	16.4
9	15	49.6	31.0	50.1	17.3
10	15	54.3	33.0	54.9	17.9
11	15	59.6	36.5	59.4	19.1
12	15	64.3	39.4	64.4	20.5
13	10	31.6	27.3	31.4	14.2
14	10	32.1	27.1	32.4	14.5
15	10	34.5	27.6	34.8	15.3
16	10	39.6	30.2	39.7	16.0
17	10	44.4	33.5	44.3	17.2
18	5	16.6	23.6	16.0	12.5
19	5	17.2	23.6	17.0	12.6
20	5	20.0	24.5	19.4	13.4
21	5	24.2	27.3	24.6	14.3
22	5	29.3	30.6	29.2	15.7
23	1	4.6	21.0	4.1	11.2
24	1	5.5	21.2	4.8	11.4
25	1	7.7	22.2	7.8	12.4
26	1	9.7	23.8	9.8	12.7
27	1	12.7	26.2	12.4	13.2

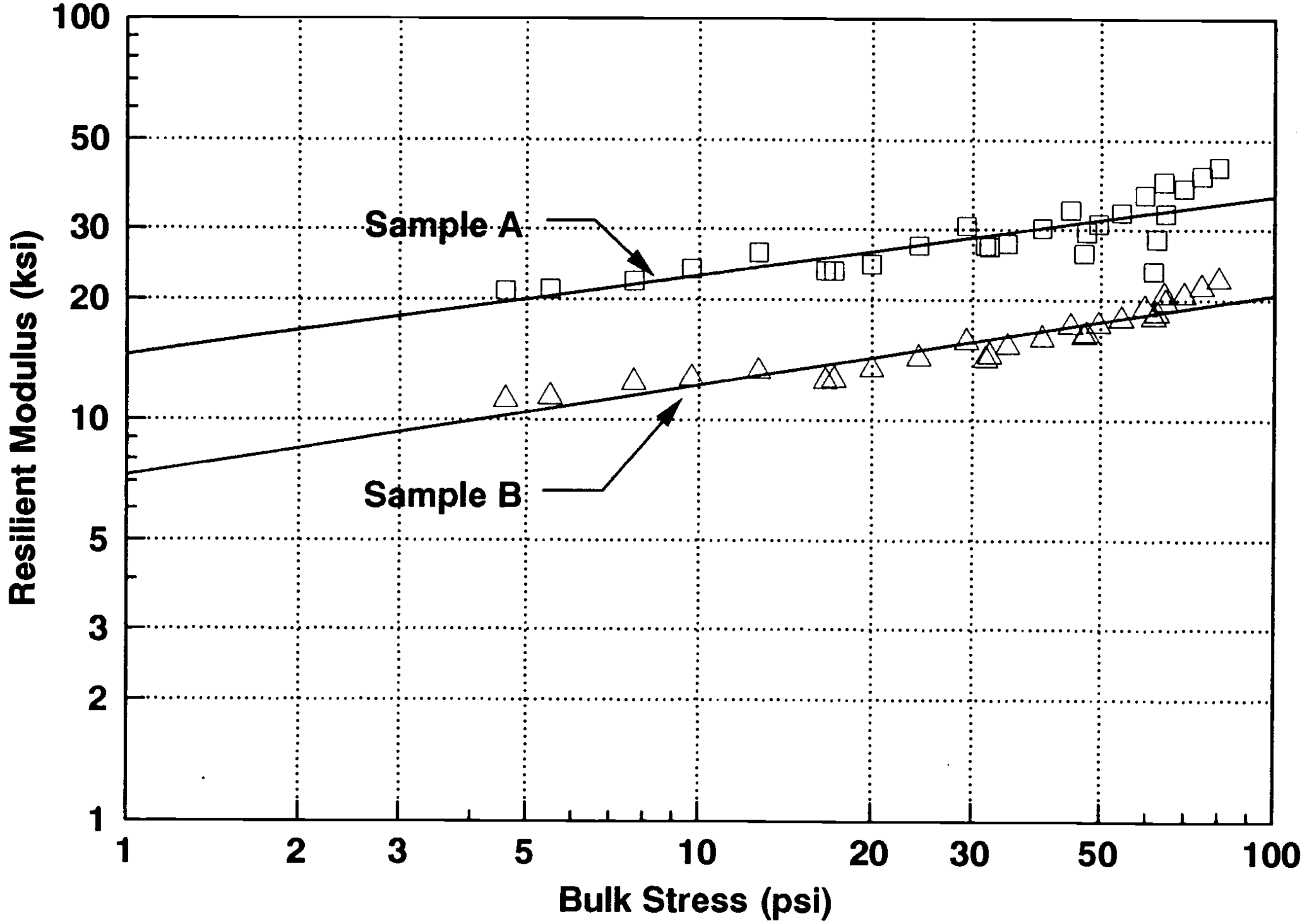


Figure 4.13 Laboratory Tested Moduli for the Rufus-Quinton Project

For the Centennial Boulevard project, the samples were prepared at the field moisture condition. The aggregate materials were delivered to the laboratory directly from the field, and samples were made immediately. Four samples were made and similar compaction efforts were applied to each sample. A potential problem with this type of preparation is that the samples may not be compacted to the maximum density or to the predetermined density. Table 4.18 presents the moisture content and density results that were measured immediately after the modulus testing, while the resilient modulus test results are summarized in Table 4.19 and plotted in Figure 4.14. The test results from this project seem to indicate that for similar materials, the relationship between the modulus and stress would be similar if the density variations are not substantial.

4.2.3.6 Comparing Backcalculated and Lab Tested Results

Figures 4.15 and 4.16 provide a comparison of the asphalt concrete layer material between the backcalculated and lab tested results, for both Rufus-Quinton and Centennial Blvd projects. The comparison on the two selected projects shows that for asphalt concrete, the backcalculated moduli are generally lower than the lab tested and also seem to be less susceptible to temperature variation. In the same temperature range, the difference can be expected to be 20 to 30 percent. For the aggregate base material, the backcalculated modulus slope (k2) is slightly higher than lab tested, as can be seen in Figures 4.17 and 4.18, for both projects respectively. However, in the range of bulk stress from 7 psi to 20 psi where actual pavement stresses generally fall, a favorable comparison can be found.

Table 4.18 Water Content and Density at Time of Testing for Centennial Project

Sample ID Density	Water Content (%)	Wet Density (pcf)	Dry (pcf)
A	5.33	131.61	124.95
B	4.79	132.01	125.98
C	7.72	131.23	121.82
D	6.68	132.81	124.28

Table 4.19 Summary of Base Material Resilient Modulus Test for Centennial Blvd Project

No.	Confin. Stress	Sample A Bulk S	Modulus	Sample B Bulk S	Modulus	Sample C Bulk S	Modulus	Sample D Bulk S	Modulus
1	20	61.9	41.1	61.4	45.8	61.5	40.1	61.3	47.3
2	20	63.1	40.9	62.4	45.8	62.8	39.1	62.6	46.7
3	20	65.6	40.9	65.4	46.7	65.9	38.2	65.5	46.5
4	20	70.1	41.5	70.0	47.7	70.1	39.1	70.3	47.4
5	20	74.5	42.5	74.5	49.2	74.8	40.6	74.5	48.3
6	20	79.4	43.6	79.4	49.7	79.9	41.9	79.8	49.2
7	15	46.0	36.6	46.2	42.6	46.3	36.7	46.3	42.1
8	15	47.3	36.3	47.2	42.5	47.4	36.2	47.2	41.6
9	15	49.9	36.3	49.8	42.3	50.8	35.1	50.1	41.8
10	15	54.9	37.6	54.8	43.4	55.2	36.4	54.8	42.8
11	15	59.3	39.1	59.4	44.8	59.7	37.8	59.1	44.3
12	15	64.2	40.8	64.2	46.1	64.4	39.5	64.5	45.5
13	10	31.3	33.5	31.3	38.8	31.3	34.1	31.1	38.6
14	10	32.6	33.3	32.6	37.9	32.8	32.9	32.1	38.1
15	10	34.4	32.8	35.1	38.0	35.3	32.5	34.9	38.0
16	10	39.2	34.4	40.0	39.3	39.9	33.6	39.5	39.2
17	10	43.7	36.2	44.4	41.0	44.4	35.4	44.2	41.0
18	10	16.3	29.9	16.0	34.7	16.2	31.5	16.4	34.5
19	5	17.4	29.5	17.0	34.1	17.6	30.3	17.1	34.3
20	5	20.0	30.0	19.6	33.9	20.2	29.8	20.3	34.6
21	5	25.1	32.1	24.4	35.5	24.4	31.2	24.8	36.2
22	5	29.4	34.3	28.8	37.5	29.1	33.6	29.0	37.7
23	1	4.2	28.3	4.3	31.2	4.1	28.7	4.2	31.0
24	1	4.9	27.6	5.1	31.0	4.9	28.7	5.1	31.1
25	1	8.0	27.9	7.5	30.8	8.1	27.9	8.0	31.3
26	1	9.9	28.7	9.4	31.5	9.6	28.5	9.5	31.9
27	1	13.3	30.2	12.6	32.9	12.5	29.9	12.9	33.5

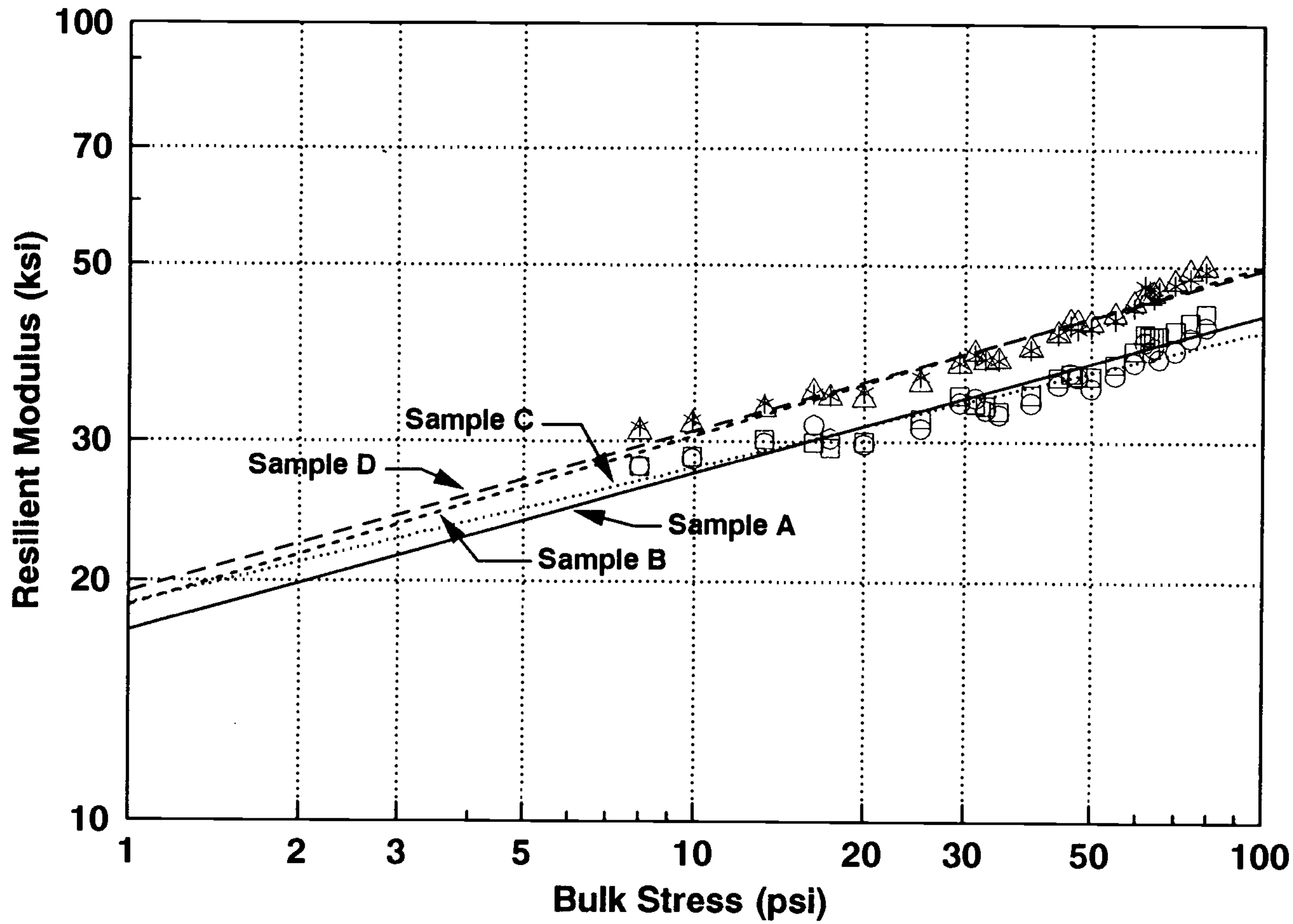


Figure 4.14 Laboratory Tested Moduli for the Centennial Blvd Project

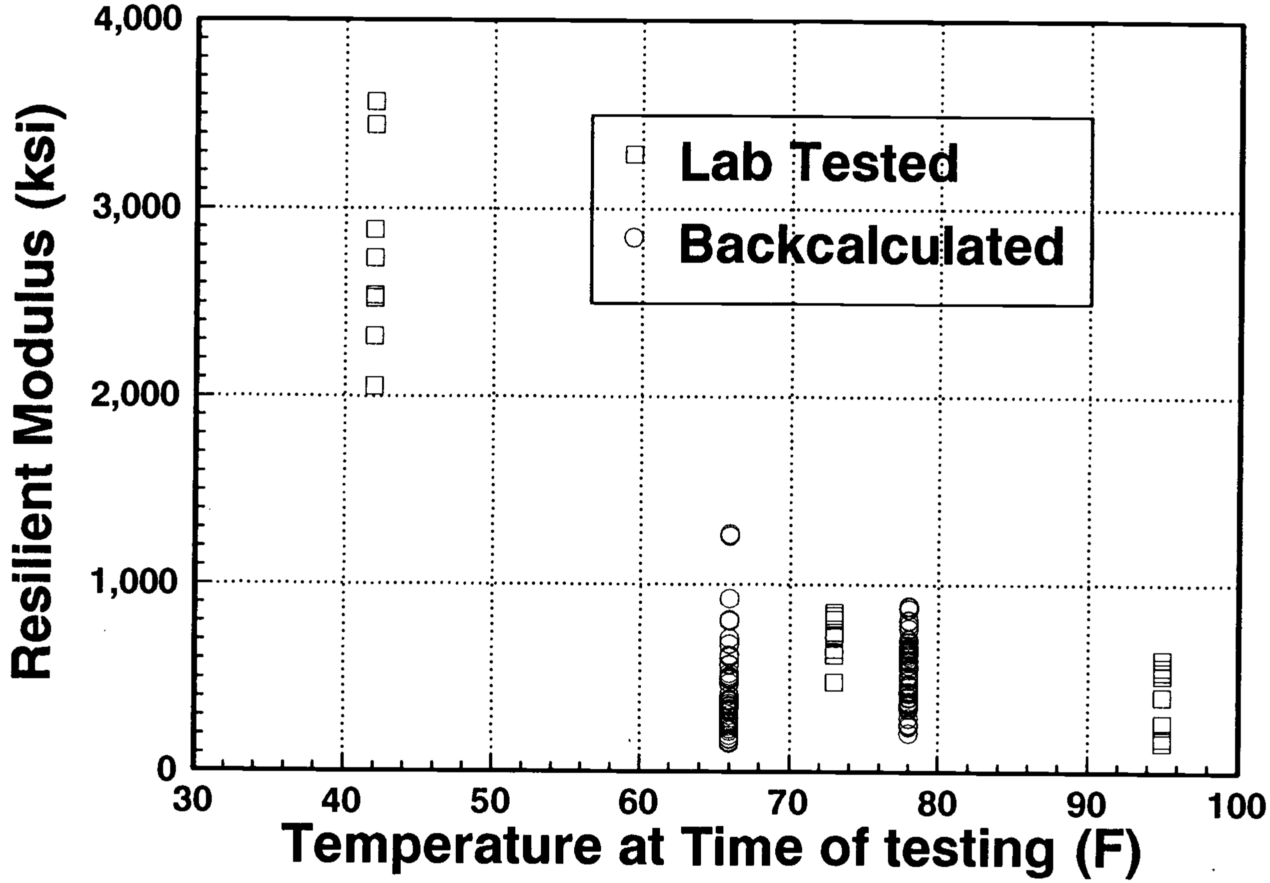


Figure 4.15 Comparison Between Laboratory Tested and Backcalculated AC Moduli for the Rufus-Quinton Project

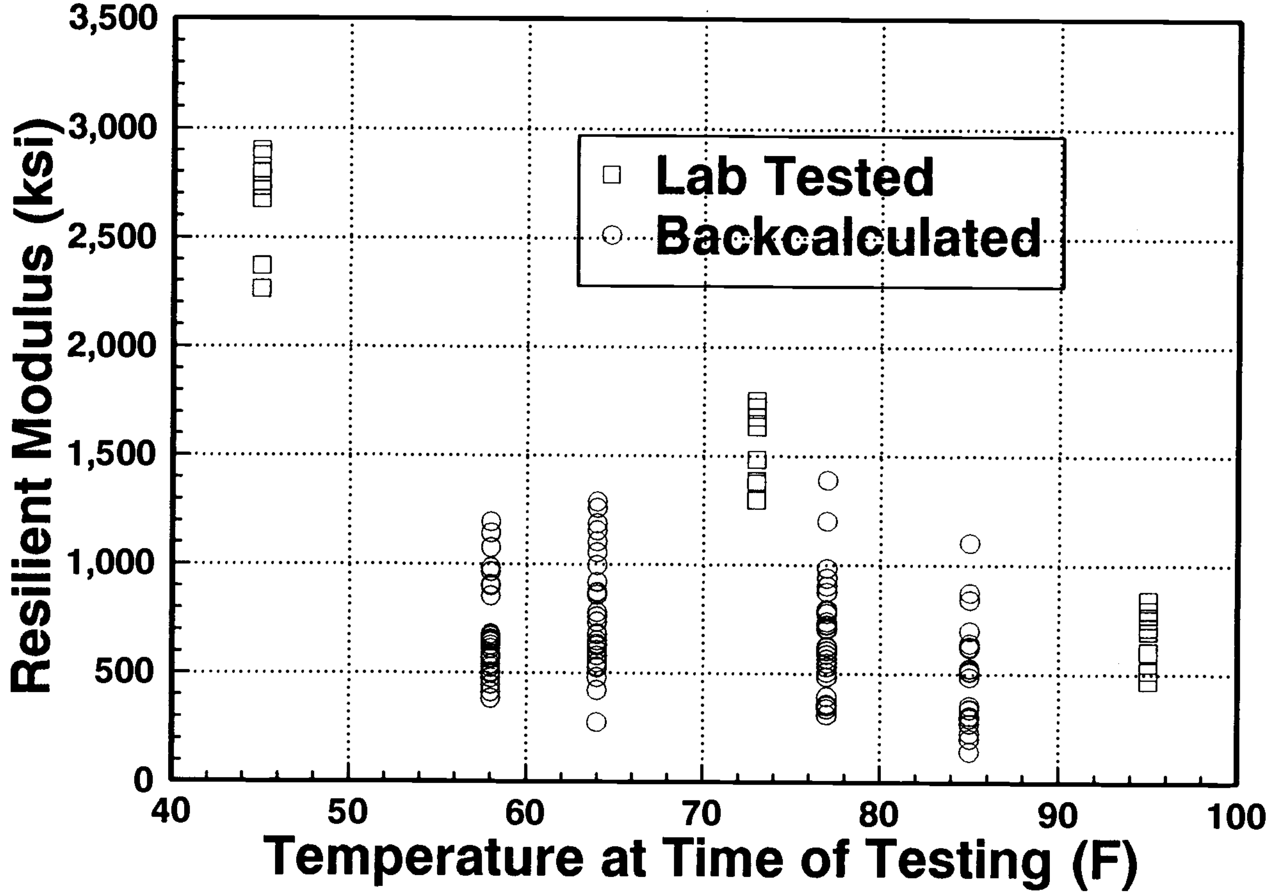


Figure 4.16 Comparison Between Laboratory Tested and Backcalculated AC Moduli for the Centennial Blvd Project

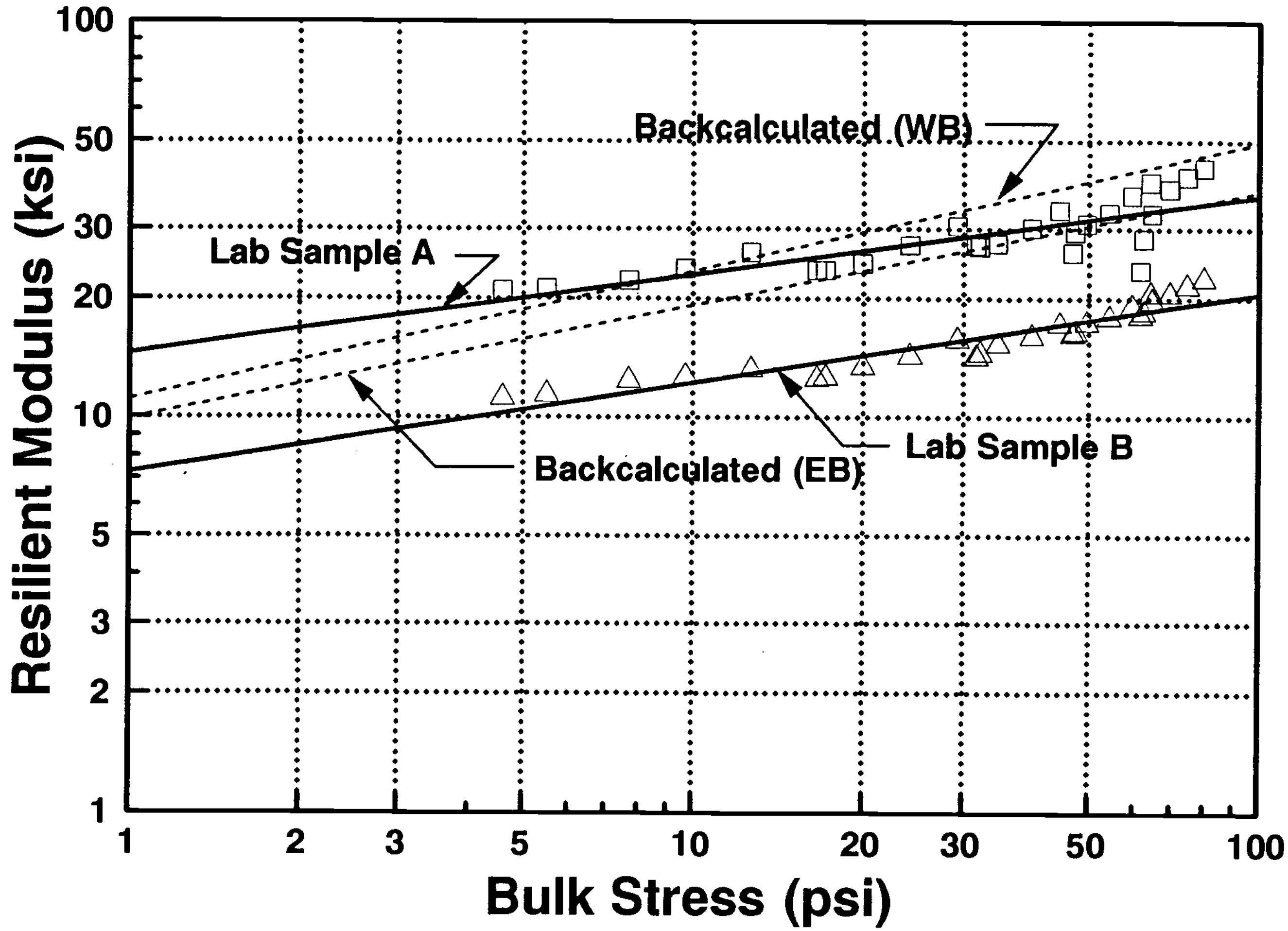


Figure 4.17 Comparison Between Laboratory Tested and Backcalculated Base Moduli for the Rufus-Quinton Project

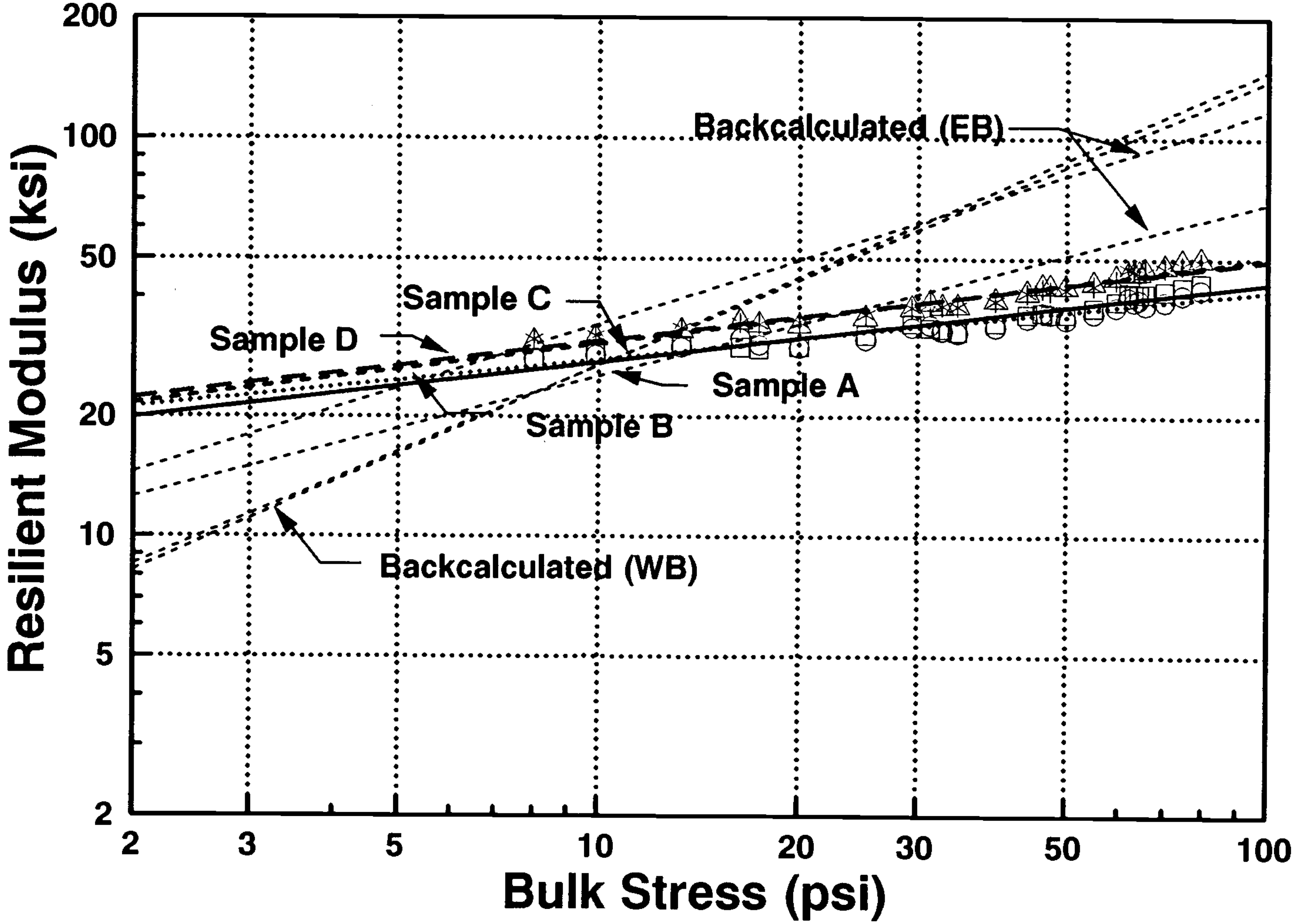


Figure 4.18 Comparison Between Laboratory Tested and Backcalculated Base Moduli for the Centennial Blvd Project

4.3 Summary

This chapter described the development of a new and improved backcalculation procedure for determining pavement layer moduli. Initial evaluation on the developed procedure was made. The evaluation was performed using in three approaches: 1) comparing backcalculated moduli with preassumed theoretical moduli, 2) comparing with other backcalculation programs, and 3) comparing backcalculated moduli with laboratory test results. The evaluation shows that the moduli backcalculated using the BOUSDEF program compare very well with the preassumed theoretical values and are very compatible with some developed programs used for comparison. The comparison with the laboratory test results on the two projects also compared favorably.

5.0 DETERMINATION OF RESILIENT MODULUS USING LABORATORY TESTS AND CORRELATIONS

One of the key elements in using a mechanistic type pavement analysis is to determine the modulus of all pavement materials. Generally, three approaches have been employed:

1. Backcalculate resilient modulus from deflection test data.
2. Determine resilient modulus by laboratory test on cores and soil samples.
3. Estimate resilient modulus using correlations developed by research investigators.

The backcalculation techniques have been described in great detail in Chapters 3 and 4. Theoretically, pavement layer moduli determined using this method represent the in-situ pavement material properties at time of testing. However, the backcalculation procedures, at the present time, are not fully capable of determining layer moduli for all circumstances. Further, the reliability of the backcalculated results still needs to be examined; therefore, the backcalculation techniques are recommended for only initial evaluation of pavement materials properties. This chapter describes briefly the second and third approaches.

5.1 Resilient Moduli from Laboratory Tests

The resilient modulus of pavement materials may also be determined through laboratory tests on undisturbed or disturbed samples. At present, there are at least two type of standard laboratory procedures for determining modulus of pavement materials. Typically, the diametral test (ASTM D4123) is used to determine the resilient modulus for asphalt concrete samples. For untreated granular materials, the triaxial test (AASHTO T-274) may be used.

5.1.1 Diametral Tests

The mechanism of this test procedure is illustrated in Figures 5.1 and 5.2. To determine the modulus of an asphalt concrete sample, the specimen is placed in the diametral yoke (Figure 5.1). The yoke, with specimen, is then placed in the load frame on a load platen with bottom loading strip attached to the cell (Figure 5.2). A load, which can be either impulse or haversine, is applied vertically to the specimen having a diameter of 4 inches and a height of 1 to 3 inches. The lateral displacement during repeated load is measured by a pair of linear variable differential transducer (LVDT) gauge heads which are mounted on the diametral yoke as shown in Figure 5.3. The resilient modulus of the specimen is calculated with the following relationship:

$$MR = \frac{0.62 * P}{t * H} \tag{5-1}$$

where:

MR = resilient modulus, psi,

P = repeated load, lbs,

t = sample thickness, inches, and

H = total recoverable horizontal displacement, inches.

The resilient modulus of the asphalt concrete specimen over a range

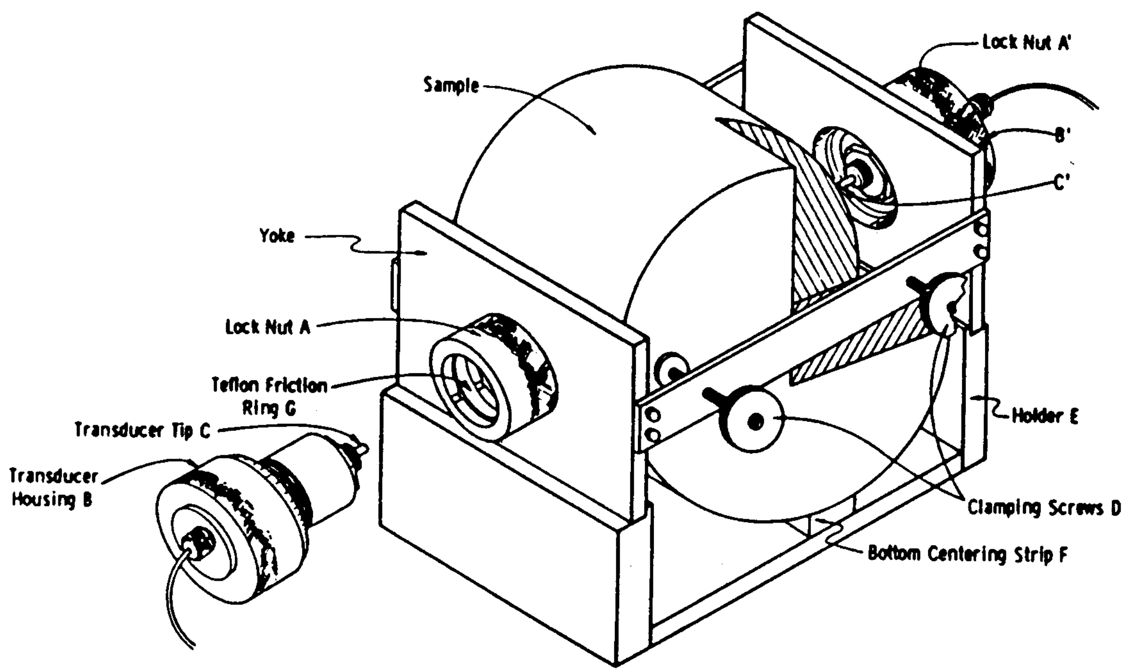


Figure 5.1 Diametral Resilient Modulus Device Yoke and Alignment Stand

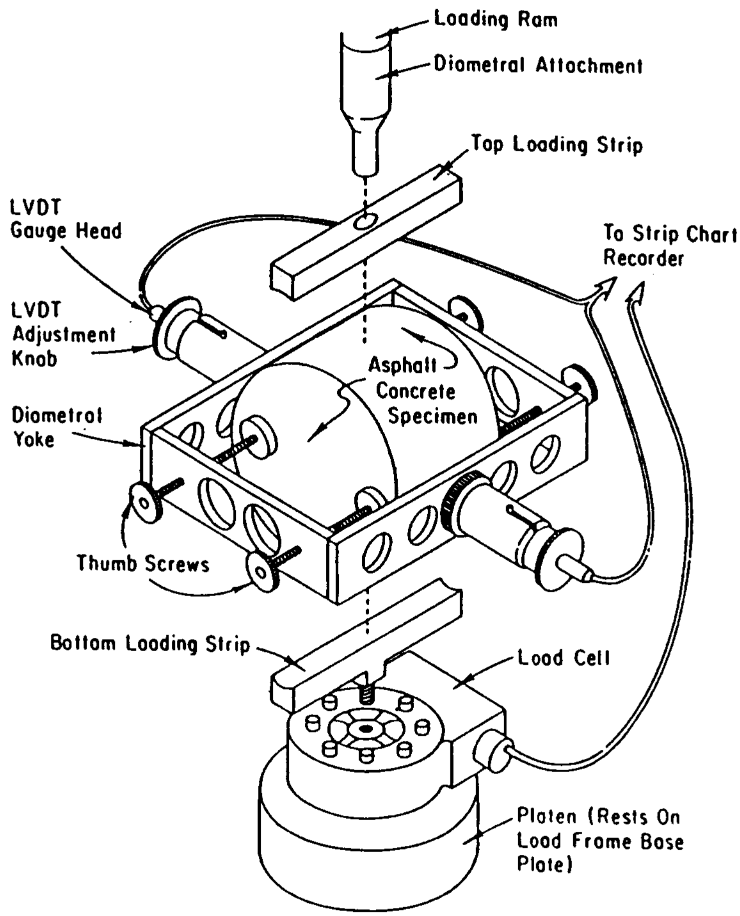


Figure 5.2 Test Specimen with Diametral Yoke and Loading Ram

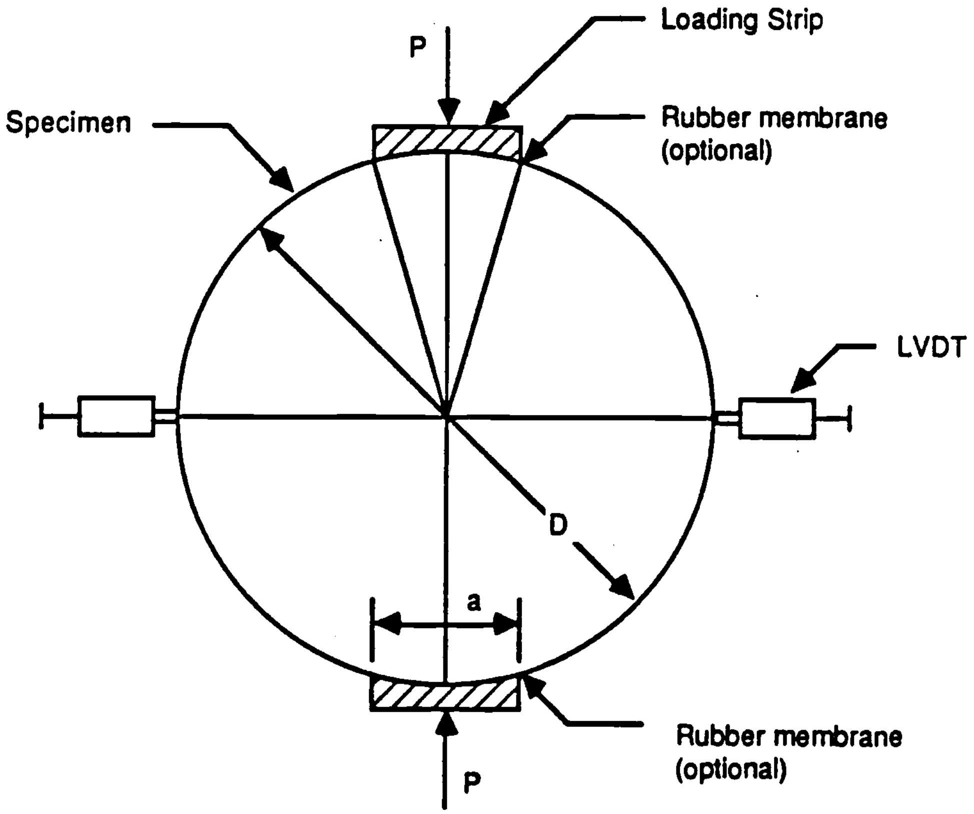


Figure 5.3 Schematic of Asphalt Concrete Laboratory Resilient Modulus Test (ASTM, 1984)

of temperatures may also be evaluated by testing the sample in a temperature chamber.

5.1.2 Triaxial Tests

The triaxial test as illustrated in Figure 5.4 is usually used to determine the resilient modulus of granular and fine materials. A schematic diagram of this resilient modulus test and definitions are illustrated in Figure 5.5. In this test, a vertical load is applied. Rather than measuring the horizontal displacement of the test sample, the vertical deformation is measured. Varying deviator and confining stresses can be applied to determine the resilient modulus at different stress conditions. The resilient modulus is calculated by dividing the vertical strain by the deviator stress applied with the following relationship:

$$MR = \frac{\sigma_d}{\epsilon_v} \qquad (5\text{-}2)$$

where:

MR = resilient modulus, (psi)

σ_d = repeated axial stress, (psi)

ϵ_v = recoverable axial strain, (in/in)

5.2 Correlations

In cases where either backcalculation or laboratory test results are not available, other developed correlations may also be used to estimate the modulus. There are several developed correlations or

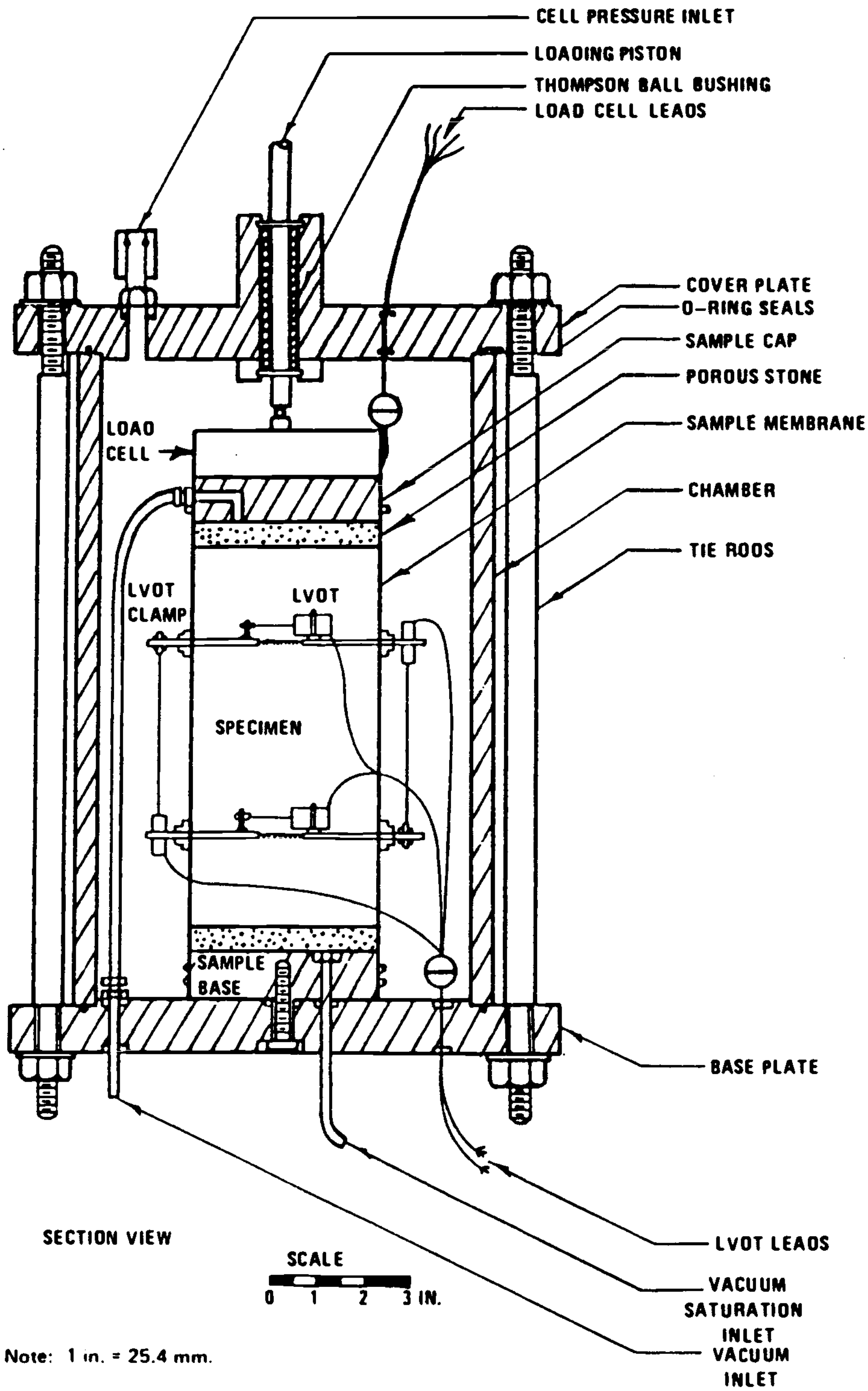


Figure 5.4 Triaxial Cell Suitable for Repeated Load Testing of Soils

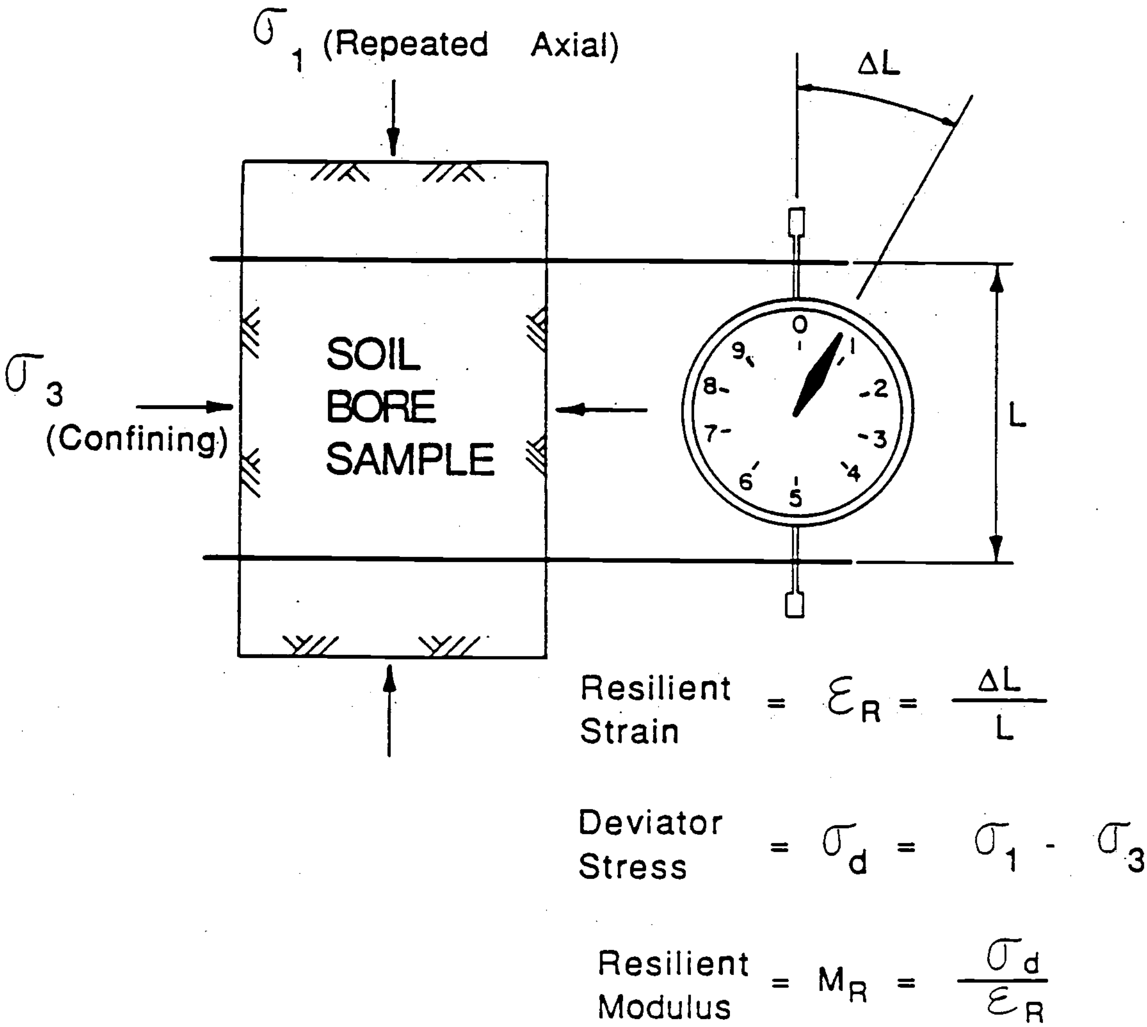


Figure 5.5 Schematic Diagram of Resilient Modulus Test

methods which can be used for estimating the resilient modulus of the pavement materials. The following describe a few of these relationships.

5.2.1 Subgrade Soil

5.2.1.1 Resilient Modulus versus CBR

The first relationship between resilient modulus and CBR was that developed by Shell (Heukelom and Klomp, 1962) and used in their design procedure. This correlation can be used to estimate subgrade resilient modulus from a known CBR value. Figure 5.6 illustrates the data used to develop the correlation. Field modulus values were obtained using vibratory loading. The developed equation is as follows:

$$MR = 1500\ CBR \qquad (5\text{-}3)$$

where:

CBR = California Bearing Ratio.

It should be noted that the coefficient (1500) can vary from 750 to 3000 as shown in Figure 5.6. Available data indicate the equation provides better results (at least within the correlation limits) at values of CBR less than about 10, i.e. the correlation appears to give more reasonable results for fine-grained soil and fine sands rather than granular materials (The Asphalt Institute, 1982).

5.2.1.2 Resilient Modulus versus R Value

The relationship between resilient modulus and R-value was originally derived from data collected on the San Diego County experiment base project (Kallas and Shook, 1977). This relationship

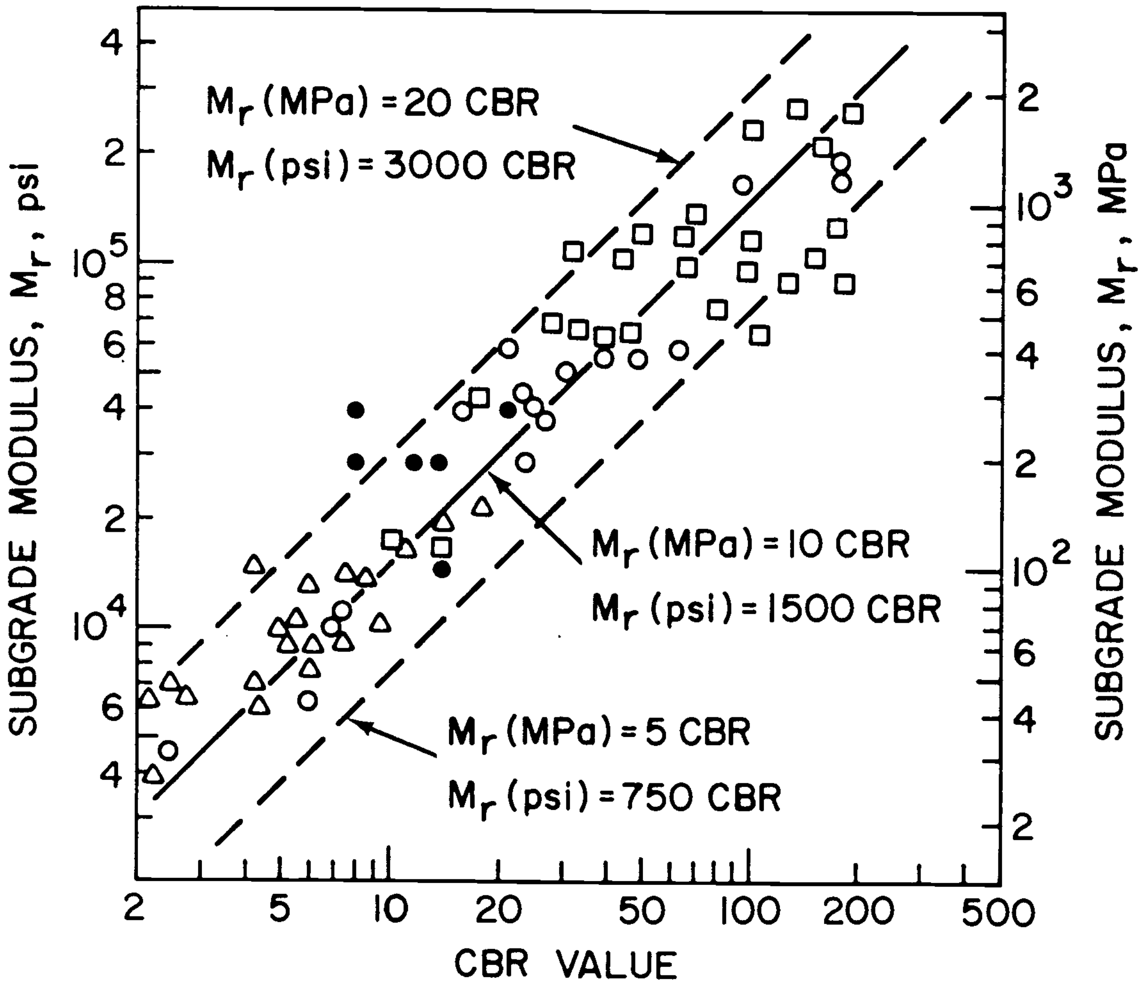


Figure 5.6 Relation Between Dynamic Modulus and CBR (Heukelom and Klomp, 1962)

is expressed as follows:

$$MR(psi) = A + B * R \tag{5-4}$$

where:

A = 772 to 1155,

B = 369 to 555, and

R = stabilimeter R-value.

In general, the following correlation may be used (AASHTO, 1986):

$$MR(psi) = 1000 + 555\ R \tag{5-5}$$

Table 5.1 illustrates a comparison of R-value, CBR, and resilient modulus data and shows a probable range for different type of soils.

The MS-1 (TAI, 1981) indicates that CBR and R-value correlations are considered applicable to materials classified as CL, CH, ML, SC, SM, and SP (Unified Soil Classification, ASTM D2487) or for materials that are estimated to have a resilient modulus of 30,000 psi or less (TAI, 1981)

5.2.1.3 <u>Resilient Modulus versus Deflection</u>

The subgrade modulus may also be estimated from deflection test data. Several regression equations have been developed for the estimation of subgrade modulus. Table 5.2 shows a few of such equations. It should be noted that the deflection measured at distance r should be far enough to reflect the subgrade response. A procedure described by Hicks et al (1988) may be used to determine the last sensor location.

Table 5.1 Comparison of R, CBR, and Resilient Modulus Data
(The Asphalt Institute, 1982)

Soil Description	R-value Test		CBR Test		Triaxial Test[a]
	R	Estimated M_r, psi	CBR	Estimated M_r, psi	Estimated M_r, psi
Sand	60	34,500	31	46,500	16,900
Silt	59	33,900	20	30,000	11,200
Sandy loam	21	12,800	25	37,500	11,600
Silt-clay loam	21	12,800	25	37,500	17,600
Silty-clay	18	11,000	7.6	11,400	8,200
Heavy clay	<5	<3,900	5.2	7,800	1,600

[a] Deviator stress = 6.0 psi, confining stress = 2.0 psi, optimum moisture and density

Table 5.2 Various Regression Equations for Subgrade Modulus

Investigator	Equation	Description
AASHTO (AASHTO, 1986)	$E_{sg} = PS_f/(d_r r)$	P = Load (lbs) S_f = Subgrade modulus prediction factor, which is a function of the Poisson ration and has value of: μ / S_f: 0.30 0.297 0.35 0.293 0.40 0.287 0.45 0.279 0.50 0.269 d_r = Deflection at distance r r = Distance to sensor
Ullidtz (Ullidtz, 1982)	$E_{sg} = \dfrac{(1-\mu_i^2)\ P\ a^2}{d_r\ r}$	μ_i = Poisson's ratio P = Contact stress a = Plate radius r = Distance to sensor d_r = Deflection at distance r
Washington (Newcomb, 1986)	$E_{sg} = 7.61(P/D_3)$	P = Load (lbs)
	$E_{sg} = 5.77(P/D_4)$	D_x = Deflection at x feet from center of NDT load, (mils)

5.2.1.4 Resilient Modulus versus Soil Classification

Soil classification infirmation may also be used to estimate the resilient modulus value. Crude empirical relationships between the modulus and soil classifications, as shown in Figure 5.7, may also be used as a reference.

5.2.2 Untreated Granular Materials

Untreated materials are most often used for base and subbase layers. The strength of the granular base or subbase is related to the stress state which will occur under operating conditions. The stiffness characteristics of the granular materials are dependent on the stress state, which is a function of pavement thickness, load, and the resilient modulus of each layer. Table 5.3 shows correlations between modulus and CBR or R-value under different stress conditions for untreated granular materials that are used for base and subbase. Another expression which is more commonly used to describe the relationship between stress state and modulus is represented by the equation $M_R = k_1 \theta^{k_2}$. Numerous studies have been conducted and typical values developed. Table 5.4 lists the ranges in k_1 and k_2 obtained by different investigators for a number of different aggregates representative of untreated base and subbase materials.

The 1986 AASHTO Guide (AASHTO, 1986) also provides some typical values for k_1 and k_2 for unbound base and subbase materials. Table 5.5 shows a range of values based on moisture condition. Therefore, the base modulus is a function of not only moisture but also the stress state, and values for the stress state within the base course vary with the subgrade modulus and thickness of the surface layer.

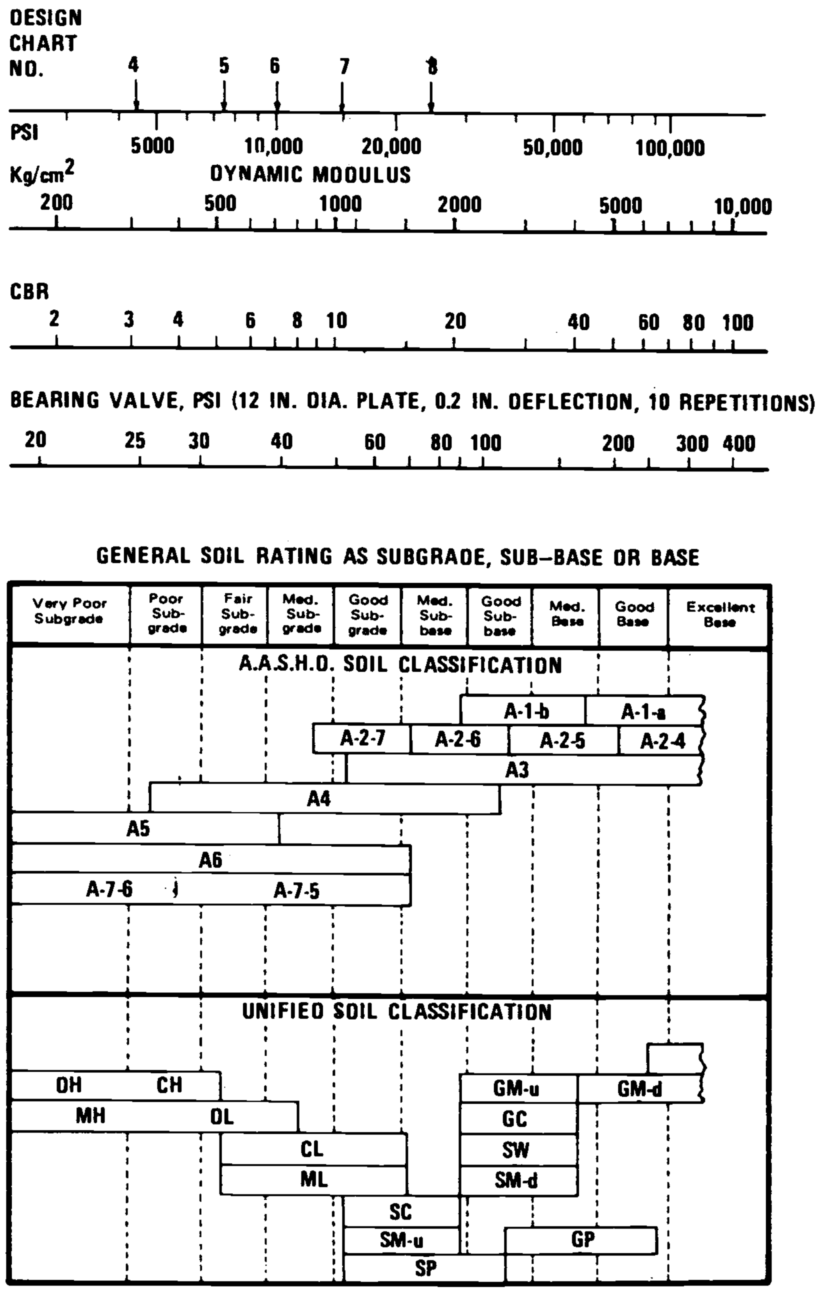


Figure 5.7 Crude Empirical Relationships Between the Dynamic Modulus of Elasticity and Routine Tests (Hicks, et al, 1980)

Table 5.3 Correlations Between MR, CBR or R and Stress State

(AASHTO, 1986)

Stress State, θ	MR (psi)	MR (psi)
100	740 * CBR	1000 + 780 * R
30	440 * CBR	1000 + 450 * R
20	340 * CBR	1000 + 350 * R
10	250 * CBR	1000 + 250 * R

Table 5.4 Summary of Repeated Load Triaxial Compression Laboratory Test Data for Untreated Granular Materials (The Asphalt Institute, 1982)

Investigator(s)	Material(s)	k_1	k_2
Hicks, 1970	Partially crushed gravel; crushed rock	1,600-5,000	0.57-0.73
Hicks, et al 1970	Untreated base - San Diego Test Road	2,100-5,400	0.61
Allen, 1973	Gravel, crushed stone	1,800-8,000	0.32-0.70
Kalcheff & Hicks, 1973	Crushed stone	4,000-9,000	0.46-0.64
Boyce, Brown, & Pell, 1976	Well graded crushed	8,000	0.67
U.C. Berkeley (Monismith, 1972)	In service base and subbase materials	2,900-7,750	0.46-0.65
Albright, 1986	Crushed aggregate (Saturated)	1,300-2,000	0.69-0.78
	Crushed aggregate (Optimum water content)	2,000-2,600	0.70-0.73

$MR = k_1 \theta^{k_2}$, where MR and θ are in psi.

Table 5.5 Typical values for k_1 and k_2 for Unbound Base and Subbase Material (AASHTO, 1986)

(a) Base

Moisture	k_1*	k_2*
Dry	6,000 - 10,000	0.5 - 0.7
Damp	4,000 - 6,000	0.5 - 0.7
Wet	2,000 - 4,000	0.5 - 0.7

(b) Subbase

Dry	6,000 - 8,000	0.4 - 0.6
Damp	4,000 - 6,000	0.4 - 0.6
Wet	1,500 - 4,000	0.4 - 0.6

* Range in k_1 and k_2 is a function of the material quality.

Typical values for use in design are given in Table 5.6.

5.2.3 Asphalt Concrete

The Asphalt Institute (1982) developed a relationship that can be used to determine resilient modulus of asphalt concrete. The relation has the following form:

$$\text{Log } |E| = 5.553833 + 0.028829\left(\frac{P_{200}}{f^{0.17033}}\right) - 0.03476\ (V_v) \qquad (5\text{-}6)$$

$$+0.070377(\eta_{70°F,}\ 10^6)+0.000005\left[t_p^{\,(1.3+0.49825\log f)}\ P_{ac}^{0.5}\right]$$

$$-0.00189\left[\frac{t_p^{\,(1.3+0.49825\log f)}\ P_{ac}^{0.5}}{f^{1.1}}\right] + 0.931757\left(\frac{1}{f^{0.02774}}\right)$$

where:

$|E|$ = dynamic modulus of asphalt concrete, psi

P_{200} = percent aggregate passing No. 200 sieve

f = frequency, Hz

V_v = percent air voids

$\eta_{70°F,10^6}$ = absolute viscosity at 70°F, poises x 10^6

P_{ac} = asphalt content, percent by weight of mix

t_p = temperature, °F (1.8°C + 32)

If sufficient viscosity data are not available to estimate $\eta_{70°F,10^6}$, then the following relationship may be used:

$$\eta_{70°F,10^6} = 29508.2\ \text{pen}_{77°F}^{-2.1939} \qquad (5\text{-}7)$$

The value of p_{ac} may be estimated as follows:

$$p_{ac} = 0.483\ V_{be} \qquad (5\text{-}8)$$

where:

Table 5.6 Typical Values of Stress State
(AASHTO, 1986)

Asphalt Concrete Thickness (in)	Roadbed Soil Resilient Modulus (psi)		
	3,000	7,500	15,000
Less than 2	20	25	30
2 - 4	10	15	20
4 - 6	5	10	15
Greater than 6	5	5	5

V_{be} = Effective volume of asphalt, percent, defined as the total asphalt content minus the quantity of asphalt lost by absorption into the aggregate particles.

or

$$p_{ac} = 0.434\ V_b \quad (5\text{-}9)$$

where:

V_b = total volume of asphalt, percent.

This equation has been computerized for use on microcomputers. The resulting program (AMOD) and its user's guide may be found in Appendix C.

5.3 Summary

This chapter describes several techniques that are widely used around the United States to determine modulus of pavement layers. These techniques include laboratory tests and correlations to determine/estimate the resilient modulus of pavement materials.

The advantage of the laboratory tests to determine resilient modulus is that it is a direct measurement of the strength of a particular material. The disadvantage is that the samples tested in the laboratory may represent only a portion of pavement material rather than an average condition that would find in the field. For example, for a badly cracked asphalt concrete surface, the cores tested in the laboratory may not truly reflect the field situation. Moreover, the laboratory tests require sophisticated equipment as well as trained personnel to perform the tests, and the laboratory tests usually take a significant amount of time. Lastly, there are several test related variables which affect test results. These variables are summarized in Table 5.7.

The advantage of using developed correlations is their availability. However, one must be aware that correlations were developed based on certain laboratory conditions. Therefore, these correlations are best suitable to situations that are similar to where the correlations were developed. Caution should be exercised when using these correlations.

In any case, material characterization is an extremely important and difficult issue. There are many variables that would affect material response both in the laboratory and in field tests. These variables, as summarized and presented in Table 5.7, must be fully realized when determining the resilient modulus values.

Table 5.7 Variables Affecting Materials Response (Hicks et al, 1980)

I. LOADING VARIABLES
   - A. Stress history (nature of prior loading)
     - 1. Non-repetitive loading (such as preconsolidation)
     - 2. Repetitive loading
       - a. Nature
         - (1) Simple
         - (2) Compound
       - b. Number of repetitive applications
   - B. Initial stress state (magnitude and direction of normal and shear stresses)
   - C. Incremental loading
     - 1. Mode of loading
       - a. Controlled stress (or load)
       - b. Controlled strain (or deformation)
       - c. Intermediate modes
     - 2. Intensity (magnitude and direction of incremental normal and shear stresses)
     - 3. Stress path (relation among stresses - both normal and shear - as test progresses)
     - 4. Time path
       - a. Static
         - (1) Constant rate of stress (or load)
         - (2) Constant rate of strain (or deformation)
         - (3) Creep
         - (4) Relaxation
       - b. Dynamic
         - (1) Impact
         - (2) Resonance
         - (3) Other
           - (a) Sinusoidal (rate of loading is variable)
           - (b) Pulsating (duration, frequency, and shape of load curve are variables)

Table 5.7 Variables Affecting Materials Response (cont.)

5. Type of behavior observed
    a. Strength (limiting stresses and strains)
    b. Deformability
6. Homogeneity of stresses
7. Drainage (drained or undrained)

II. MIXTURE VARIABLES

A. Mineral particles
1. Maximum and minimum size
2. Gradation
3. Shape
4. Surface texture
5. Angularity
6. Mineralogy
7. Adsorbed ions
8. Quantity

B. Binder
1. Type
2. Hardness
3. Quantity

C. Water
1. Quantity

D. Voids
1. Quantity
2. Size
3. Shape

E. Construction Process
1. Density
2. Structure
3. Degree of anisotrophy
4. Temperature

F. Homogeneity

III. ENVIRONMENTAL VARIABLES

A. Temperature

B. Moisture

C. Alteration of Material Properties
1. Thixotropy
2. Aging
3. Curing
4. Densification

6.0 DEVELOPMENT OF AN IMPROVED MECHANISTIC OVERLAY DESIGN PROCEDURE FOR FLEXIBLE PAVEMENTS

One of the major objectives of this study is to develop an improved mechanistic overlay design procedure for routine design work. To achieve this objective, this chapter first reviews some mechanistic design procedures developed in the past and then presents an improved overlay design procedure.

6.1 Review of Current Mechanistic Overlay Design Methods

Several mechanistic overlay design have been developed in the past few years. These methods generally follow a framework presented by Finn and Monismith (1984) as shown in Figure 6.1. Table 6.1 summarizes some of these developments, while the following sections review three of the procedures developed by: 1) ARE (Austin Research Engineers, Inc., 1975), 2) WSDOT (Mahoney, et al., 1988), and 3) ADOT&PF (Yapp, et al., 1988).

6.1.1 ARE Method

This method was developed for the Federal Highway Administration by Austin Research Engineers (ARE). The following describes some of the major steps involved in this overlay design procedure.

6.1.1.1 Nondestructive Testing

Nondestructive testing can be performed using any type of deflection equipment that provides satisfactory deflection results. The frequency of deflection measurement is dependent on the terrain, as shown in Table 6.2. Condition surveys are conducted at the same

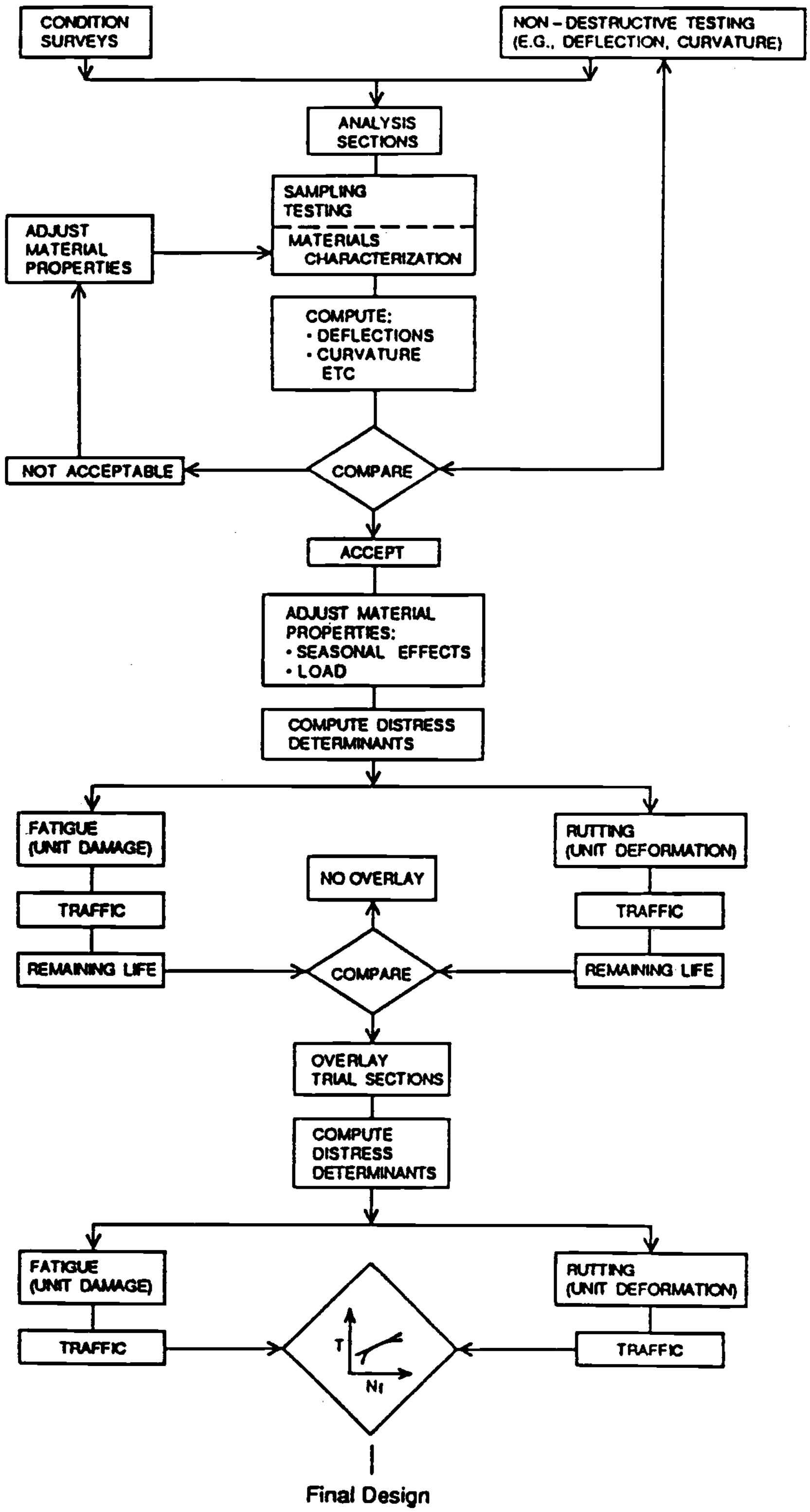


Figure 6.1 Flowchart for the Mechanistic Method (Finn & Monismith, 1984)

Table 6.1 Analytically Based Overlay Design Procedures[a] (Hicks and Zhou, 1988)

Procedure	Nondestructive Pavement Evaluation	Stiffness Determinations		Analysis Procedure	Distress Mechanisms		Provision for Existing Pavement	Overlay Thickness Determination
		In-Situ Measurement	Lab Testing		Fatigue	Rutting		
Shell Research	Falling weight deflectometer	Yes	No	BISAR computer program	Yes	Yes	Yes	Overlay thickness selected to (a) limit fatigue and (b) limit rutting for anticipated traffic; thickness also selected assuming existing pavement is cracked
FHWA-ARE	Dynaflect; Benkelman beam	No	Yes	ELSYM computer program	Yes	Yes	Yes	Overlay thickness selected to (a) limit fatigue and (b) limit rutting for anticipated traffic; asphalt concrete assigned different stiffness values depending on conditions
FHWA-RII	Dynaflect and others	Yes	Opt.	ELSYM computer program	Yes	No	Yes	Overlay thickness selected to limit fatigue for anticipated traffic; asphalt concrete assigned different stiffness values depending on conditions.
Kentucky	Road Rater	Yes	No	Graphic solution[b]	Yes	No	Yes	Overlay thickness selected as difference between pavement thickness required to accommodate all traffic (both applied and anticipated) and effective thickness of existing pavement as determined by nondestructive evaluation of existing pavement.
Alaska	Falling weight deflectometer	Yes	Opt.	ELSYM computer program	Yes	Yes	Yes	Overlay thickness selected to (a) limit fatigue and (b) limit rutting for anticipated traffic; thickness also selected considering seasonal effect as well as traffic for each season.
Washington DOT	Falling weight deflectometer	Yes	Opt.	CHEVRON computer program	Yes	Yes	Yes	Overlay thickness selected to (a) limit fatigue and (b) limit rutting for anticipated traffic; thickness also selected based on sum of damage ratio.

[a]All procedures require a condition survey, represent the pavement as a multilayer elastic solid, and provide an estimate of remaining life.
[b]Based on Chevron computer solution for multilayer elastic solid.

Table 6.2 Guidelines for Nondestructive Testing (Finn and Monismith, 1984)

Type of Location	Spacing
Rolling terrain	100 ft
Numerous cut-to-fill transitions	100 ft
Level with uniform grading	250 ft

time that the deflection measurements are made. Cracking and rutting are recorded and measured. Other general information, such as soil type, drainage conditions, and cut/fill transitions, are also noted.

Deflection profiles are generated for the entire length of the project to assist in establishing the analysis sections. Statistical procedures are used to compare adjacent sections to ensure that the sections are different. The design deflection for each section is determined from:

$$\delta_d = \bar{\delta} + Z * S \tag{6-1}$$

where:

δ_d = design deflection

$\bar{\delta}$ = average deflection

Z = deviation from mean to selected significance level on a normal distribution curve.

S = standard deviation

6.1.1.2 <u>Material Characterization</u>

The pavement structure is represented as a multi-layer elastic system. Each layer's properties are defined by modulus (stiffness) and Poisson's ratio. For the asphalt-bound layer(s), modulus values should be defined over a range in temperatures at a time of loading corresponding to moving traffic. For design purposes, the stiffness at a temperature of 70°F is recommended for use. Poisson's ratio is assumed to be 0.3 for the asphalt concrete, 0.4 for the base and subbase, and 0.45 for subgrade. For a cracked asphalt concrete layer, it is assigned a modulus of 70,000 psi if the cracking is defined as class 2; or a value equal to the base modulus (or 20,000 psi), whichever is greater, if the cracking is defined as class 3. Table 6.3 presents the definitions for both classes of cracking. Figure 6.2 illustrates the pattern of the cracking of the two classes.

Treated base course materials can be tested in the same way as the asphalt concrete. Unbound base course materials should be tested at representative conditions of water content and dry density in repeated loading by following AASHTO test procedures. Subgrade materials should be tested over a range in deviator stresses to permit defining a relationship of the form:

$$M_R = A\ \sigma_d^b \qquad (6\text{-}2)$$

where:

M_R = resilient modulus, psi

σ_d = applied deviator stress, psi, and

A, b = laboratory determined coefficients.

To select an appropriate subgrade modulus for analysis, it is necessary to use the design deflection selected for the particular analysis section and with an iterative procedure, select a modulus value from equation (6-2) that provides the same value for the computed as measured deflection. As seen in Figure 6.3, some adjustments in the laboratory data may be required to achieve compatibility.

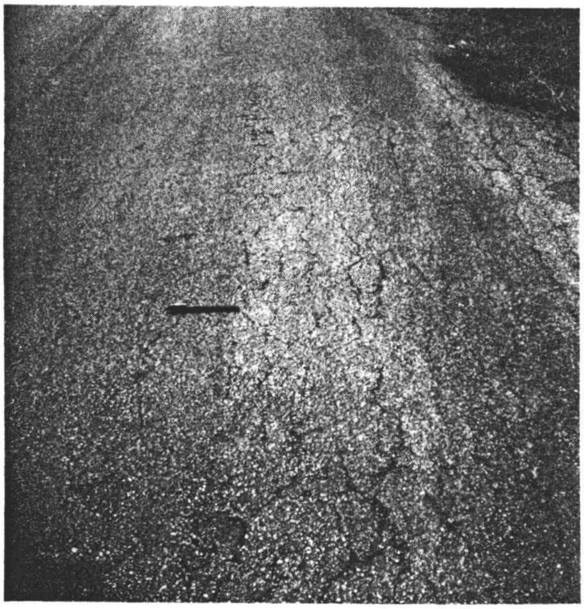
6.1.1.3 Distress Determinants

Two major structural distresses are considered in this method; fatigue and rutting. Fatigue cracking in the asphalt-bound layer is controlled by limiting tensile strain on the underside of the asphalt concrete layer using the following relationship, which is also plotted in Figure 6.4:

Table 6.3 Classes of Cracking (ARE, 1975)

Class Cracking	Definition	AC Modulus
Uncracked	No cracks	Overlay MR
2	Cracking that has progressed to the pavement where cracks have connected together to form a grid-type pattern. (mildly cracked, failed in fatigue)	70,000 psi
3	When the asphalt concrete segments have become loose. (severely cracked, failed in fatigue)	20,000 psi

Note: Variation of the modulus with temperature is not applied to the class 2 and class 3 cracked surface.



Class 2 Cracking

Class 3 Cracking

Figure 6.2 Photographs of Class 2 and Class 3 Cracking (ARE, 1975)

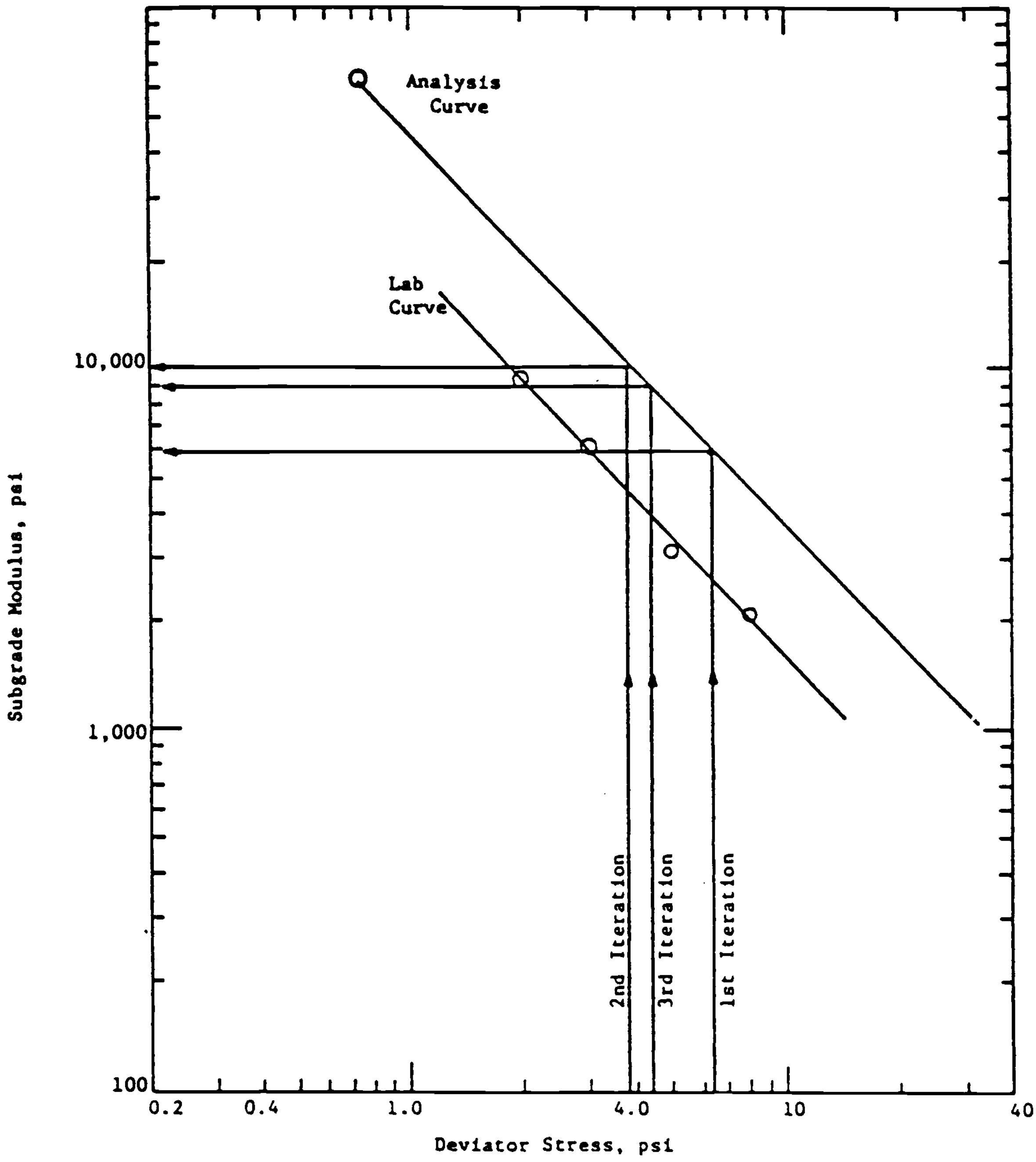


Figure 6.3 Relationship of Resilient Modulus and Repeated Deviator Stress (ARE, 1975)

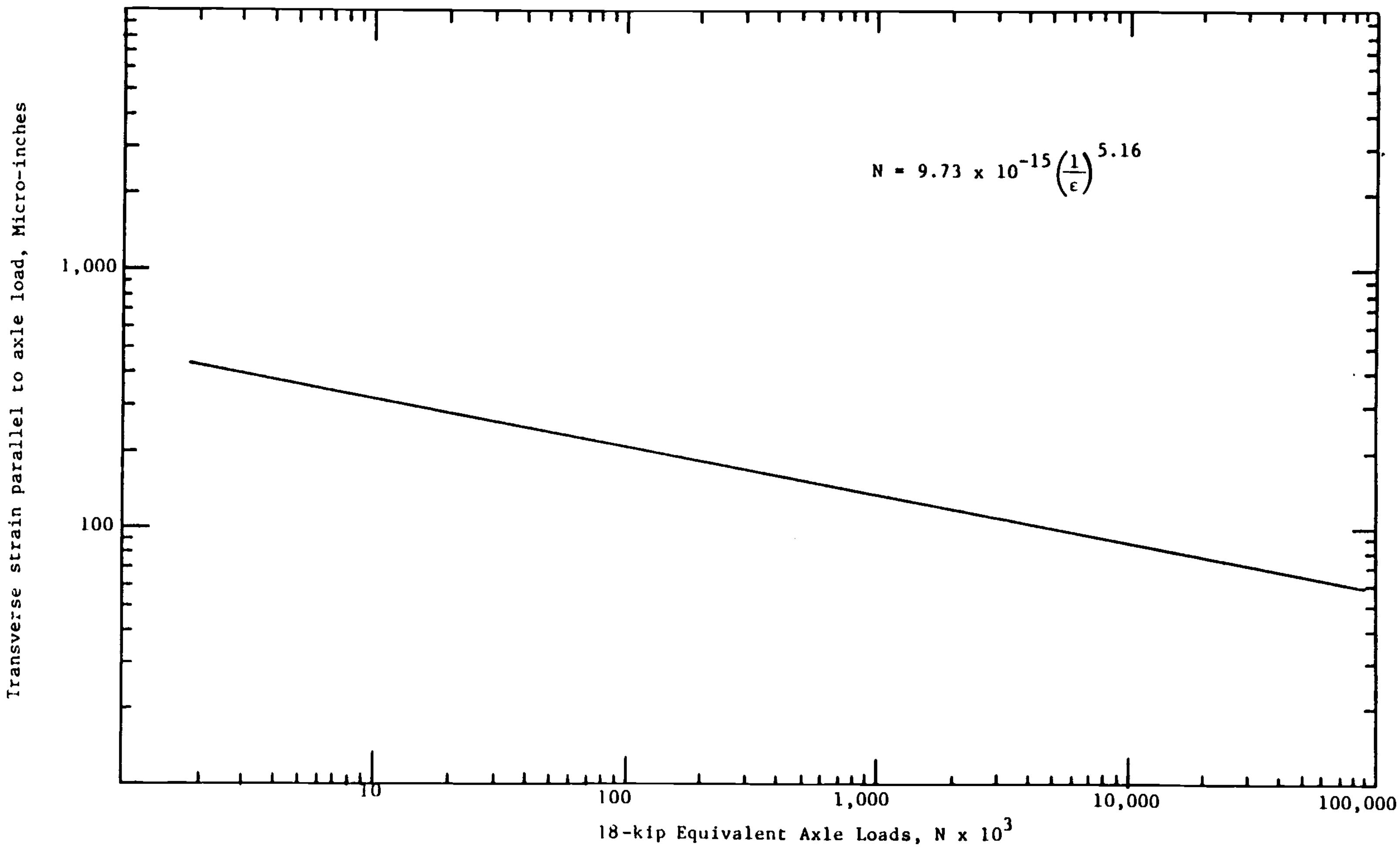


Figure 6.4 Fatigue Curve for 18-kip Load Applications to Time of Class 2 Cracking (ARE, 1975)

$$N_{18} = 9.73 * 10\text{-}15 * \epsilon_t^{-5.16} \quad (6\text{-}3)$$

where:

N_{18} = allowable number of 18-kip single-axle load applications and,

ϵ_t = horizontal tensile strain on the underside of asphalt-bound layer being analyzed.

Rutting is controlled by a regression equation of the general form:

$$\begin{aligned}\log N_{18} = {} & 7.5145 + 0.96831\, R + 0.01173\, (\epsilon_{1z}/\sigma_{1z}) \\ & + 0.04322\sigma_{2z} - 0.01687\sigma_{2x} \\ & + 0.05608\sigma_{3z} + 0.10803\epsilon_{4z} \\ & + 0.18032\sigma_{5z} + 0.10226\epsilon_{5z} + \log(365/d_T)\end{aligned} \quad (6\text{-}4)$$

where:

N_{18} = the allowable 18-kip equivalent load applications

R = allowable rut depth, in.

ϵ_{1z} = vertical strain at bottom of the top layer $x10^4$, in/in

σ_{1z} = vertical stress at bottom of the top layer, psi

σ_{2z} = vertical stress (psi) at the bottom of the second layer, psi

σ_{2x} = horizontal stress, parallel to the axle load, at the bottom of the second layer, psi

σ_{3z} = vertical stress at the bottom of the third layer, psi

ϵ_{4z} = vertical strain at the bottom of the fourth layer, $x10^4$, in/in

σ_{5z} = vertical stress at the top of the fifth (subgrade) layer, psi

ϵ_{5z} = vertical strain at the top of fifth (subgrade) layer $x10^4$, in/in

d_T = number of days per year when average daily temperature is equal to greater than 64°F (should be a five year average)

The sign convention used is positive for tension and negative for compression. In a pavement system, vertical stresses and strains are compressive.

When using the equation, a five layer pavement analysis must be used where the first layer is the proposed overlay, the second layer is the existing surface layer, the third and fourth layers are the granular base and subbase, and the fifth layer is the subgrade. If either the base or subbase layer is not present, then the granular layer which is present is divided into two layers of equal thickness.

An 18-kip single axle is used in the analysis of the stresses and strains. The stresses and strains are analyzed both under and between the dual tires. The maximum value of the stress or strain is then used in the equation. Depending upon the geometry of the pavement, the maximum value can occur either under a tire or between the tires. Also an allowable rut depth must be selected.

6.1.1.4 Remaining Life Estimation and Overlay Design

Remaining life can be determined for an uncracked pavement. This requires an estimation of the amount of traffic, in terms of 18-kip single axle loads applied to date, and the tensile strain(s) on the underside of the asphalt-bound layer.

Mixed traffic is converted to repetitions of the 18-kip single axle using AASHTO equivalency factors. Tensile strains can be computed using ELSYM computer program with the knowledge of modulus values and Poisson's ratios for the various layers. The total number of load repetitions (N_{18}) can be estimated using equation (6-3). The remaining life is then calculated using the cumulative damage hypothesis, i.e.,

$$\frac{n_r}{N_1} = 1 - \frac{n_D}{N_1} \tag{6-5}$$

where:

n_r = number of additional 18-kip single-axle loads can be carried at the computed strain level,

N_1 = allowable number of applications of 18-kip EAL's according to fatigue criteria, and

n_D = number of 18-kip EAL's applications to date.

If the value for n_r is less than the additional traffic to be carried, an overlay will be needed. Example overlay thickness design curves using this method are shown in Figure 6.5.

The above procedures have been combined into two computer programs termed DEFANL and OVLANL.

6.1.2 WSDOT Method

This mechanistic-based overlay design procedure was developed by the University of Washington (Mahoney, 1988) for the state of Washington (WSDOT). The concept for this method is illustrated in Figure 6.6.

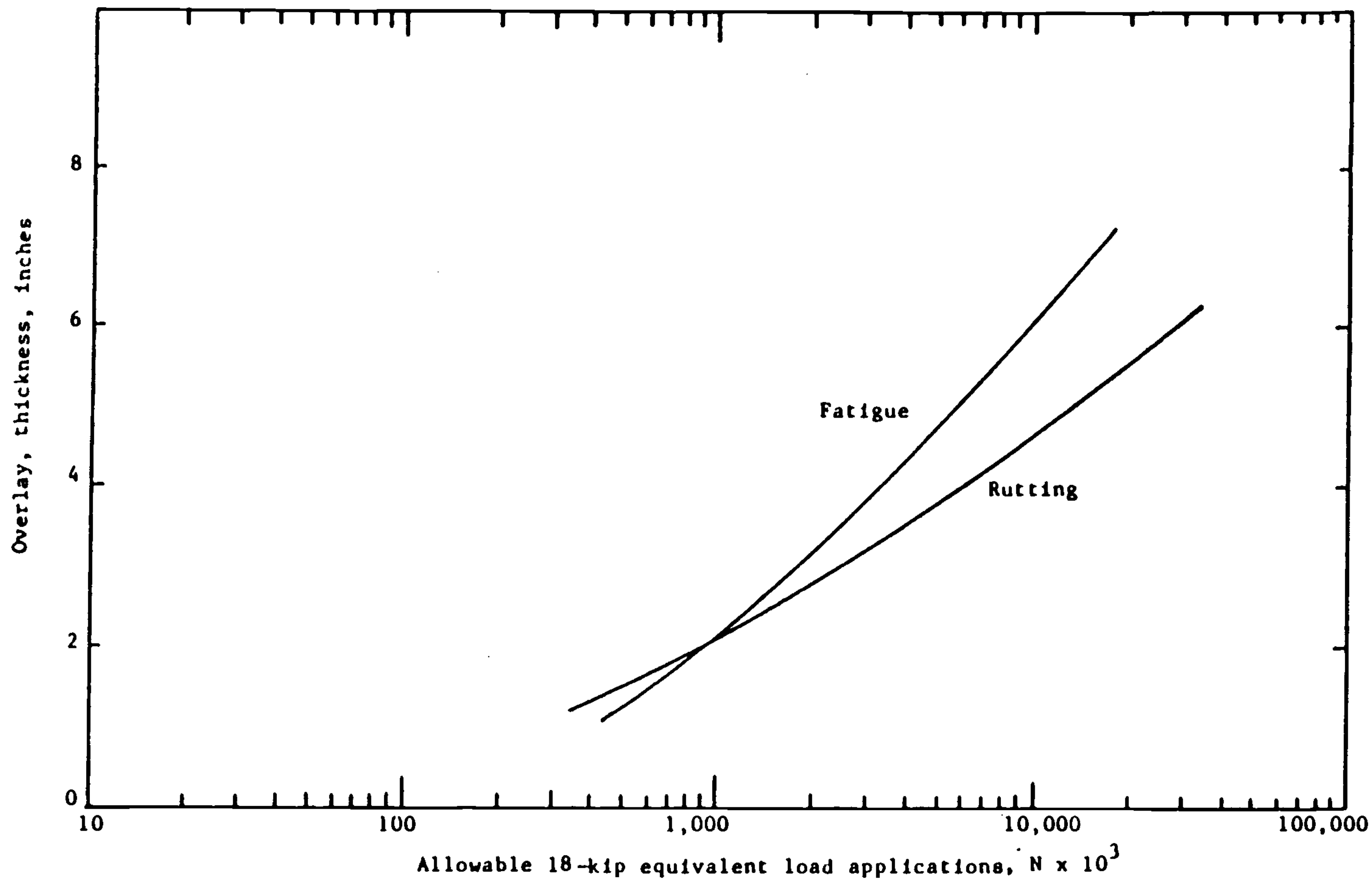


Figure 6.5 Sample Overlay Thickness Design Curves (ARE, 1975)

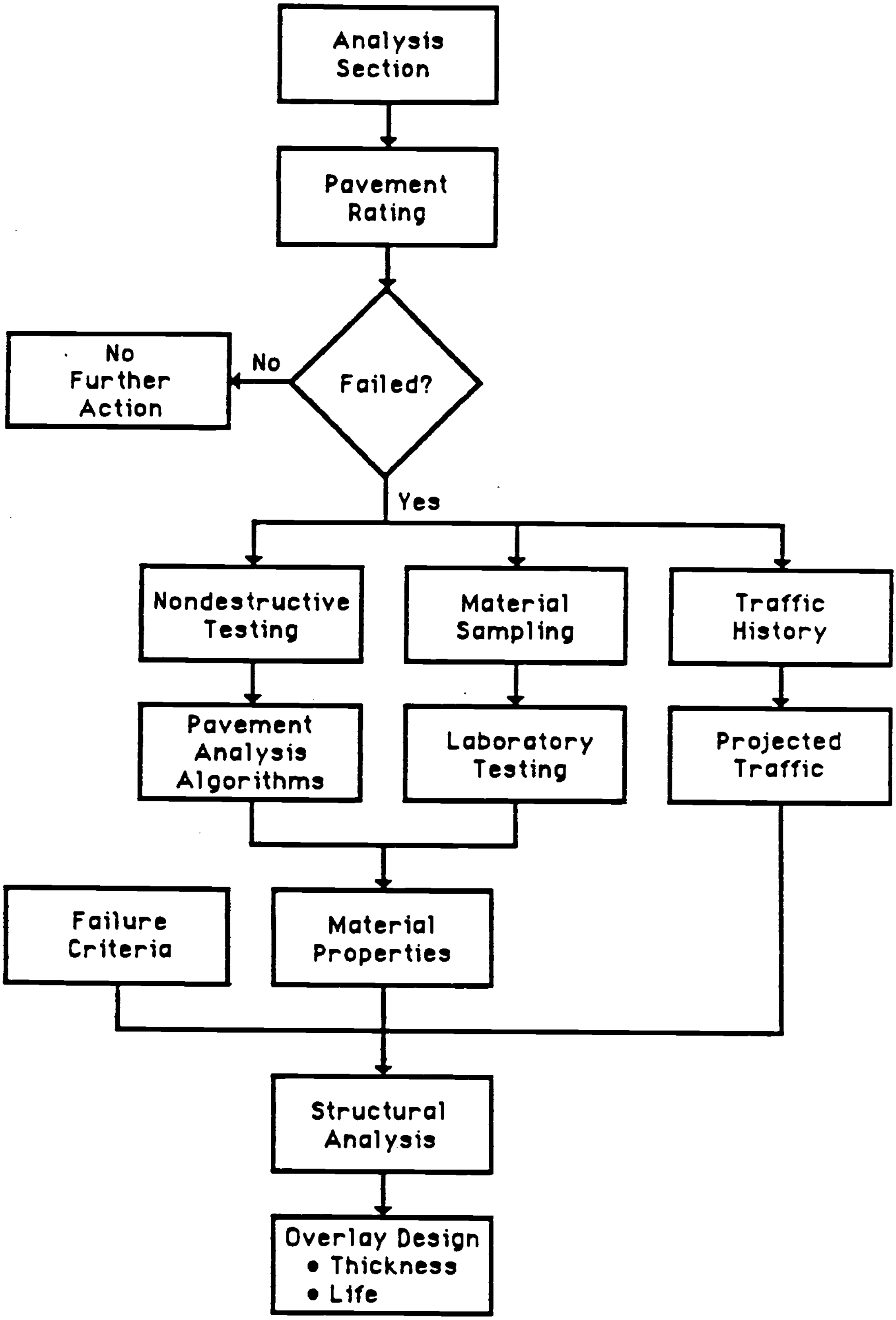


Figure 6.6 Pavement Overlay Design Concept (Mahoney, 1987)

6.1.2.1 Analysis Section and Pavement Rating

There is no description in the report how the pavement analysis section and pavement rating were carried out. However, it is believed that the pavement rating is conducted based on field condition survey information to classify the pavement serviceability. If the pavement rating for the analysis section is below acceptable level, further overlay design steps are recommended.

6.1.2.2 Nondestructive Testing and Pavement Analysis Algorithms

Nondestructive testing is performed through deflection measurements using falling weight deflectometer (FWD). The deflection were measured every 50 ft within each test site, with four load levels at each test stop and two drops at each load level. The load levels were approximately 6000, 9000, 12000, and 15000 lbs. There is no indication whether this is a standard practice. Evaluation of layer moduli is accomplished through backcalculation of pavement surface deflection basins. EVERCALC (Mahoney, 1987), a pavement analysis algorithm based on CHEVRON N-LAYER program and developed at the University of Washington, is used for backcalculating the layer moduli.

6.1.2.3 Material Sampling and Laboratory Testing

Material sampling and laboratory testing were used primarily to verify the backcalculation results. Material sampling also provide layer thickness information to be used in backcalculation. Extensive laboratory testings were performed on asphalt concrete, base course, and subgrade materials. These tests include resilient modulus tests, bulk and maximum specific gravity tests, asphalt extraction tests, asphalt recovery, aggregate gradation, Lottman conditioning tests, and asphalt penetration, and viscosity tests. Laboratory tests which are direct measures of the resilient modulus are diametral test (ASTM D4123) for asphalt bound material, and triaxial test (AASHTO T-274) for unbound materials.

6.1.2.4 Traffic History and Projected Traffic

Traffic volume is expressed in terms of 18-kip equivalent single axle loads (ESAL). AASHTO's load equivalent factor is used for mixed traffic. Traffic load information is accumulated in the format of the Federal Administration's W-4 loadometer tables, which include the number of axles observed with a series of category.

Design traffic volume is determined from average daily traffic (ADT), truck percentage, and the ESAL per truck for each road section. Both historical and projected traffic are used in the overlay design method.

6.1.2.5 Material Properties

Seasonal adjustments for the asphalt-bound materials are obtained using the relationship between the modulus and temperature. Seasonal variations for unbound material are determined using the ratios as given in Table 6.4. These ratios were developed using the backcalculated moduli from three years of FWD test data and climatic data (Mahoney, 1987).

For AC bound material, the relationship between the modulus and temperature for WSDOT class B AC, as shown in Figure 6.7, was used to determine the AC material properties. This relationship is expressed as follows:

Table 6.4 Coefficients for Seasonal Variations
(Mahoney, 1987)

Region	Base		Subgrade	
	Wet/Thaw	Dry/Other	Wet/Thaw	Dry/Other
Eastern Washington	0.65	1.00	0.95	1.00
Western Washington	0.80	1.00	0.90	1.00

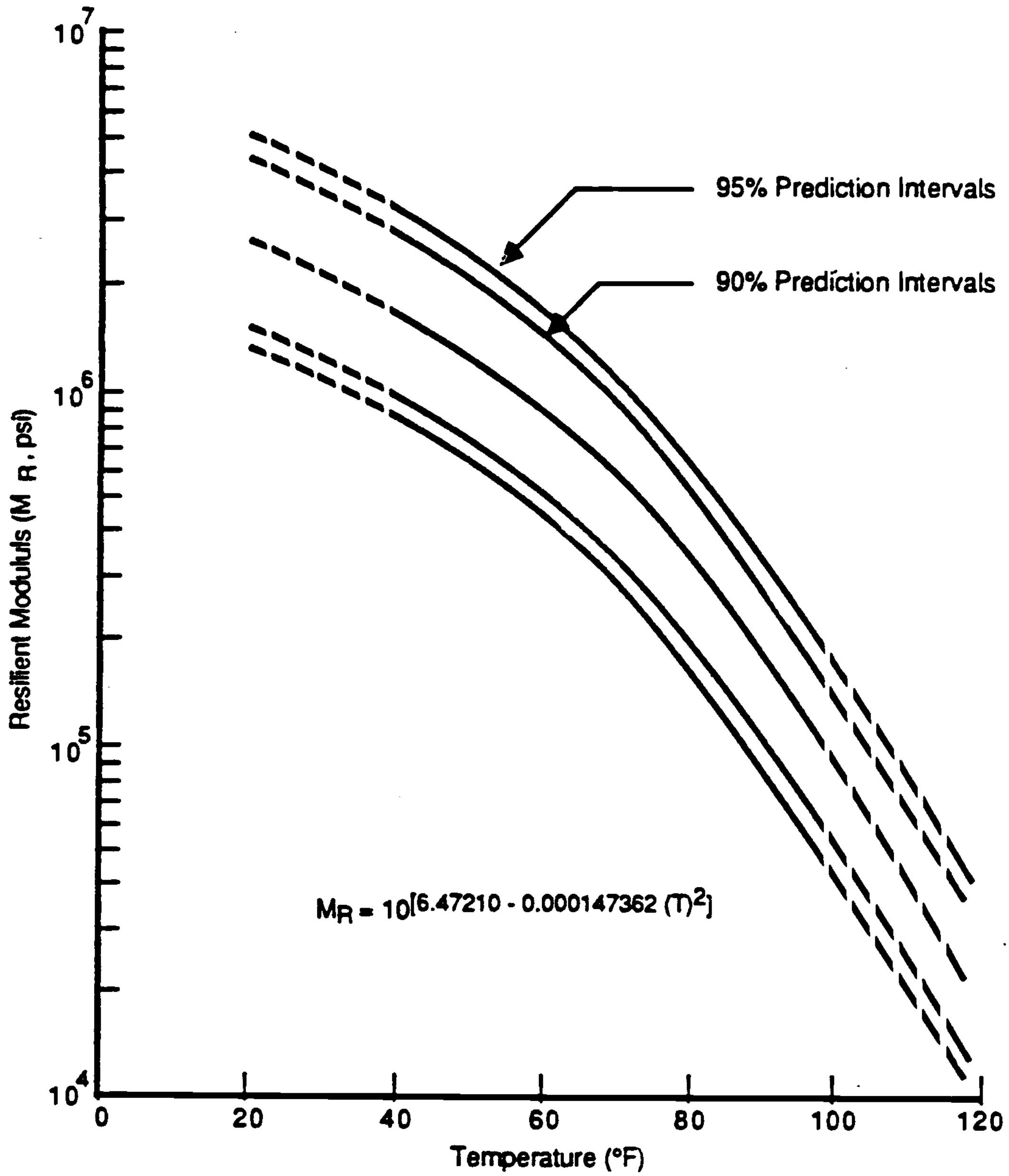


Figure 6.7 General Stiffness-Temperature Relationship with 90 and 95% Prediction Intervals for Class B Asphalt Concrete In Washington State (Bu-Bushait, 1985)

$$\log E_{ac} = 6.4721 - 0.000147362\ (T_p)2 \qquad (6\text{-}6)$$

where:

E_{ac} = resilient modulus of AC (psi), and

T_p = pavement temperature (°F).

The pavement temperature is estimated from Figure 6.8, knowing pavement surface temperature, the previous five-day mean air temperature, and pavement thickness.

For unbound materials, the following relationships are used:

$$E_{bs} = k_1\ \theta^{k_2} \qquad \text{for coarse-grained materials} \qquad (6\text{-}7)$$

$$M_R = k_3\ \sigma_d^{\ k_4} \qquad \text{for fine-grained materials} \qquad (6\text{-}8)$$

where:

E_{bs} = resilient modulus of coarse-grained materials and soils (psi),

M_R = Resilient modulus of fine-grained soil (psi),

θ = Bulk stresses (psi),

σ_d = Deviator stress (psi), and

k_1, k_2, k_3, k_4 = Regression coefficients.

6.1.2.6 Failure Criteria

The two pavement failure criteria used are fatigue cracking and subgrade rutting. Monismith's laboratory model (Monismith and Epps, 1969) is used for fatigue, as shown below:

$$\log N_f = 14.82 - 3.291 \log(\epsilon_t) - 0.854 \log(E_{ac}/1000) \qquad (6\text{-}9)$$

where:

N_f = loads to failure,

ϵ_t = initial tensile strain (10^{-6} in/in), and,

E_{ac} = modulus of asphalt-bound material (psi).

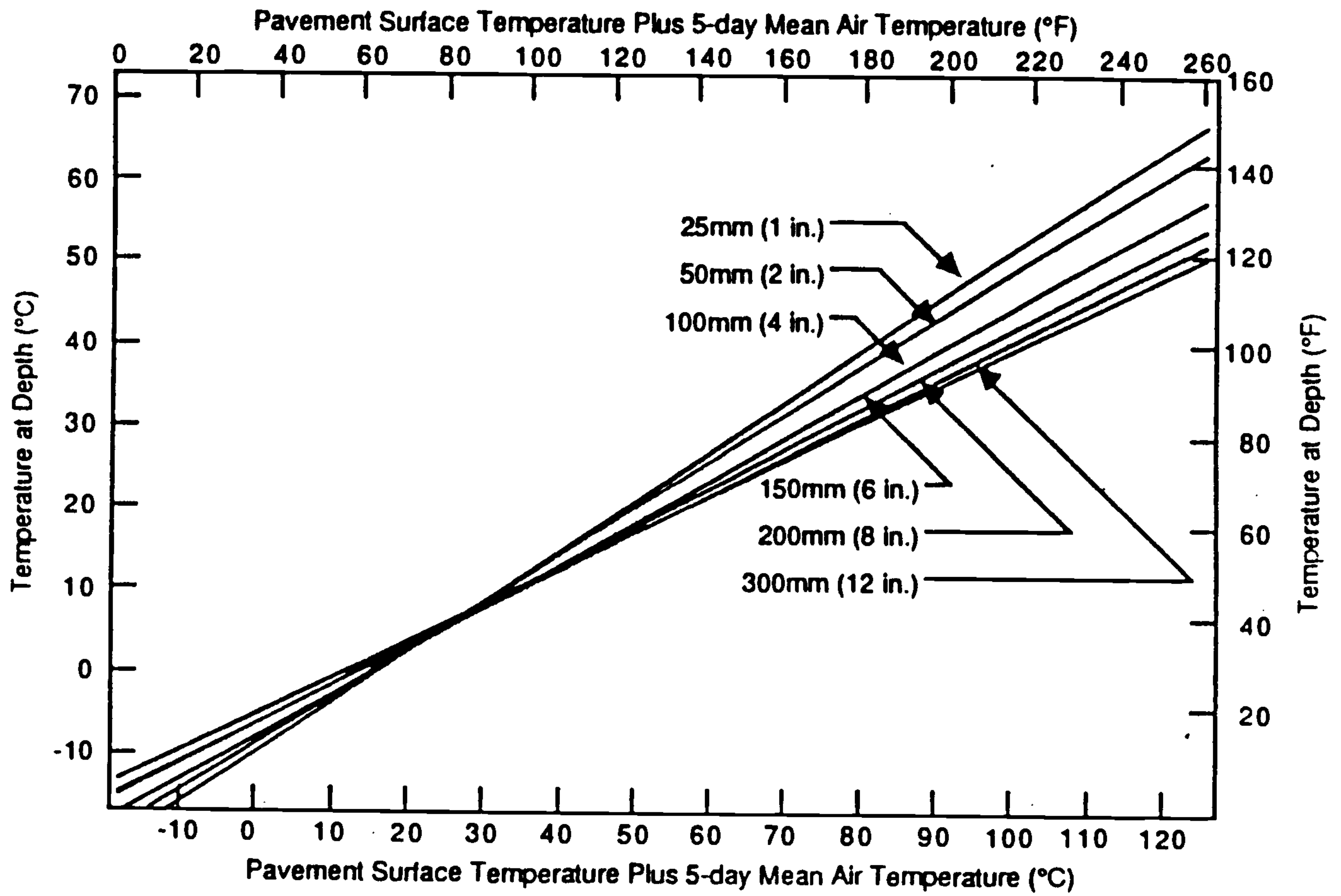


Figure 6.8 Estimation of Pavement Temperature (Southgate, 1975)

The laboratory model is adjusted to field conditions by multiplying a shift factor. For the state of Washington, a factor of 3 to 5 is used.

The Chevron equation (Santucci, 1977) was used to design for rutting. It is as follows:

$$N_r = 1.077 * 10^{18} * (\epsilon_v)^{-4.4843} \quad (6\text{-}10)$$

where:

N_r = number of loads needed to cause approximately a 0.75-inch deep rut,

ϵ_v = vertical compressive strain at the top of the subgrade (10^{-6} in/in).

6.1.2.7 Structural Analysis

Structural analysis is based on a multilayered linear elastic model. The CHEVRON N-LAYER, which was developed by the Chevron Research Company (Michelow, 1963), is used for pavement structural analysis.

6.1.2.8 Overlay Design

Overlay design is conducted using a computer program EVERPAVE (Mahoney, 1987) which is based on multilayered elastic analysis and the design criteria for fatigue and rutting failure. A flowchart of this program is shown in Figure 6.9. The input data include design traffic volume, seasonal variations of material properties, temperature, the shift factor for fatigue failure, the minimum overlay thickness, thickness increment, and unbound material properties, which include coefficients k_1, k_2, k_3, and k_4, as indicated in equations (6-7) and (6-8).

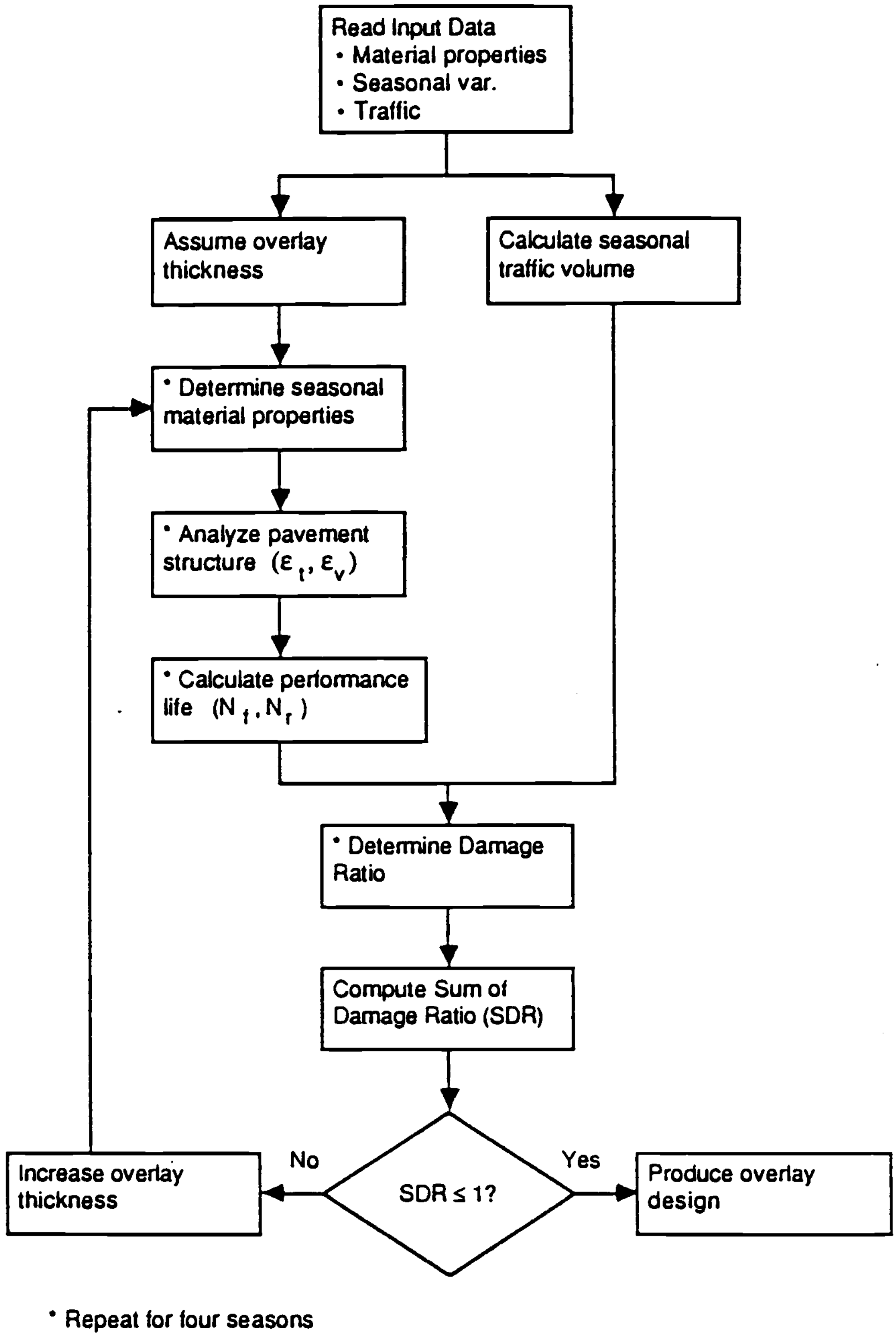


Figure 6.9 Overlay Design Procedure by EVERPAVE (Mahoney, 1988)

6.1.3 Alaska Method

This mechanistic overlay design procedure was developed by Oregon State University for the State of Alaska (Yapp et al, 1987). The original procedure include two approaches; one is a simplified mechanistic procedure and another is a fully mechanistic approach.

6.1.3.1 Simplified Procedure

The proposed simplified approach was developed by Fernando (1986) at Pennsylvania State University. A flowchart of this simplified mechanistic procedure is illustrated in Figure 6.10.

In using this procedure, once the critical analysis section has been determined, which is done by conducting condition survey and deflection test, design of the overlay can begin. The past and future traffic, together with the AC modulus, are needed to compute the tolerable pavement strains using appropriate fatigue and permanent deformation criteria. Remaining life of the existing pavement can then be determined. For overlay design, an overlay thickness is first assumed and tensile strain at the bottom of the existing asphalt layer and the compressive strain at the top of subgrade are calculated. The calculated overlay strains are then compared with the tolerable strains, which are determined based on a fatigue relationship developed by ARE (ARE, 1985) and a subgrade strain criterion developed by Luhr et al (1983). Iterative procedures are used to determine the final overlay thickness. Since the method was developed based on a regression analysis for conditions in Pennsylvania, it may not be valid for use in the state of Alaska.

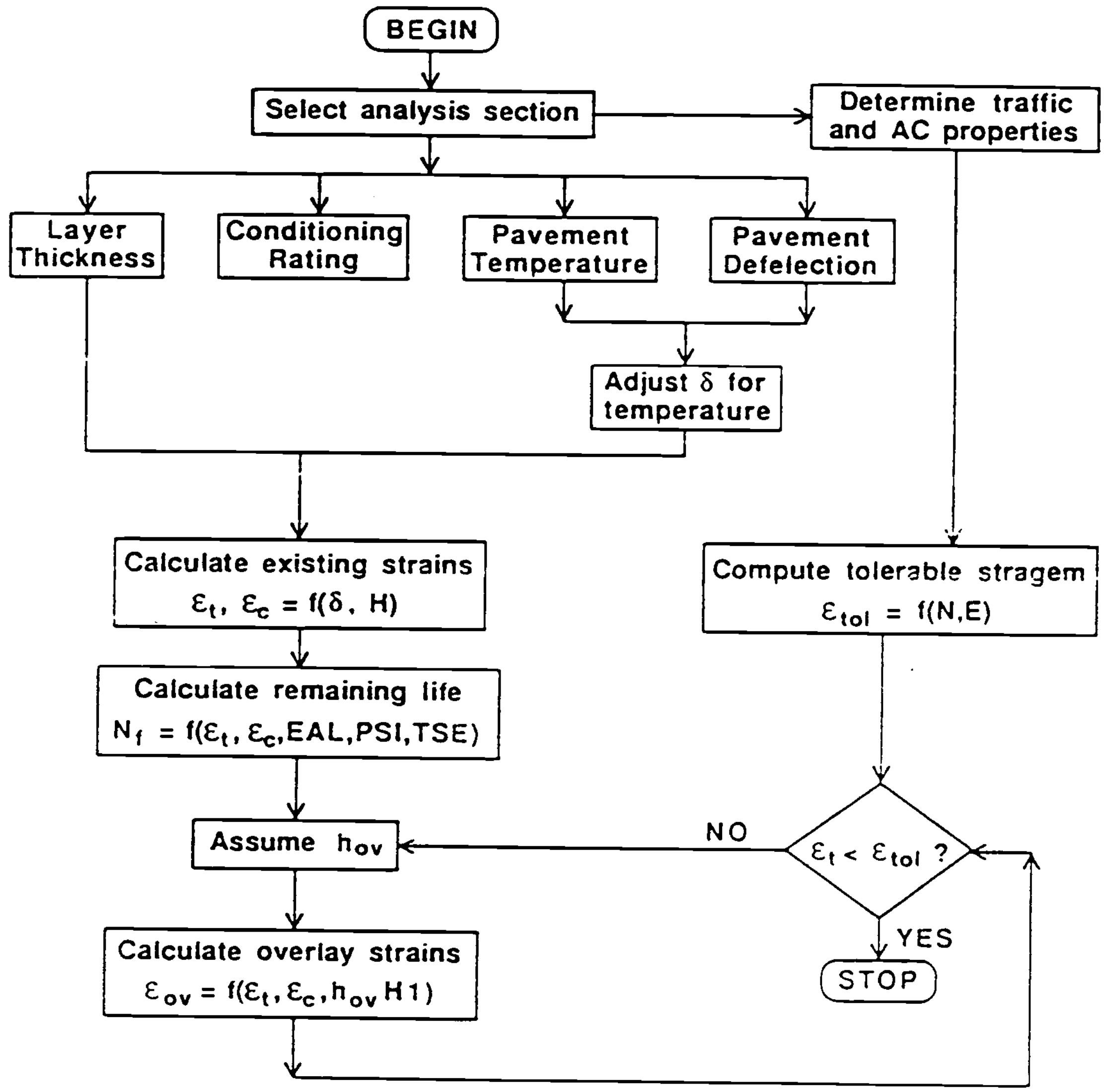


Figure 6.10 Flowchart for the Simplified mechanistic Procedure (Yapp, 1987)

6.1.3.2 Mechanistic Procedure

The proposed mechanistic overlay design procedure follows the flowchart developed by Finn (1984), as shown in Figure 6.1. The following discusses some of the main points.

6.1.3.2.1 Nondestructive Testing and Material Characterization

In the procedure, nondestructive pavement tests, condition survey, and traffic data are required as inputs. In addition, some knowledge of the stiffness properties and distress characteristics of various materials comprising the pavement structure are needed. Stiffness characteristics of the various pavement components can either be determined by test on undisturbed or disturbed specimens of the pavement materials, or backcalculated from NDT measurements.

Nondestructive testing is performed using the Dynatest FWD. For determining pavement properties from NDT test data, the programs ELSDEF, developed by Brent Rauhnt Engineers (Lytton, et al., 1986), and ELMOD, developed by Dynatest (Ullidtz, 1987), are used.

6.1.3.2.2 Distress Determinants

In this procedure, the ELSYM5 program is recommended to determine the critical strains in the pavement. The tensile strain at the bottom of the asphalt concrete layer is used to control fatigue while the compressive strain on the top of the subgrade is used to control rutting. Currently, the equations developed by the Asphalt Institute (The Asphalt Institute, 1982) are adopted as fatigue criteria. These equations are:

a) For fatigue:

$$N = 18.4 * C * 0.004325 * \epsilon_t^{-3.291} * E_{ac}^{-0.854} \quad (6\text{-}11)$$

where:

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

ϵ_t = horizontal tensile strain on underside of AC layer,

E_{ac} = modulus of AC layer, psi, and

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

$$C = 10^M$$

where:

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

V_b = volume of asphalt, %, and

V_v = volume of air voids, %.

b) For permanent deformation:

$$N = 1.36 * 10^{-9} * \epsilon_v^{-4.48} \qquad (6\text{-}12)$$

where:

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

For determining the tolerable strains, the equations (6-11) and (6-12) can be rearranged and ϵ_t and ϵ_v solved. In this procedure, these two strains are used in determining the required overlay thickness.

6.1.3.2.3 Remaining Life and Overlay Design

Cumulative historic traffic data are necessary to determine the remaining life of the existing pavement. The percentage of remaining life is determined using Miner's Hypothesis:

$$\frac{N_r}{N_D} = \frac{1 - N_A}{N_D} \qquad (6\text{-}13)$$

or

$$R_f = 1 - N_A / N_D$$

where:

$N_r/N_D = R_f$ = percentage of remaining life,

N_r = additional number of applications of EALs that can be applied to the existing pavement,

N_A = number of applications of EALs to date,

N_D = allowable number of applications of EALs according to fatigue relations.

If a negative R_f value occurs, it indicates that the life of the pavement has been used up and an overlay or reconstruction may be required.

The required overlay thickness for carrying anticipated traffic volume is a function of the remaining life, the reliability level desired, and design EALs. The reliability of a pavement design-performance process is defined as the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period (AASHTO,1986). The selection of reliability is based on functional class. In general, a higher reliability level would lead to a thicker overlay.

With a knowledge of the allowable traffic applications and pavement design life, the tolerable pavement strains can be determined using equations (6-11) and (6-12). If the calculated strains are greater than the tolerable ones, the overlay thickness needs to be increased. The determination of an overlay thickness involves re-iteration. The following procedures are followed:

1) Assumed an overlay thickness.
2) Use the ELSYM5 program to compute the pavement strains.
3) Determine tolerable strains for projected traffic.

4) Compare pavement strains with the tolerable strains.

5) If the pavement strains are greater than the tolerable strains, increase the overlay thickness and go to step 2.

The above procedure is repeated until the pavement strains are less than the tolerable ones, and the final overlay thickness is then recommended.

6.1.4 Summary of Review

Review of the three mechanistic design procedures indicates that one common ground for these developed procedures is that they all use multi-layered elastic theory to model a flexible pavement structure and to determine pavement life using various design criteria. This kind of approach is also being used by an on-going research activity, NCHRP project 1-26 (Thompson, 1989). It is expected that the next edition of the AASHTO Guide on Flexible Pavement Design will move in this direction.

One weak aspect in all three procedures is characterizing the seasonal effects on the pavement materials properties. In both the ARE and the Alaska methods, pavement properties at a representative temperature of 70°F is recommended for design purposes rather than those at different seasons. In the WSDOT method, seasonal variations are considered. However, for the base and subgrade materials, modulus ratios between the dry and wet materials are used rather than a direct consideration of the base and subgrade material properties for each season.

Since the seasonal effects have great influence on pavement layer properties (and some other factors such as traffic distribution), this results in varying pavement damage during the year. Therefore, an improved approach to address the seasonal effects seems to be necessary.

6.2 Development of an Improved Mechanistic Overlay Design Procedure

6.2.1 Framework

Figure 6.10 illustrates, in a flowchart format, an improved mechanistic overlay design procedure for flexible pavements. This improved procedure is based on the concept similar to that of Alaska method. The following sections describe some of the major points in more detail.

6.2.2 Condition Survey

The first step in the overlay design is to perform a condition survey. The purpose of the condition survey is to obtain information regarding the existing pavement condition. Condition surveys usually involve a fair amount of detail. They generally include not only the type of distress that has occurred, but also its severity, its extent, and the location (Haas and Hudson, 1982). Typically, for flexible pavements, the pavement condition survey includes rutting, alligator cracking, longitudinal cracking, transverse cracking, block cracking, bleeding, ravelling, potholes, patches, and punchouts. The condition survey results may provide very important information in estimating qualitatively the structural capacity of the existing pavements.

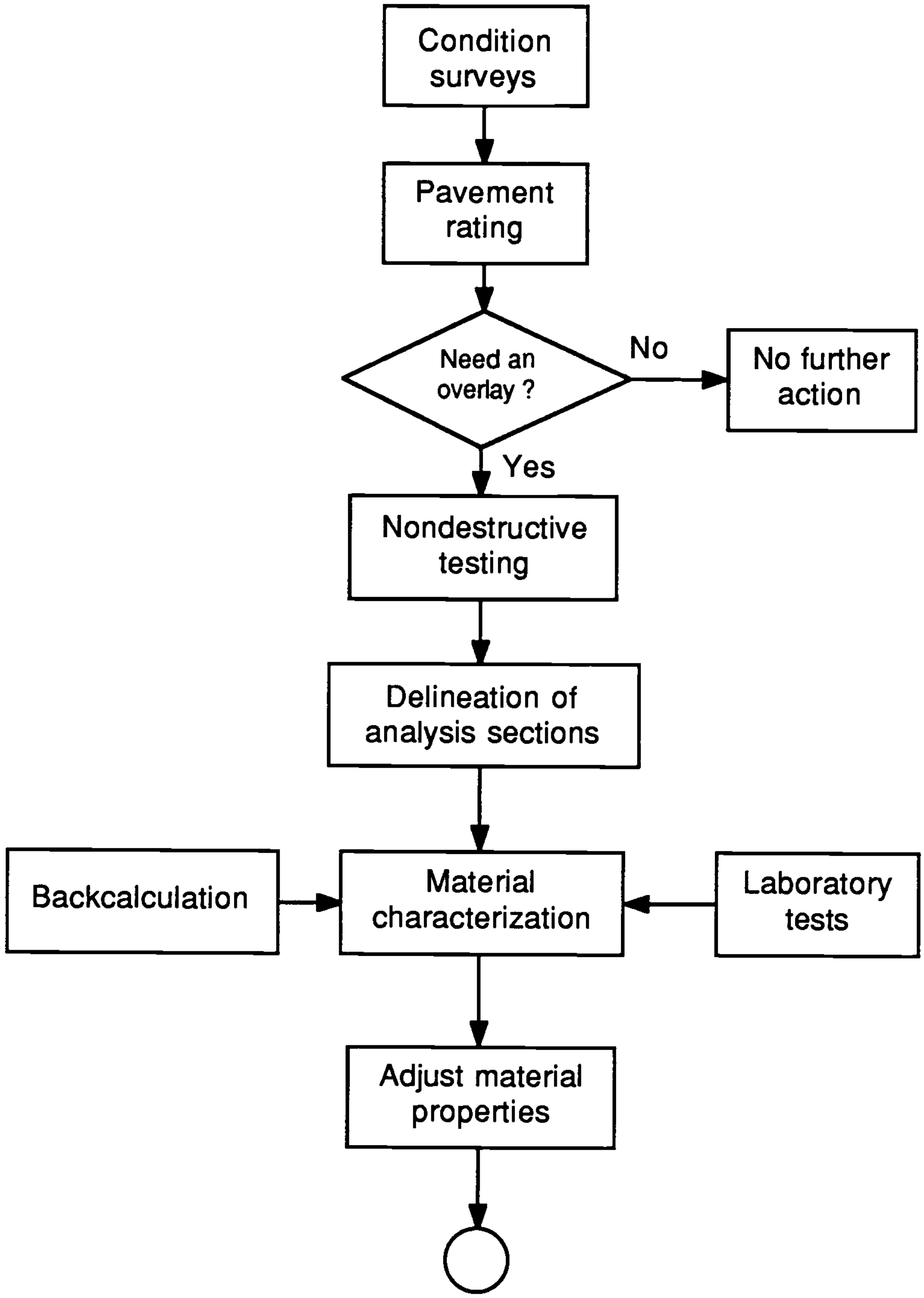


Figure 6.11 Flowchart for the Improved Overlay Design Approach

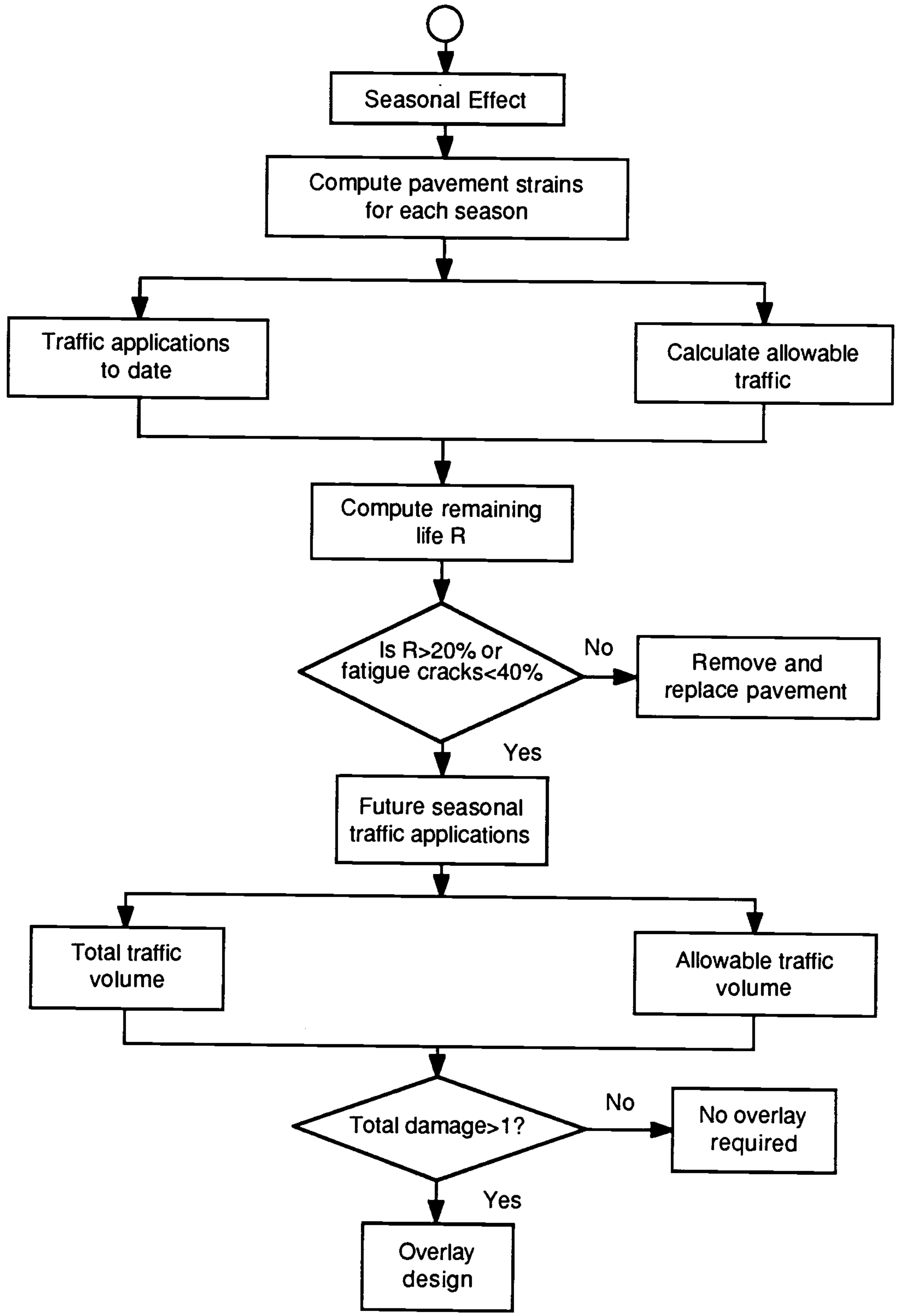


Figure 6.11 Flowchart for the Improved Overlay Design Approach (cont.)

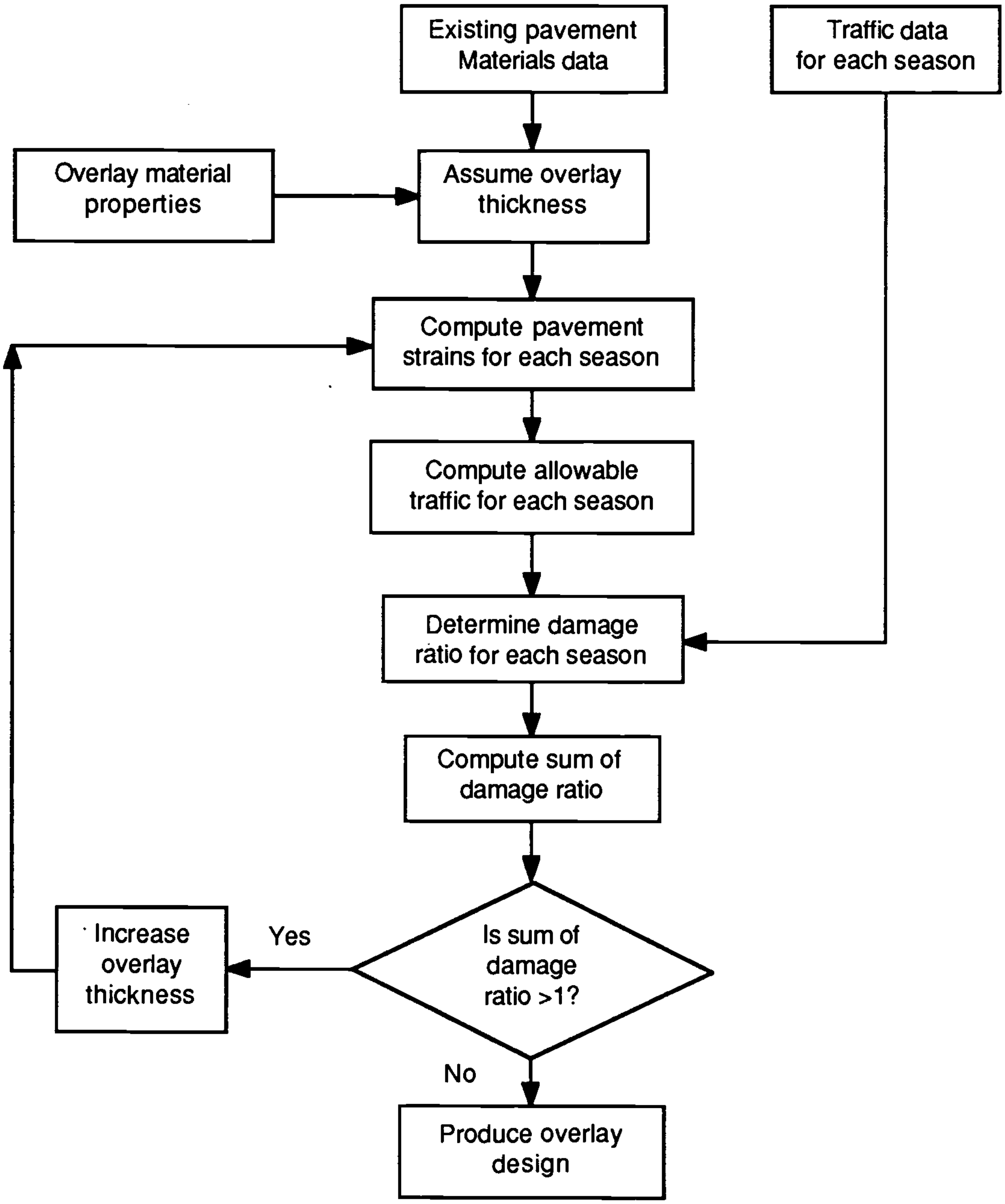


Figure 6.11 Flowchart for the Improved Overlay Design Approach (cont.)

6.2.3 Nondestructive Testing

The second step is to perform nondestructive testing. The nondestructive testing should be conducted using a falling weight deflectometer (FWD) since this device has the highest utility (Lytton, 1986) and may provide test results which are closer to a standard axle loading. Frequency of the measurements should be based on designers' requirement. Typically, the deflections should be measured at a space of 200 to 250 ft. In some cases, an interval of 50 ft may be specified.

6.2.4 Delineation of Analysis Section

With the use of the FWD, a large quantity of deflection data can be obtained. These data generally include description of the milepoint, test location, pavement temperature at time of testing, FWD load plate radius, load levels, sensor spaces, and deflection readings at corresponding sensor locations. In many cases, use of all the deflection test data to backcalculate material properties for a specific project is impractical, because it may require too much time for analyzing the data.

A better approach is to use statistical analysis to define delineation units so that pavement sections having similar response may be characterized by representative values. The cumulative differences technique, as recommended by AASHTO (1986), can be used for this purpose. The concept of the cumulative differences technique and a computer program which uses this technique for delineating analysis sections are presented in Appendix D.

6.2.5 Material Characterization

Materials characterization can be achieved through backcalculation using NDT deflection test data. The BOUSDEF program described in Chapter 4 is recommended for initial evaluation of the deflection data to determine moduli for each pavement layer. Laboratory tests should be performed on a limited scale and primarily used for verification purposes. The backcalculated and/or laboratory tested modulus should be carefully evaluated using engineering judgement or experience for the type of materials.

6.2.6 Consideration of Seasonal Effect

The major seasonal effects on pavement structures are temperature variation and moisture changes in the pavement layers. The strength and deformation properties of bituminous materials and bituminous mixtures are substantially influenced by temperature. The effect of temperatures on the dynamic modulus is illustrated in Figure 6.12. The stiffness of bituminous mixtures is also dependent on both temperature and time of loading as shown in Figure 6.13. In general, the seasonal effects on the resilient modulus of bituminous materials can be illustrated in Figure 6.14. As the temperature increases, the modulus value decreases. The higher the temperature, the lower the modulus would be. Therefore, the resilient modulus of the bituminous materials in summer is much lower than in winter.

Poisson's ratio of the asphalt concrete can also be affected by the temperature variation as illustrated in Figure 6.15. For mechanistic pavement analysis, typical values of Poisson's ratio in Table 3.1 may be used.

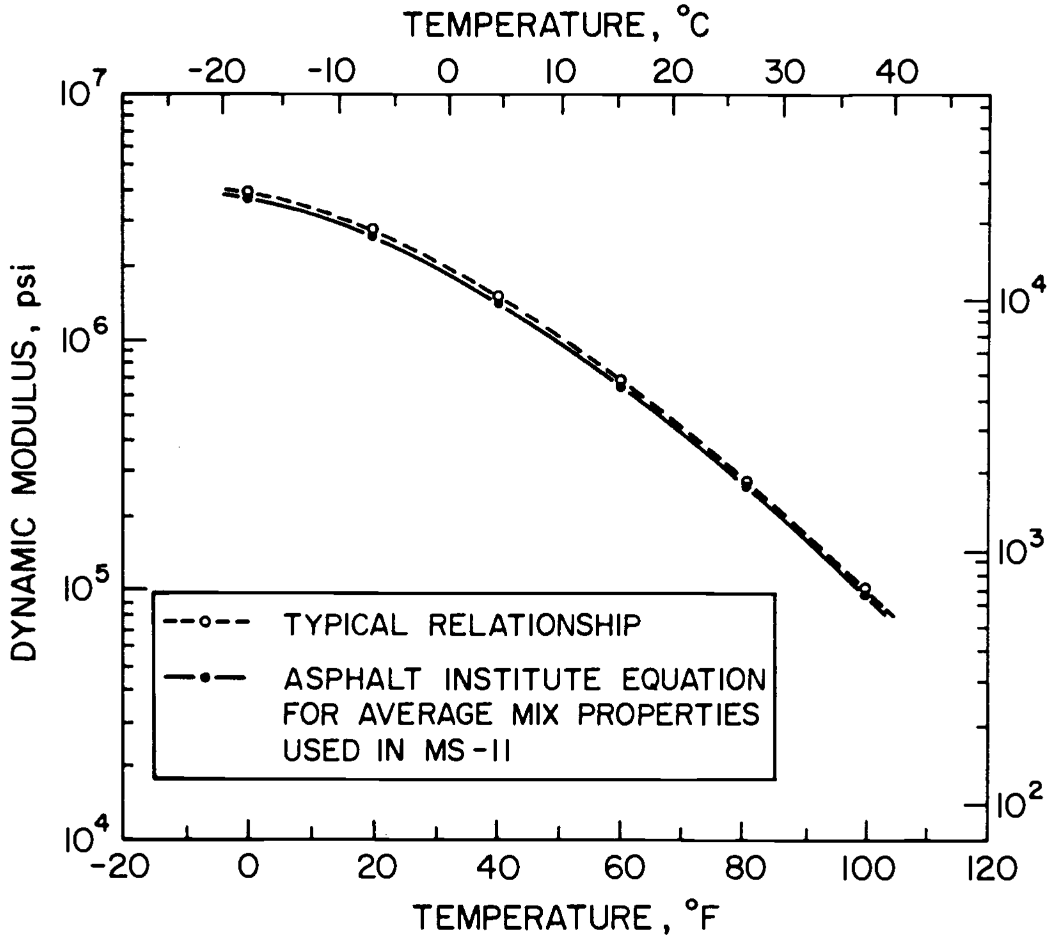


Figure 6.12 Comparison of MS-1 Prediction Equation to Modulus-Temperature Relationship Used in MS-11 (TAI, 1982)

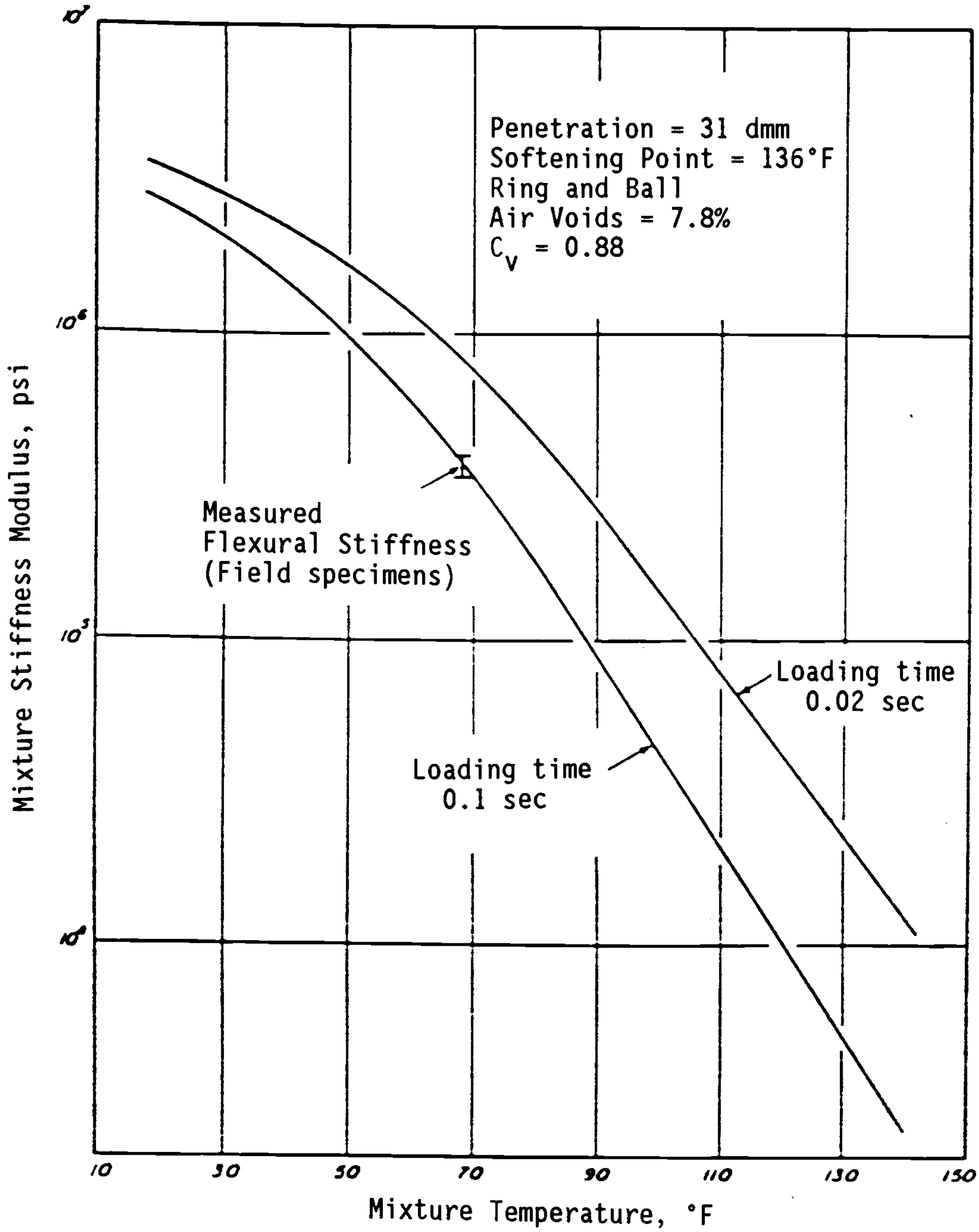


Figure 6.13 Computed Relations Between Mixture Stiffness and Temperature (Monismith, 1973)

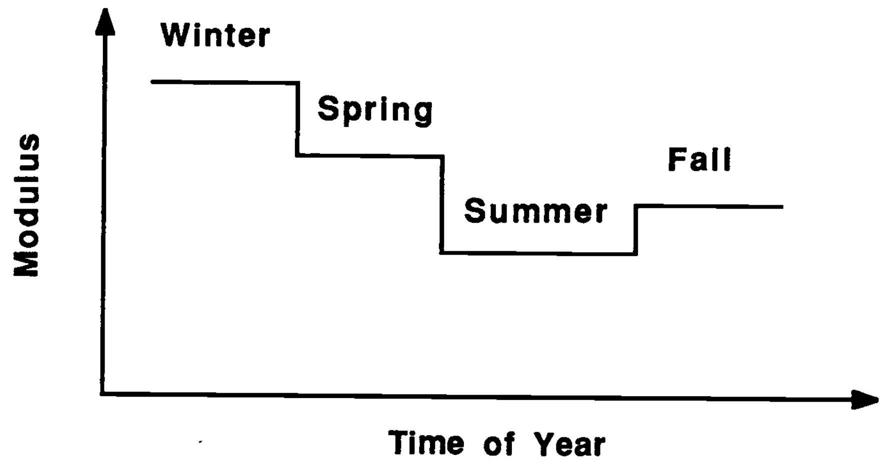


Figure 6.14 Seasonal Influence on Asphalt Concrete Layer Modulus (Hicks et al, 1988)

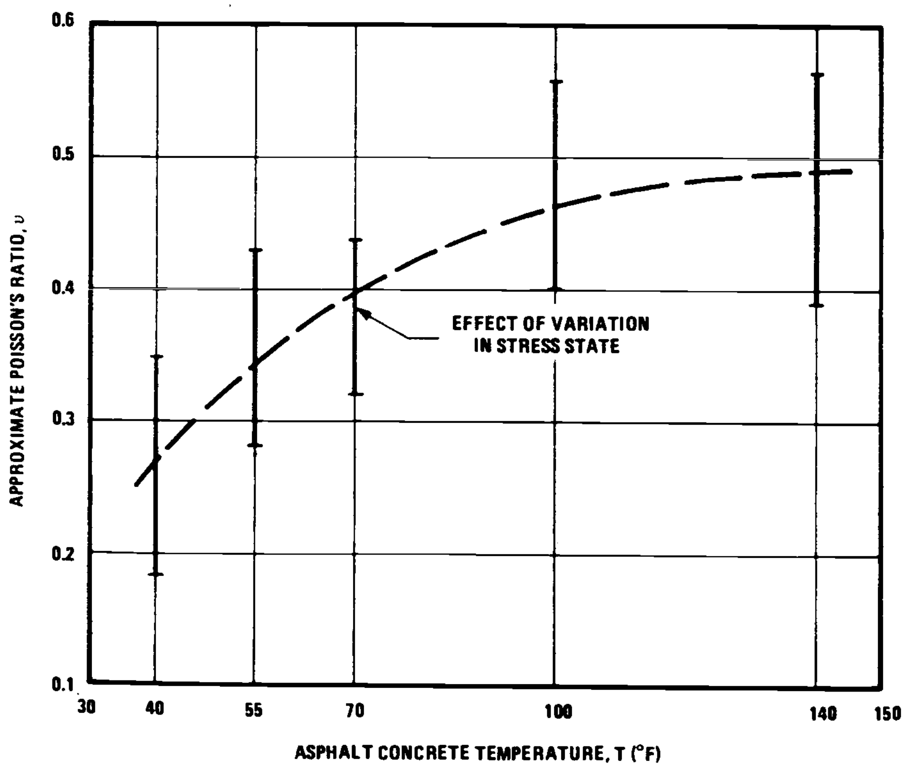


Figure 6.15 Temperature Influence on Poisson's Ratio (Barksdale and Hicks, 1973)

Water content is the major climatic factor influencing the strength and deformation properties of granular materials. As the degree of saturation increases, the resilient modulus decreases, as illustrated in Figure 6.16.

Moisture content also has a pronounced effect on the strength and deformation properties of subgrade materials. A general trend can be found in Figure 6.17. As the water content increases, the dry density of the subgrade soil would decrease. Consequently, the resilient modulus is also reduced.

It is expected that moisture content would vary during the year, and this would result in a variation of the subgrade modulus, as conceptually illustrated in Figure 6.18. In areas where freezing and thawing are expected, variation of the resilient modulus could be vary dramatic, as can be seen in Figure 6.19.

The above discussion addresses the importance of considering seasonal effects in pavement design and the various factors that have considerable impacts on pavement material properties. In the improved procedure, pavement material properties for each season are directly considered in terms of the pavement layer moduli, which as discussed above, are directly influenced by temperature and moisture content.

Traffic distribution may also vary with the season as illustrated in Figure 6.20. The varying traffic distribution may result in varying pavement damage within each season. Traffic applications (in terms of 18-kip EAL's) for each season are taken into consideration in the improved approach. This allows a better estimation of pavement damage occurred in each season of the year.

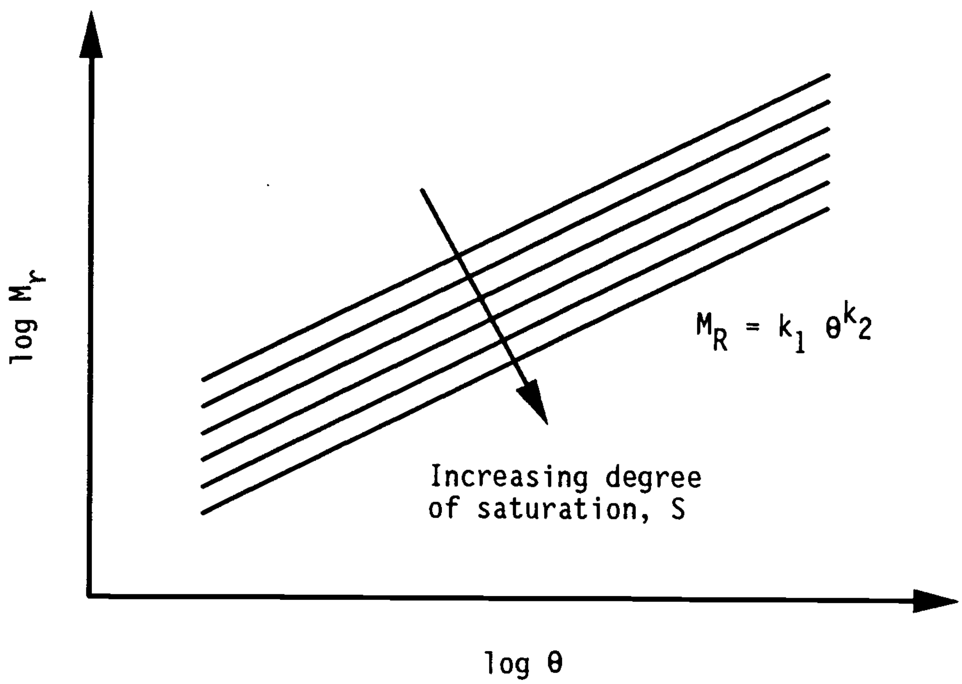


Figure 6.16 Influence of Degree of Saturation on Stiffness Characteristics of Untreated Granular Material (Monismith, 1989)

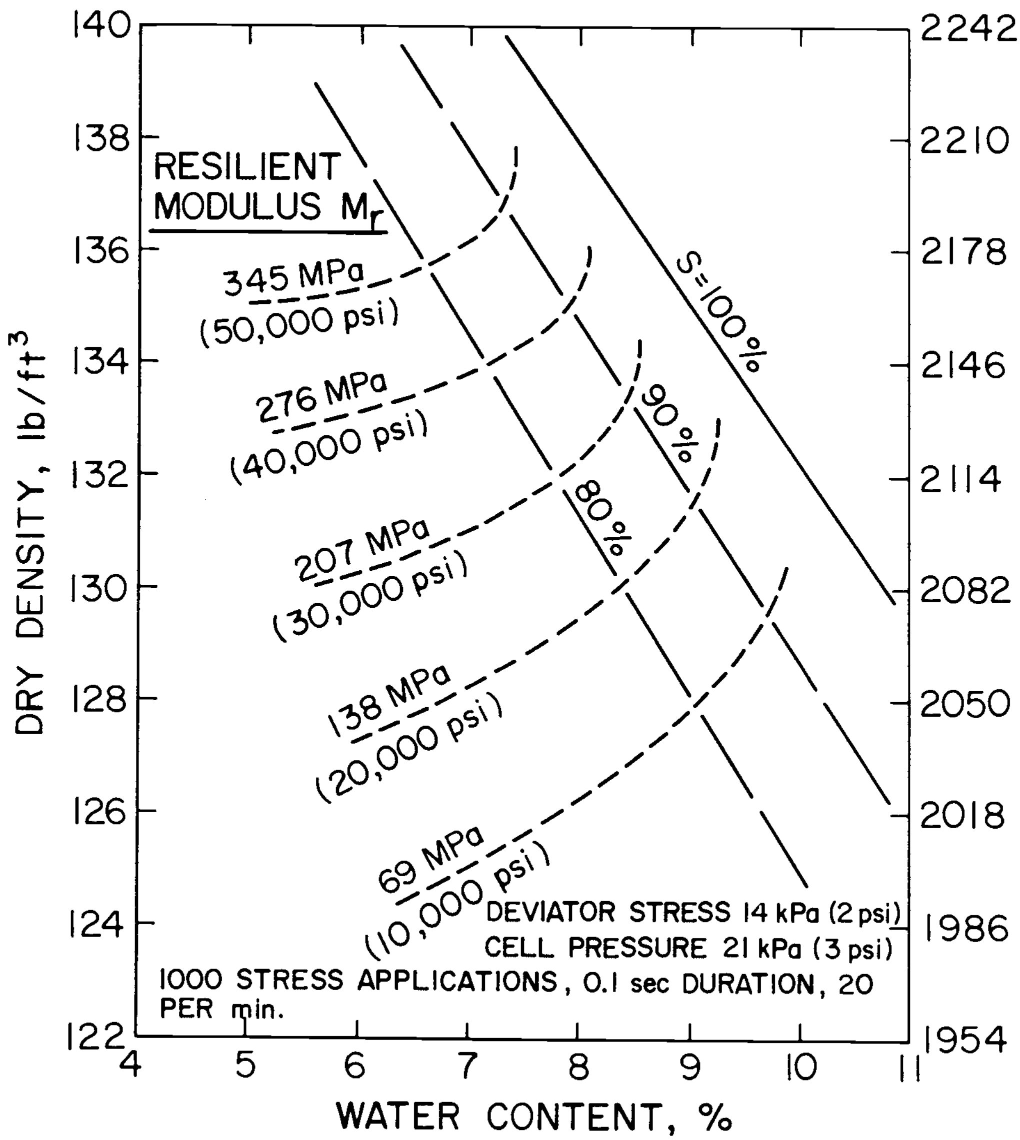


Figure 6.17 Water Content - Dry Density - Resilient Modulus Relationship for Subgrade Soil (Monismith, 1973)

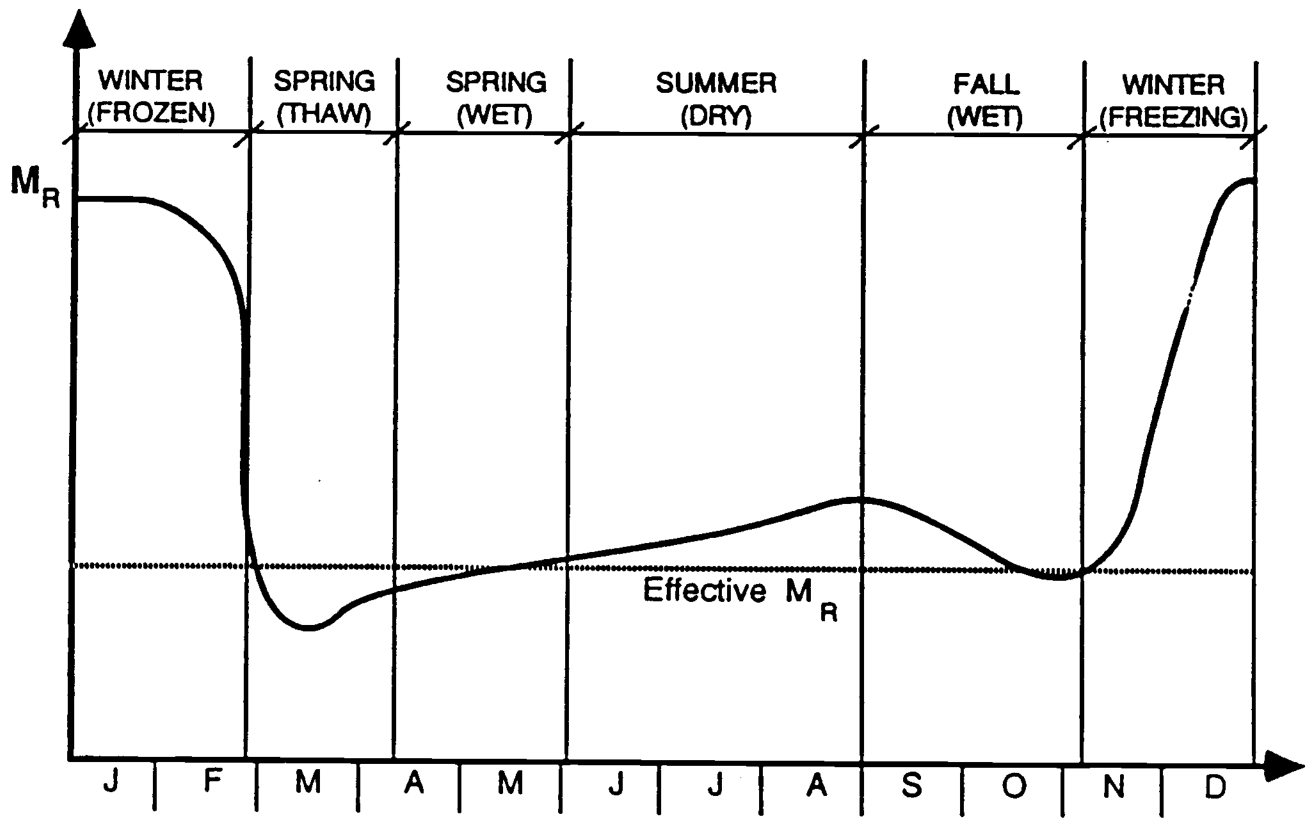


Figure 6.18 Concept of Seasonal Roadbed Soil Variation

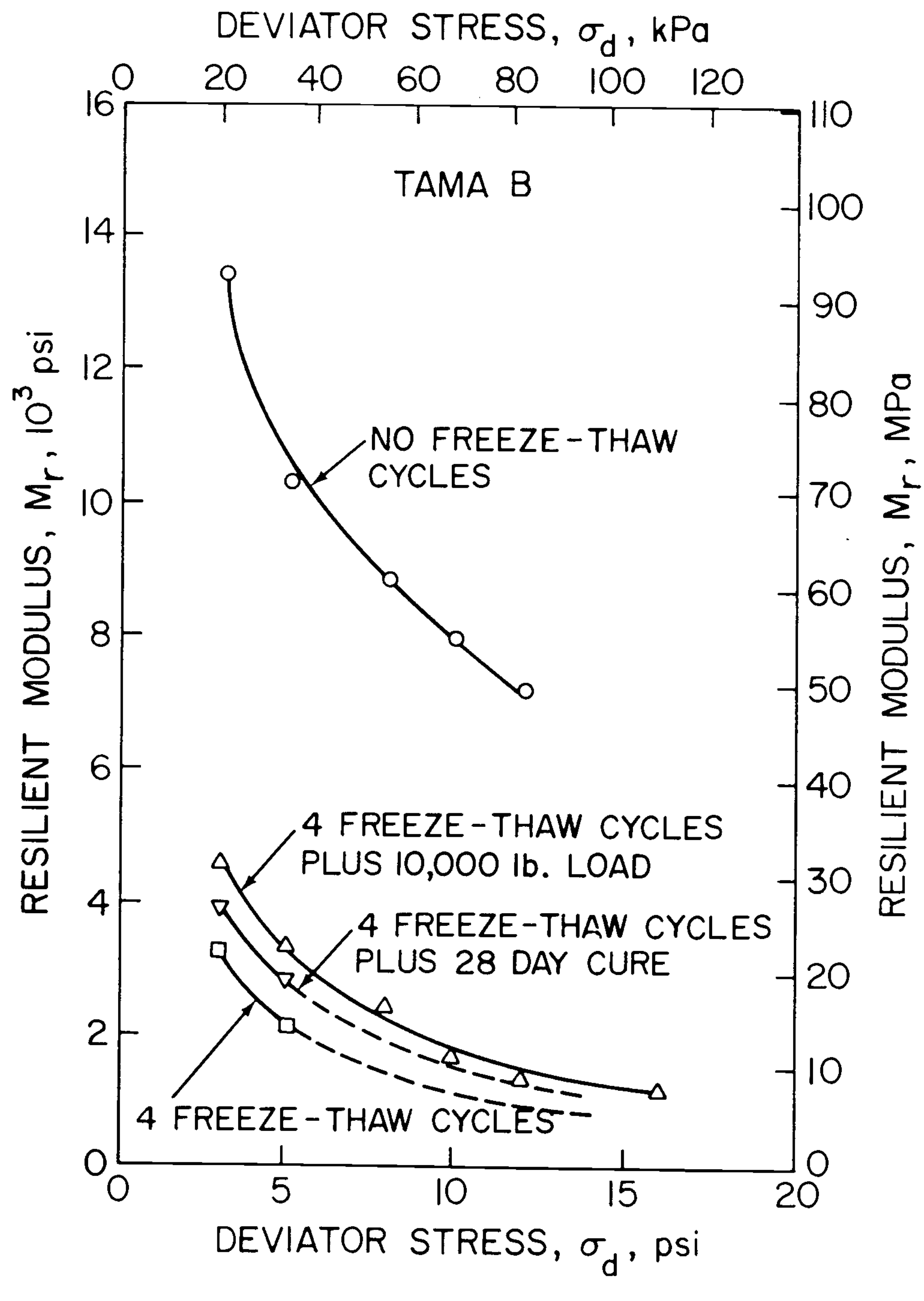


Figure 6.19 Effect of Freeze-Thaw, Additional Loading, and Additional Curing on Resilient Response of a Natural Tama B Soil (Monismith, 1989)

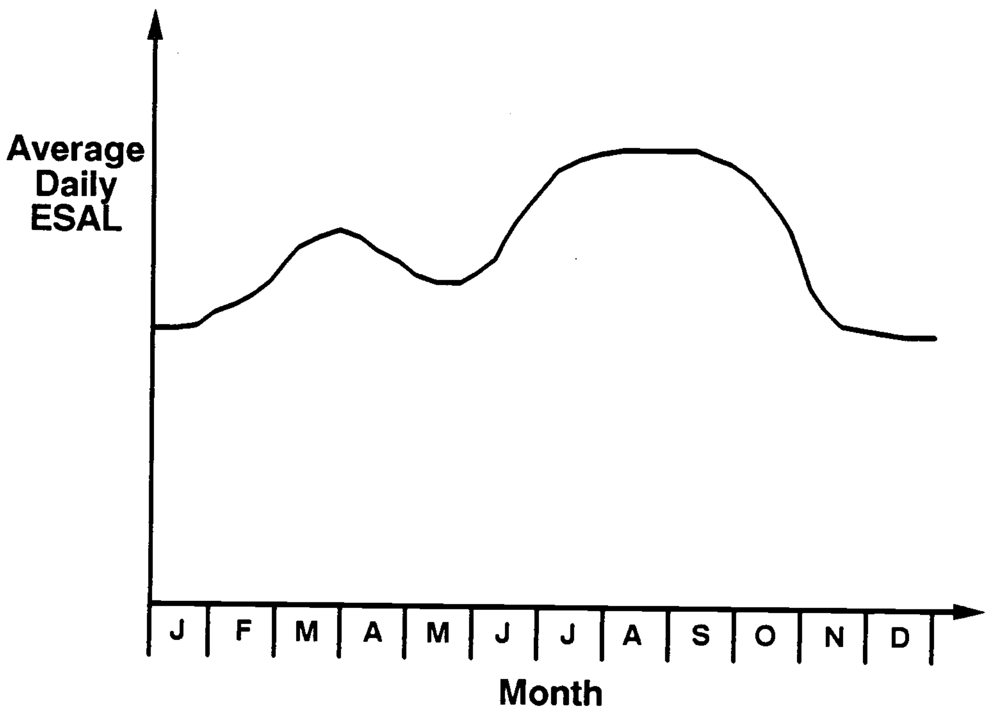


Figure 6.20 Concept of Seasonal Variation on Traffic Distribution

6.2.7 Critical Pavement Strains

Under traffic load, the pavement structure experiences stresses, strains, and deformations. For flexible pavements, it is generally accepted that two pavement strains are critical and used for design purposes (Figure 6.21): 1) the horizontal tensile strain on the underside of asphalt-bound layer, and 2) the vertical compressive strain on the top of the subgrade.

These two critical strains are considered to be associated with the major causes of pavement fatigue and rutting. If the horizontal tensile strain (ϵ_t) is excessive, fatigue cracking of the asphalt-bound layer will result. If the vertical compressive strain (ϵ_v) is excessive, rutting or permanent deformation will result at the surface of the pavement structure from overloading the subgrade. In the development of this improved procedure, a linear elastic layer computer program (ELSYM5) is modified and used as a subroutine for the determination of the critical strains. Rutting in the asphalt layer and/or in the base layer is not considered at present. Future improvement of the developed procedure will take this into consideration.

6.2.8 Determination of Allowable Traffic Repetition

6.2.8.1 Fatigue Evaluation

The most prevalent mode of distress in flexible pavements in the U.S. was reported to be fatigue cracking resulting from repeated traffic loads (Highway Research Board, 1973) and it is still believed to be the case. The fatigue properties of the pavements may be determined from 1) laboratory tests conducted directly on the asphalt

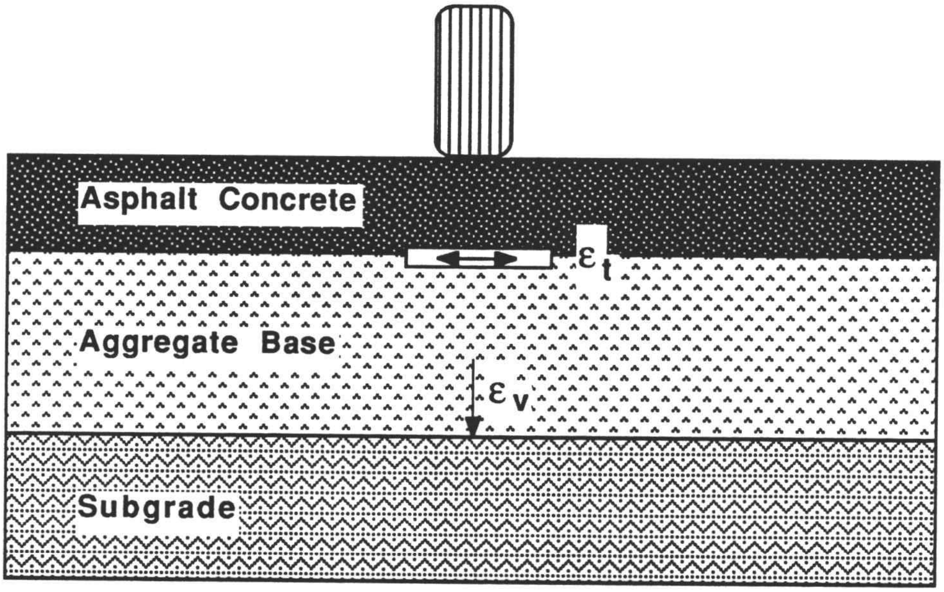


Figure 6.21 Location of the Critical Strains

concrete mixture under consideration, or 2) analysis of pavements in service compared with observed cracking. A very large amount of information has been published on such fatigue properties for various materials, test conditions, and test methods. The data are usually presented as plots of initial tensile strain, ϵ_t, versus log of number of load repetitions to failure, N_f.

Finn et al (Finn, 1973) summarized, in Figure 6.22, a set of fatigue curves for some California mixes. For cold climate conditions, Bergan and Pulles (1973) developed a group of curves by varying temperatures rather than the varying moduli, as shown in Figure 6.23. In general, the pavement fatigue performance can be expressed as a function of tensile strain and/or resilient modulus of the asphalt concrete as follows:

$$N_f = A\left(\frac{1}{\epsilon_t}\right)^b \left(\frac{1}{E_{ac}}\right)^c \qquad (6\text{-}14)$$

where:

N_f = number of load applications to failure,

ϵ_t = tensile strain on the underside of asphalt bound layer,

E_{ac} = modulus of asphalt bound material, and

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

If the resilient modulus is ignored, the relationship expressed in equation (6-14) may be rewritten as:

$$N_f = A\left(\frac{1}{\epsilon_t}\right)^b \qquad (6\text{-}15)$$

In the above equations, A, b, and/or c for a pavement design

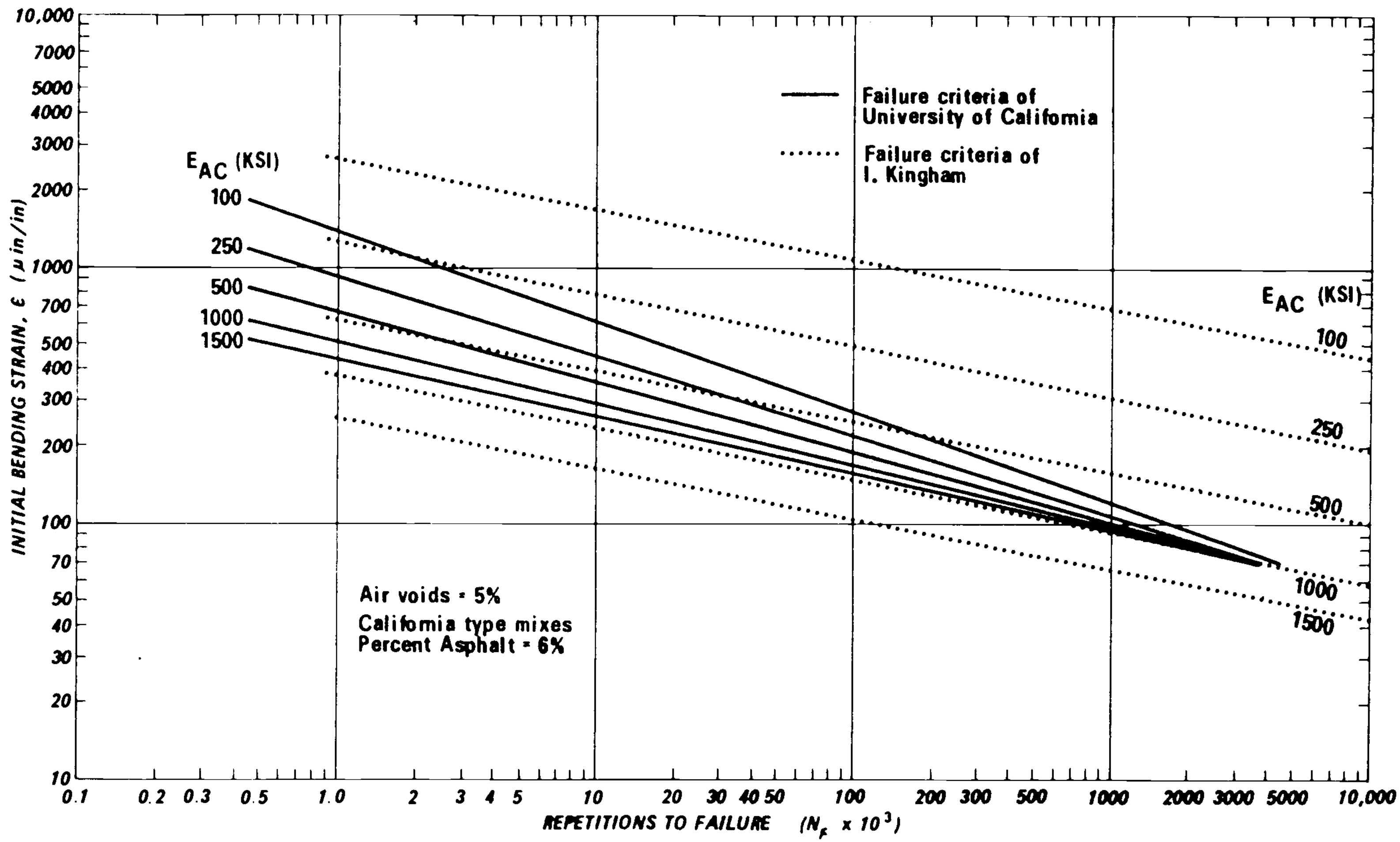


Figure 6.22 Fatigue Curves for Some California Mixes Using Different Failure Criteria (Finn et al, 1973)

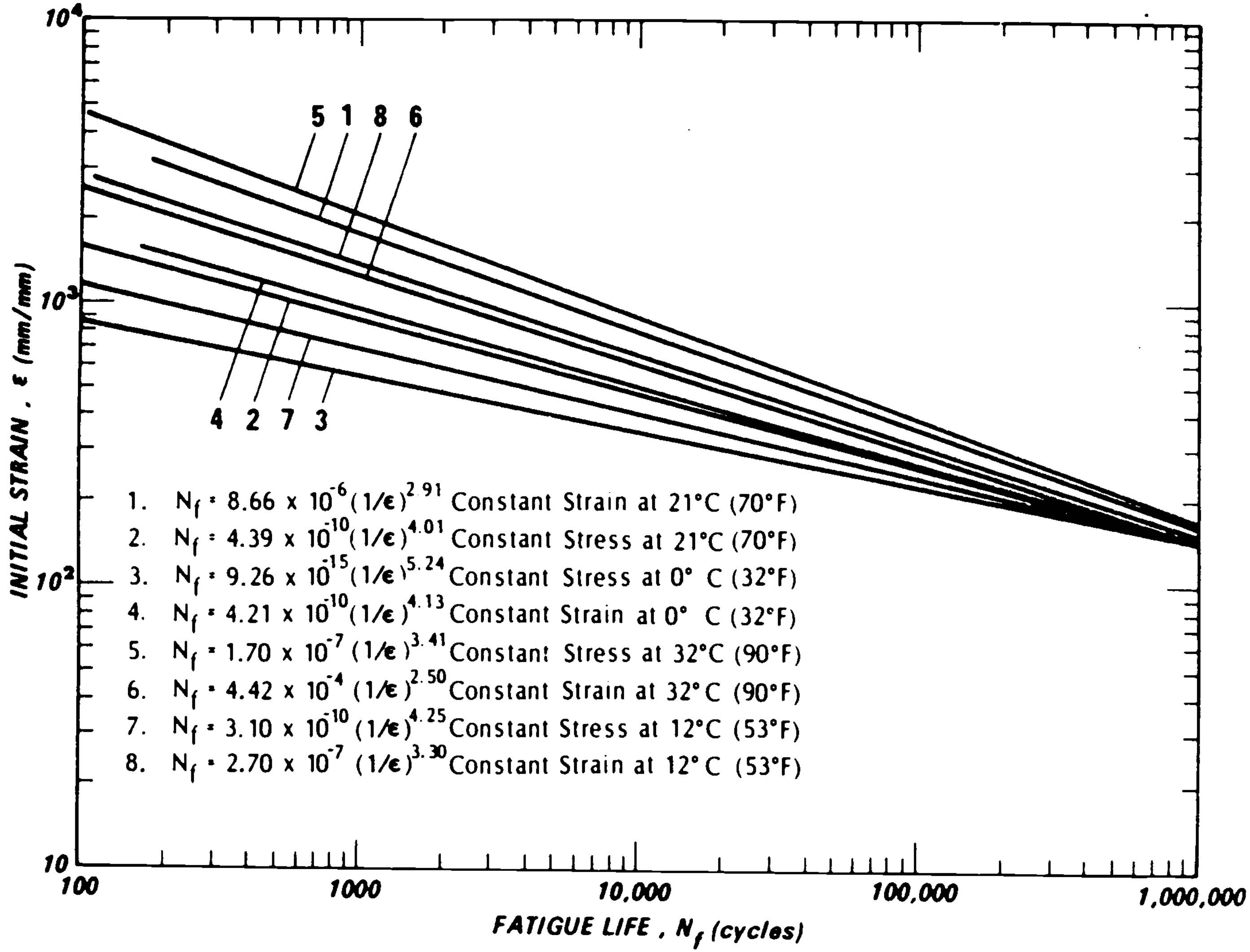


Figure 6.23 Fatigue Curves for Asphaltic Concrete
(Bergan and Pulles, 1973)

procedure are usually established based on laboratory fatigue tests and "field calibration" studies or "derived" by relating "structural model response data" to observed pavement performance. Quite a few of such asphalt concrete fatigue relations have been developed (Table 6.5), and the following describes some of the more important.

6.2.8.1.1 <u>The Asphalt Institute</u>

The fatigue equation used in the Asphalt Institute MS-1 thickness design manual (The Asphalt Institute, 1981) is based on previous work done by Finn et al in NCHRP Project 1-10B (Finn, 1986), and modified to reflect the effect of air void content and asphalt content based on laboratory determined fatigue data developed by Pell and Cooper (Pell, 1975), and Epps (Epps, 1968). The fatigue relationship is expressed by the following equation:

$$N = 18.4 * C * 0.004325 * \epsilon_t^{-3.291} * E_{ac}^{-0.854} \qquad (6\text{-}16)$$

where:

N	=	number of 18-kip equivalent single axle loads,
ϵ_t	=	horizontal tensile strain on underside of AC layer,
E_{ac}	=	modulus of AC layer, psi, and
C	=	a function of voids and volume of asphalt in the mix design, and can be determined by the following:

$$C = 10^M$$

where:

M	=	$4.84 * [V_b/(V_v+V_b) - 0.69]$
V_b	=	volume of asphalt, %, and
V_v	=	volume of air voids, %.

Table 6.5 Summary of Some Fatigue Criteria

Investigator	Fatigue Criteria	Reference
Asphalt Concrete		
AASHO Road test	$\text{Log } N_f(10\%) = 15.947 - 3.291 \text{ Log}(\epsilon/10^{-6}) - 0.854 \text{ Log}(E/10^3)$	Finn,1986
AASHO Road test	$\text{Log } N_f(45\%) = 16.086 - 3.291 \text{ Log}(\epsilon/10^{-6}) - 0.854 \text{ Log}(E/10^3)$	Finn,1986
FHWA-ARE	$N_f = 9.73 * 10^{-15} (\epsilon)^{-5.16}$	ARE, 1975
FHWA-RII	$N_f = 7.56 * 10^{-12} (\epsilon)^{-4.68}$	Majidzadeh and Ilves, 1980
Shell	$N = 4.91*10^{-13} (0.86 V_b + 1.08)^{0.5} (\epsilon)^5 * (E_{mix})^{-1.8}$	Shell,1978
Illinois	$N = 5 * 10^{-6} (\epsilon)^{-3.0}$	Thompson, 1987
TRRL	$N = 4.17*10^{-10} (\epsilon)^{-4.16}$	Powell, 1984
	$N = 1.66*10^{-10} (\epsilon)^{-4.32}$	
Emulsified Asphalt Mixes		
Santucci	$N_f = 13.31 - 3.7058 \text{ Log}(\epsilon/10^{-6}) - 0.6384 \text{ Log}(E/10^3)$	Santucci, 1977
Soil Cement		
Mitchell	$N_f = 30.91 - 13.874 \text{ Log}(\epsilon/10^{-6})$	Mitchell, 1974
Ullidtz	$N_f = 3.4*10^{-21} V_b^{5.62} \epsilon^{-5.62}$	Ullidtz, 1977

6.2.8.1.2 PDMAP - NCHRP Project 1-10B

The models used in the PDMAP program developed in NCHRP project 1-10B (Finn, 1986) are:

a) For 10% cracking

$$\text{Log } N = 15.947 - 3.291 \text{ Log}(\epsilon) - 0.854 \text{ Log}(E) \qquad (6\text{-}17)$$

b) For 45% cracking

$$\text{Log } N = 16.086 - 3.291 \text{ Log}(\epsilon) - 0.854 \text{ Log}(E) \qquad (6\text{-}18)$$

where:

ϵ = AC tensile strain, microstrain, and

E = AC modulus, ksi.

6.2.8.1.3 Illinois DOT and University of Illinois

The model used in the Illinois Department of Transportation thickness design procedure (Thompson, 1986) is a deflection-based fatigue algorithm for full-depth asphalt concrete pavements. For a typical Illinois DOT Class I AC, a dense-graded mixture, the fatigue equation is as follows:

$$N = 5*10^{-6}(1/\epsilon)^{3.0} \qquad (6\text{-}19)$$

The equation was developed based on consideration of mixture composition factors, split strength characteristics, and field calibration studies (Thompson, 1986).

6.2.8.1.4 SHELL Pavement Design Manual

The model used in the SHELL pavement design manual (SHELL, 1978) is expressed by the following relationship:

$$N = 4.91*10^{-13}(0.86V_b + 1.08)^{5.0}(1/\epsilon)^{5.0}(1/S_{mix})^{1.8} \qquad (6\text{-}20)$$

where:

V_b = volume of asphalt in the mix, in percent,

ϵ = maximum tensile asphalt concrete strain, in/in; and

S_{mix} = dynamic modulus of the asphalt mix, in ksi.

6.2.8.1.5 Nottingham

The fatigue model developed at the University of Nottingham has the following form:

$$\text{Log } N = 15.8 \text{ Log}(\epsilon_t) - 40.7 - (5.13 \text{ Log}(\epsilon_t) - 14.39) * \text{Log}(V_B) - (8.83 \text{ Log}(\epsilon_t) - 24.2) * \text{Log}(SP_i) \quad (6\text{-}21)$$

where:

ϵ_t = tensile strain in asphalt concrete,

V_B = volume of bitumen, and

SP_i = softening point of bitumen.

A plot of this equation may be found in Figure 6.24.

6.2.8.1.6 Transport and Road Research Laboratory (TRRL)

The AC fatigue cracking model developed by the TRRL was based on an analysis of the field performance of several experimental flexible pavements (Powell, 1984). For 85% probability of survival and an equivalent temperature at 68°F, the fatigue equation is as follows:

a) For dense bitumen Macadam roadbase

$$N = (4.17*10^{-10}) (1/\epsilon)^{4.16} \quad (6\text{-}22)$$

b) For rolled asphalt road base

$$N = (1.66*10^{-10}) (1/\epsilon)^{4.32} \quad (6\text{-}23)$$

6.2.8.1.7 Denmark

The fatigue model developed by Ullidtz (1977) has the following form:

$$N = (3.4*10^{21}) (V_b)^{5.62} (1/\epsilon)^{5.62} \quad (6\text{-}24)$$

where:

V_b = percentage of bitumen by volume.

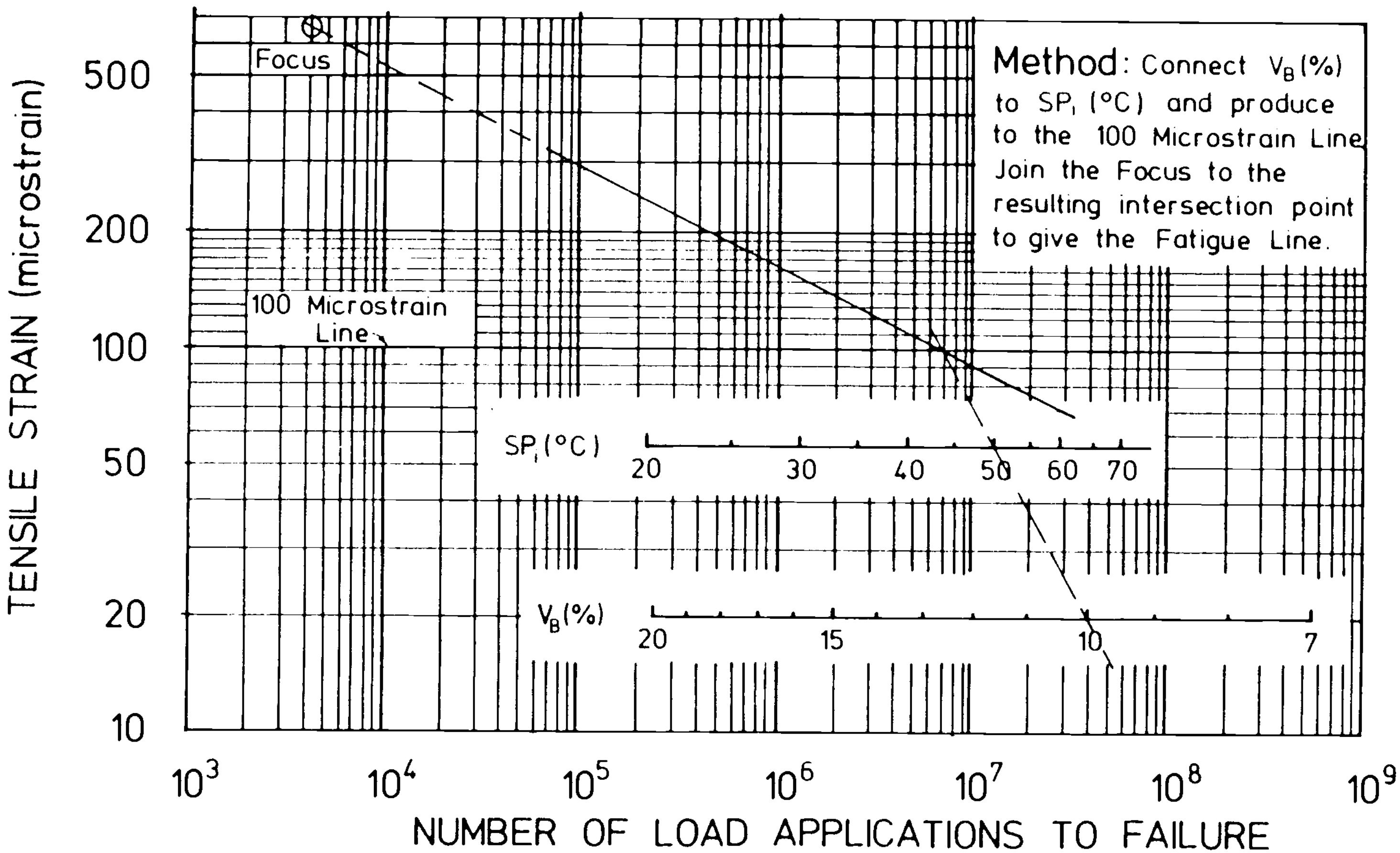


Figure 6.24 Fatigue Curves Developed by Nottingham (Brown, 1980)

6.2.8.1.8 BELGIAN Road Research Center

The fatigue model used in Belgium is expressed by the following equation:

$$N = (4.92*10^{-14})\ (1/\epsilon)^{4.76} \qquad (6\text{-}25)$$

6.2.8.2 Rutting Evaluation

Another major distress mode is the rutting or permanent deformation. Excessive rutting in highway pavements can accelerate other forms of structural deterioration and can create a safety hazard. With increasing magnitudes and repetitions of loads, the problem may become more severe.

One approach to preventing excessive rutting is to limit the vertical compressive strain on the subgrade. The compressive strain can be calculated by elastic layer theory. The allowable subgrade strain criteria are generally represented by a form which is similar to that of asphalt concrete:

$$N_f = c\left(\frac{1}{\epsilon_v}\right)^d \qquad (6\text{-}26)$$

where:

ϵ_v = vertical compressive strain on the top of subgrade,

c,d = parameters.

Table 6.6 presents some criteria developed by different agencies.

It does not appear feasible at this time to accurately predict AC rutting depth development, which may be contributed by a variate of factors such as construction variability, asphalt source, and gradation variability. A procedure which classifies the rutting

Table 6.6 Summary of Some Rutting Criteria

Method	Rutting Criteria	Rut Depth	Reference
The Asphalt Institute	$N = 1.365 * 10^{-9} \epsilon_v^{-4.477}$	0.5	TAI, 1982
Chevron	$N = 1.3379 * 10^{-9} \epsilon_v^{-4.4843}$		Santucci, 1977
Shell 50% Reliability	$N = 6.1466 * 10^{-7} \epsilon_v^{-4.0}$		Shell, 1978
85% Reliability	$N = 1.9448 * 10^{-7} \epsilon_v^{-4.0}$		
95% Reliability	$N = 1.0498 * 10^{-7} \epsilon_v^{-4.0}$		
Nottingham * & Mobil Design	$N = 1.1262 * 10^{-6} \epsilon_v^{-3.5714}$	0.8	Brown, 1984
Nottingham *	$N = 4.5256 * 10^{-8} \epsilon_v^{-3.7037}$	0.4	Brown, 1984
TRRL **	$N = 6.178 * 10^{-8} \epsilon_v^{-3.9527}$	0.4	Powell, 1984
Belgian Road Research Center	$N = 3.05 * 10^{-9} \epsilon_v^{-4.3478}$		Verstraeten, 1982

* For "Hot Rolled Asphalt" base. Increased strains are permitted for AC mixture that display "better resistance" to permanent deformation

** For 85% reliability design level

resistance of AC mixtures appears to be better suited for a pavement design process.

6.2.8.3 Criteria Used in the Improved Procedure

6.2.8.3.1 Fatigue Criterion

In the improved procedure, Finn's fatigue model (1986) is used. This model is expressed by the following relationship:

$$\log N = 16.086 - 3.291 \log (\epsilon_t) - 0.854 \log (E_{ac}) \qquad (6\text{-}27)$$

where:

N = load applications to failure,

ϵ_t = tensile strain on the underside of asphalt-bound layer, in μ-strain, and

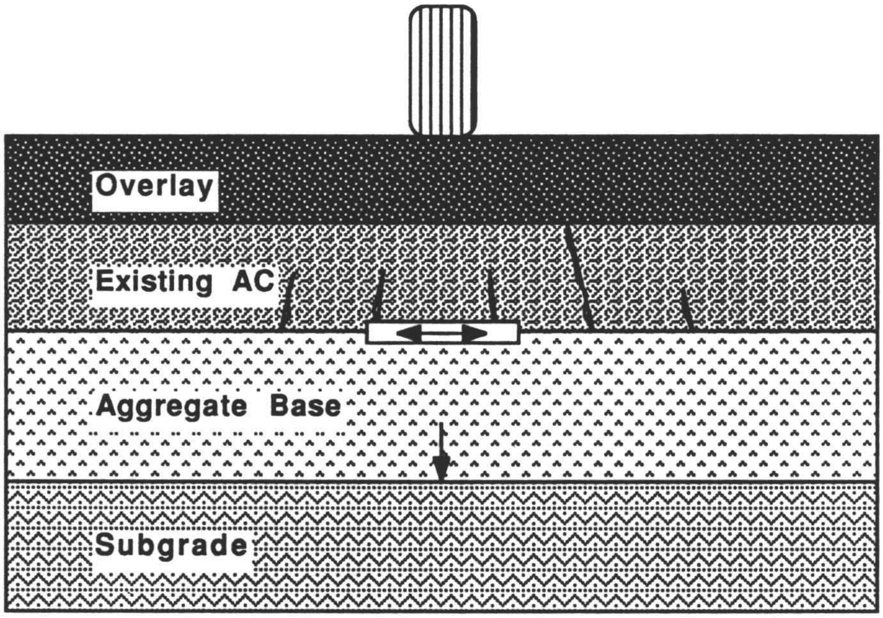
E_{ac} = stiffness modulus of asphalt-bound material, in ksi.

This particular relationship was obtained from laboratory fatigue data (Monismith et al., 1972) which had been adjusted to provide an indication of approximately 45 percent fatigue cracking (based on total pavement area) in selected sections of the AASHTO Road Test.

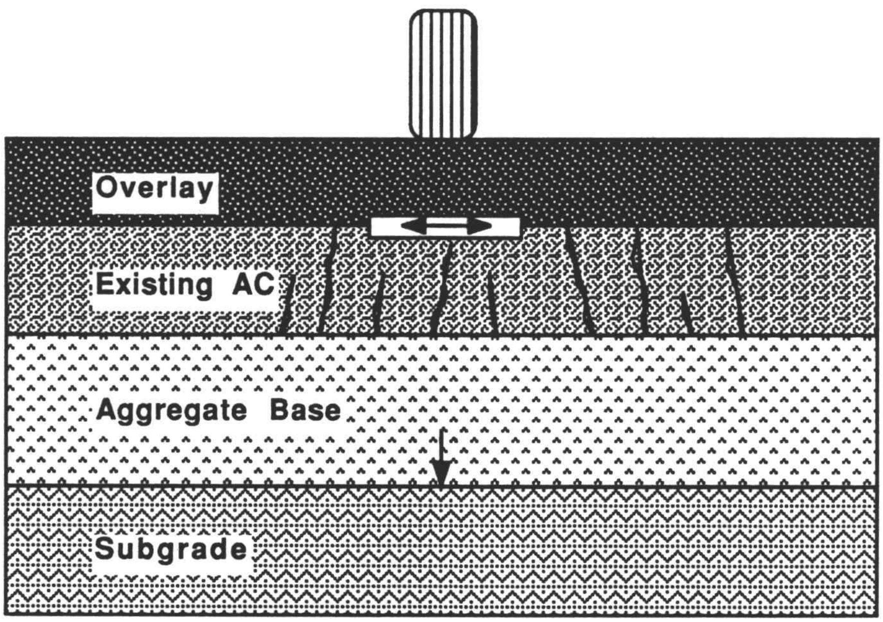
For the evaluation of fatigue performance, the critical tensile strain considered in the improved method is that occurring on the bottom either of the existing pavement surface layer or the overlay. Two cases are considered, as shown in Figure 6.25. For existing surface with resilient modulus greater than 70,000 psi, tensile strain in the existing surface is used to estimate the fatigue life. For existing surface with modulus less than 70,000 psi, tensile strain in the overlay is used.

6.2.8.3.2 Rutting Criterion

Rutting or permanent deformation is controlled by limiting the



a) Modulus of Existing Surface >70,000 psi



b) Modulus of Existing Surface <=70,000 psi

Figure 6.25 Critical Strain Locations for Overlay Design vertical compressive strain at the top of the subgrade. A relationship developed by the Asphalt Institute (1982) is used in the improved procedure. The relationship is expressed as follows:

$$N = 1.36 * 10^{-9} (\epsilon_v)^{-4.48} \qquad (6\text{-}28)$$

where:

N = number of load applications, and

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

Figure 6.25 also shows the location of the critical strain for rutting analysis.

6.2.9 Determination of Pavement Damage

For every load application, there is some pavement damage. Pavements fail when the total damage accumulates to a point that the pavement serviceability is unsatisfactory. Miner's rule, a cumulative damage theory, is commonly used to assess the damage caused by mixed traffic loads. In the improved method, Miner's rule is also used and it has the following form:

$$\sum_{i=1}^{\gamma} \frac{n_i}{N_i} \leq 1 \qquad (6\text{-}29)$$

where:

i = season i in analysis,

n_i = actual number of cycles of load applied to the pavement with season i,

N_i = allowable number of cycles to failure, based on failure criteria for season i, and

γ = up to 4 seasons can be considered for analysis.

6.2.10 Overlay Thickness Design

The overlay design steps, as described above, have been computerized. The resulted computer program MECHOD (Zhou et al, 1989), stands for MECHanistic Overlay Design, can now be used for routine design work. Figure 6.26 shows a flowchart of this program, while the User's guide may be found in Appendix E.

To begin with, the MECHOD program first reads input data related to pavement structure, traffic, material characteristics. Seasonal effects are considered in traffic distribution and resilient modulus variation for four seasons. However, the pavement damage that occurs in a particular season of the year may also be evaluated. A layered elastic program (ELSYM5) is then called to calculate critical pavement strains as shown in Figure 6.21. The allowable traffic for each season is then calculated and pavement damage evaluated.

The pavement condition rating is not being used in this program because the relationship between the pavement condition rating and the pavement structural characteristics is unclear. However, the importance of a condition survey prior to overlay design should not be underestimated. For the existing pavement, if the damage is greater than 80% or its remaining life less than 20% (either fatigue or rutting), an overlay is required. If the existing pavement still has more than 20% of remaining life, the program will further consider projected future traffic to determine if the existing pavement is able to carry those future load applications. The total pavement damage is determined at this stage. If this total pavement damage is greater than unity, it indicates that the existing pavement is not capable of carrying the projected traffic. In such a case, the

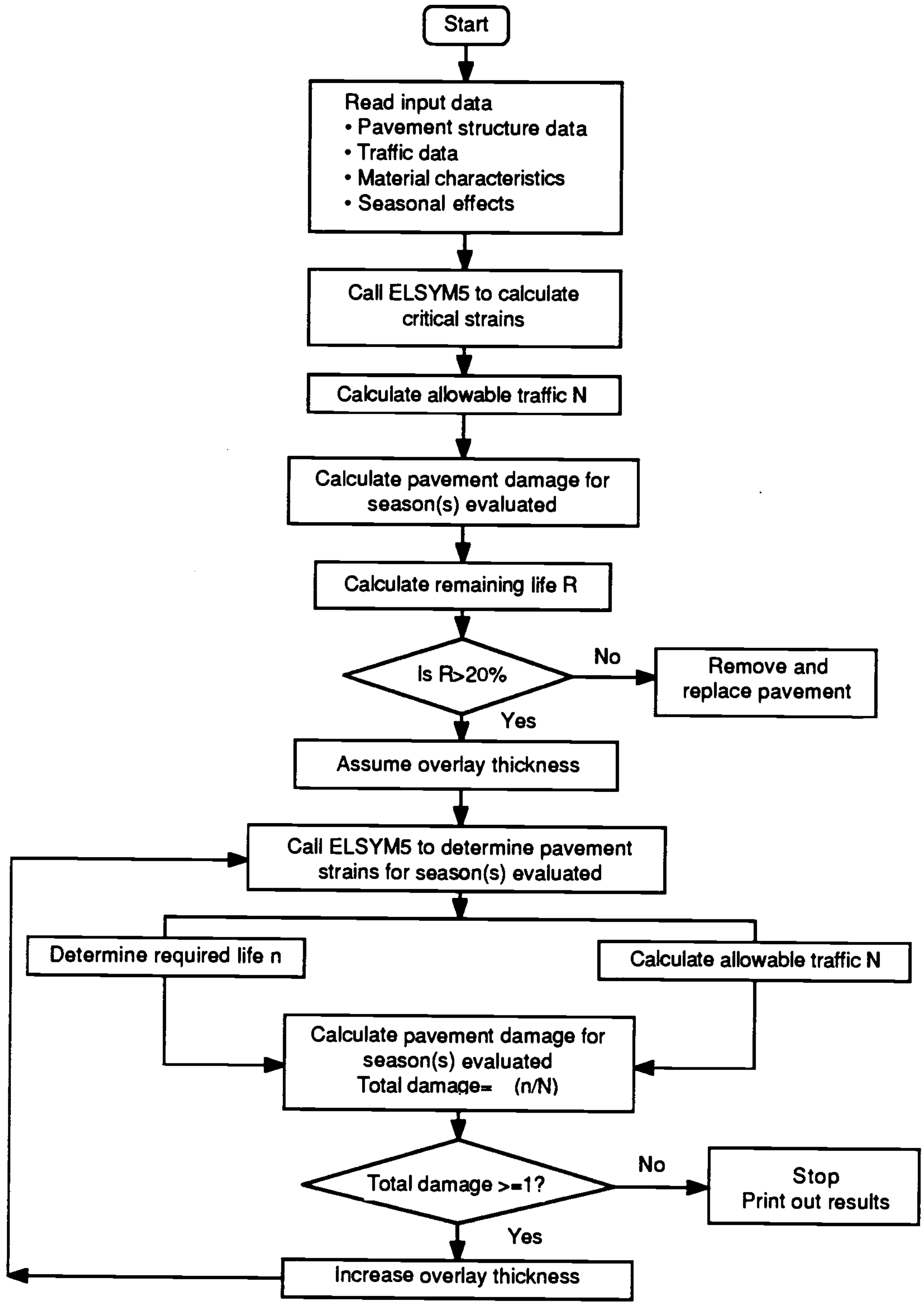


Figure 6.26 MECHOD Program Flowchart

program will also perform an overlay design.

In the process of overlay design, the program first asks for the resilient modulus of the overlay material for the seasons being considered, and uses an initial overlay thickness of 1 inch as a starting value. As shown in Figure 6.26, ELSYM5 is used to calculate critical pavement strains for the season(s) considered. Equations (6-27) and (6-28) are then used to determine the allowable traffic application for the season(s) considered. Total pavement damage is determined for overlaid pavement by using Miner's rule. Both fatigue and rutting are checked. If either has a total pavement damage greater than unity, it is used as the controlling factor. Determination of overlay thickness is an iterative process. An increment of half-inch overlay thickness is used in the program for the next iteration. The above process is repeated automatically until the total pavement damage is less than unity. This overlay thickness is then recommended.

6.3 Summary

This chapter first reviewed three developed mechanistic overlay design procedures. These procedures included the 1) ARE procedure for the Federal Highway Administration, 2) University of Washington procedure for the state of Washington, and 3) Oregon State University procedure for the state of Alaska. Based on the review, an improved mechanistic overlay design procedure was presented. The major improvement over the three developed procedures is in the direct consideration of seasonal effects on pavement material properties and pavement damage due to traffic loadings within each season.

The improved procedure has been computerized and can be operated on IBM or compatible microcomputers. The resulting computer program MECHOD is easy to use and is user friendly. An initial evaluation was performed on several actual pavements from the states of Oregon and Alaska, as will be described in greater detail in the next chapter.

7.0 EVALUATION OF THE DEVELOPED PROCEDURE

Evaluation of the developed overlay design procedure (MECHOD) was accomplished by selecting actual projects in the states of Oregon and Alaska. The general procedures followed are described below:

1. Select projects for evaluation.
2. Perform condition survey and deflection tests using FWD.
3. Determine pavement layer moduli for overlay design.
4. Perform overlay design using the developed procedure.
5. Compare overlay design results with standard procedures.

The following describes the evaluation process in more detail.

7.1 Overlay Design Using MECHOD

7.1.1 Selection of Project Sites

Two projects in Oregon and two in the state of Alaska were selected for the evaluation of the developed procedure. These projects are typical conventional pavement structures consisting of an asphalt concrete, an aggregate base, and subgrade. One project (Nelchina) in the state of Alaska contains an aggregate subbase. Figure 7.1 shows the location of these projects. Two projects, the Rufus-Quinton project and the Centennial Boulevard project that were selected for the purpose of evaluating the BOUSDEF program, were again used as candidates for the evaluation of the MECHOD program. Pavement parameters for these projects are summarized in Table 7.1.

Condition survey information are also presented in Table 7.1. The condition survey on the Nelchina project indicates that the existing pavement is totally alligator cracked in 3 to 6" blocks from

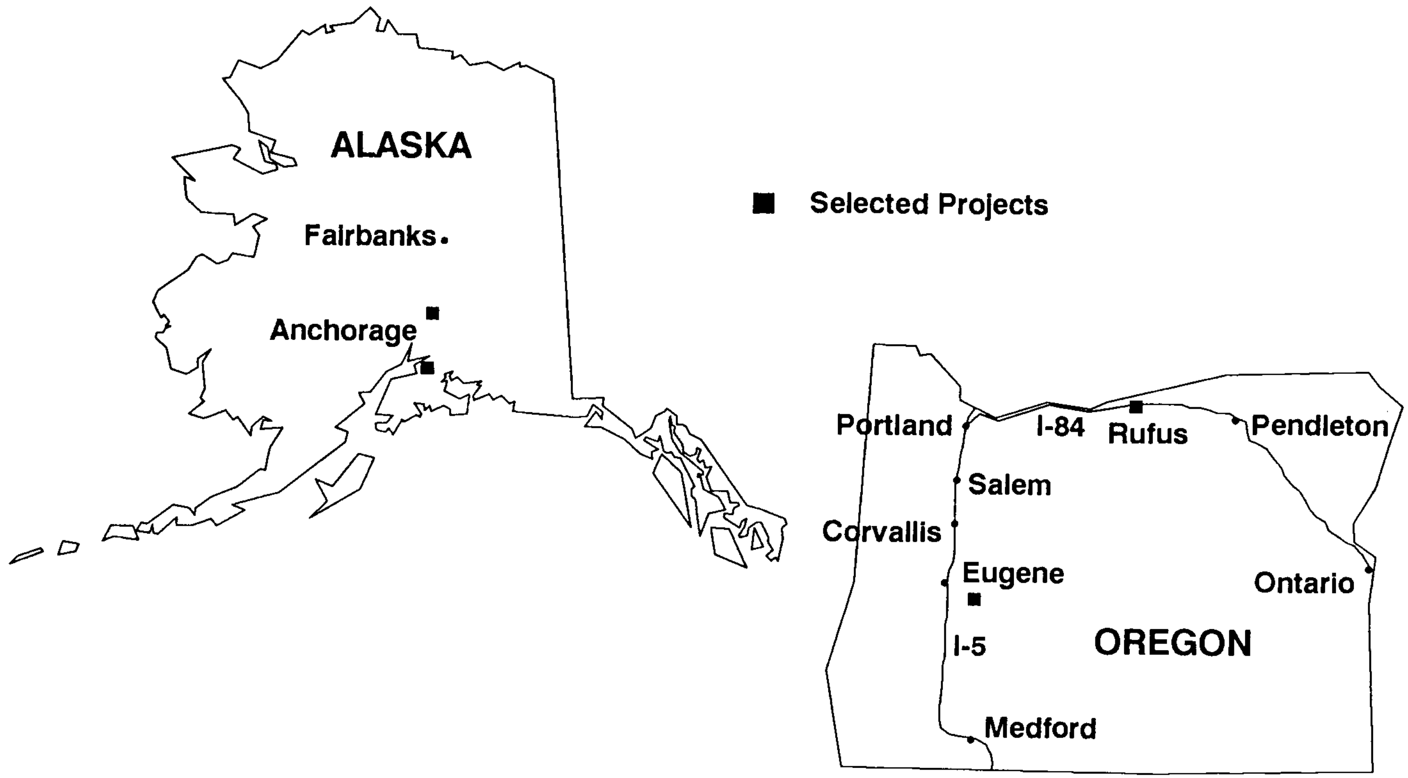


Figure 7.1 Location of Selected Project Sites

Table 7.1 Summary of Selected Projects

Project Name	Layer Thickness	Condition survey
Rufus-Quinton (OR)	6.8" AC 18.0" Aggregate Base	Fair to poor Moderate rutting, extensive cracking, and apparent delamination
Centennial Blvd (OR)	4.0" AC 16.0" Aggregate Base	Fair to poor Light to moderate alligator cracking, moderate transverse cracking
Nelchina (AK)	1.5" AC 4.5" Crushed Gravel Base 6.0" Gravel Subbase 18.0" Selected "Clean" Gravel	Fair to poor Heavy alligator cracking and rutting between stations 62 and 81. Other areas are in relatively good to excellent condition.
Tudor (AK)	2.5 - 5.0" AC (avg. 3.2") 10.5-15.0" Aggregate Base (avg. 12.0" Aggregate Base)	Fair to Good Moderate to severe rutting

station 62 to 81, while from stations 0 to 61 and stations 82 to 127 the pavements is in relatively good to excellent condition. Therefore, the following analysis focuses on pavement section from station 62 to 81.

Pavement thicknesses for each layer listed in Table 7.1 are average values. It is expected the thickness varies in the field. From the data received, the asphalt concrete thicknesses for the Rufus-Quinton Project vary from 5 to 9 inches. For the Nelchina project, the AC thickness is expected to vary by ±0.5 inch. For the Tudor project, the AC thicknesses are in the range 2.5 to 5 inches.

7.1.2 Deflection Tests

Deflection tests for the two Oregon projects are described in Section 4.3.3.2. For the Alaska projects, the Dynatest FWD was used for the deflection measurements. Detailed deflection data may be found in Appendix B. For the Nelchina project, deflection tests were performed on a hundred-foot intervals from station 62 to 81. One NDT load, approximately 9,000 lbs, was dropped at each test spot. Deflection tests at the same sites were conducted both in May (Spring) and August (Summer) of 1989. For the Tudor project, deflections were measured for each station. Four NDT loads, ranging from 6,000 to 14,000 lbs, were used to measure deflections at varying load levels. The deflection measurements were also performed for both spring and summer of 1989.

7.1.3 Determination of Pavement Moduli for Overlay Design

BOUSDEF was used to backcalculate pavement moduli using the FWD deflection data at the time of testing. Table 7.2 summarizes the backcalculation results for the projects evaluated. Detailed backcalculation results may be found in Appendix F.

The backcalculated moduli represent the material properties corresponding to the temperature at the time of NDT testing. These modulus values may be converted to a standard design temperature of 70°F, using a relationship shown in Figure 7.2. For instance, in the AASHTO design procedure, the backcalculated moduli are used to determine the "effective" in situ structural layer coefficient (a_i), the determined moduli must be corrected to a common 70°F temperature so that the corrected a_i correlation value can be obtained. The converted moduli for each project are presented in Table 7.3.

In order to consider seasonal effects on the pavement materials, a representative temperature for each season can be selected based on local weather data. This representative temperature can be an average temperature for each season, as used in this study. Table 7.4 presents the temperature values used for characterizing the material properties within each season.

Knowing the temperature for each season, the resilient modulus for each season can be determined by adjusting the asphalt concrete modulus to the corresponding temperature, using Figure 7.2. Modulus values corrected for temperature for the asphalt concrete are presented in Table 7.5.

Based on the backcalculated resilient moduli and temperature information, modulus values used for overlay design analysis can be determined, as shown in Table 7.6. It should be noted that engineering judgement is necessary to determine what moduli should be

Table 7.2 Summary of Backcalculated Moduli

Project Name		AC (ksi)	Base (ksi)	Subbase (ksi)	Subgrade (ksi)	Temperature at time of NDT testing (°F)
Rufus-Quinton		479,843[a]	25,536	-	26,670	72
		221,124[b]	16,531	-	6,218	6
Centennial Blvd		677,940	43,945	-	15,319	71
		287,039	17,825	-	4,791	12
Nelchina[c]	(spr)	1,200,000[d]	35,425	14,439	11,831	44
		0	8,401	4,145	1,969	0
	(sum)	1,000,000[d]	63,982	46,088	12,167	50
		0	20,984	20,216	2,675	0
Tudor	(spr)	1,751,905	17,505	-	51,419	45
		591,186	7,574	-	18,279	0
	(sum)	1,200,162	28,850	-	44,856	56
		571,821	12,059	-	16,267	0

a Average modulus

b Standard Deviation

c From station 62 to station 82.

d Fixed AC values, due to difficulties in obtaining reasonable results from backcalculation. These fixed values were estimated based on the temperature at the time of NDT testing from Figure 6.12. It should be noted these values might be dramatically different from the actual condition, since the existing pavement is severely cracked.

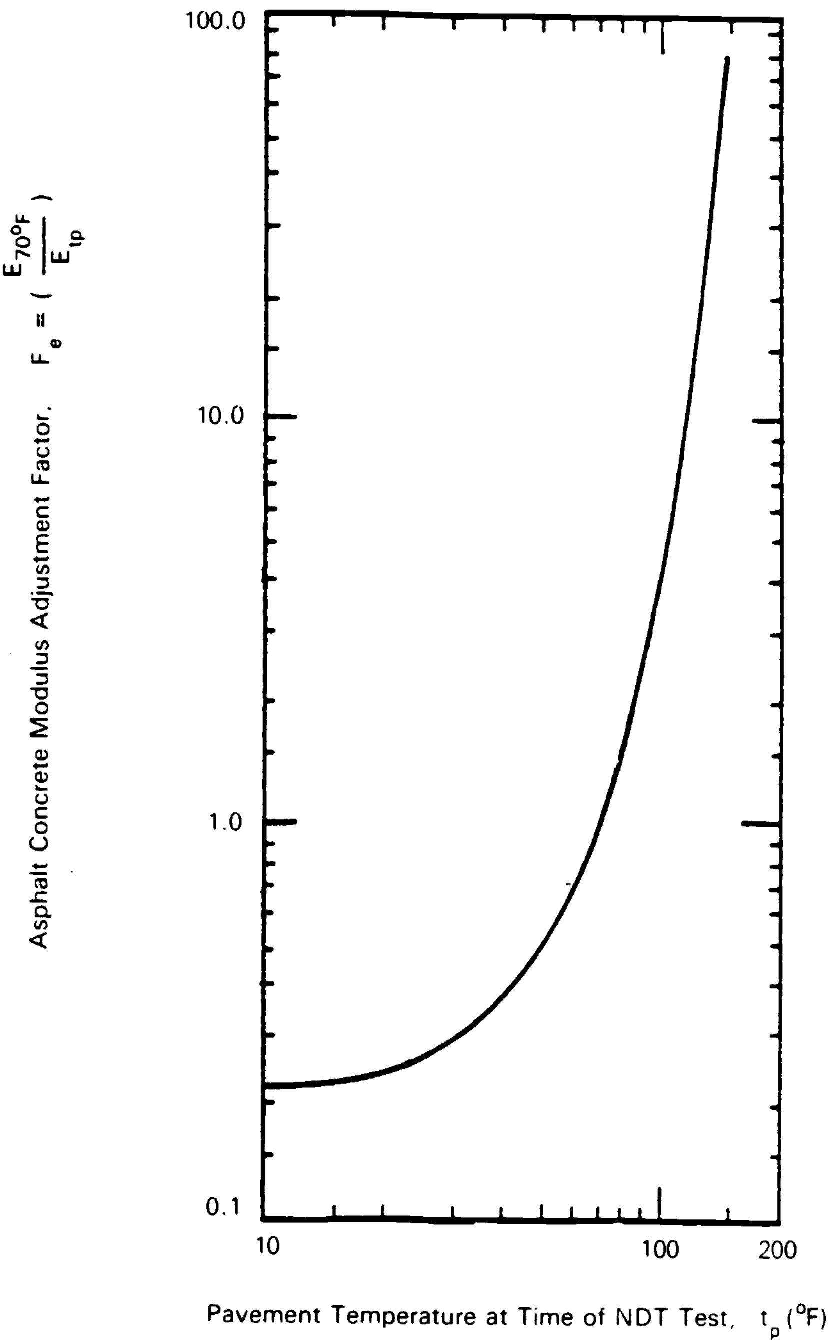


Figure 7.2 Asphalt Modulus Temperature Adjustment Factor (AASHTO, 1966)

Table 7.3 Backcalculated AC Moduli Converted to 70°F

Project Name	NDT Test Season	Conversion Factor	AC Modulus (psi)	Average MR (psi)
Rufus-Quinton	Summer	1.10	436,221	436,221
Centennial Blvd	Spring	1.05	645,657	645,657
Nelchina	Spring	0.44	528,000	524,000
	Summer	0.52	520,000	
Tudor	Spring	0.45	788,357	778,231
	Summer	0.64	768,104	

Table 7.4 Representative Temperature Used for Evaluation

Project Name	Spring °F	Summer °F	Fall °F	Winter °F
Rufus-Quinton	49 (0.50)[a]	70 (1.00)	48 (0.48)	37 (0.34)
Centennial Blvd	50 (0.52)	64 (0.83)	49 (0.50)	42 (0.41)
Nelchina	39 (0.35)	50 (0.52)	N/C N/C	20 (0.24)
Tudor	39 (0.35)	50 (0.52)	N/C N/C	20 (0.24)

[a] Conversion Factor relative to 70°F (From Figure 7.2).

N/C= Not Considered.

Table 7.5 Modulus Values (psi) Corrected for Temperature for AC

Project Name	Spring	Summer	Seasons Fall	Winter
Rufus-Quinton	872,000	436,000	908,000	1,283,000
Centennial Blvd	1,246,000	777,000	1,291,000	1,574,000
Nelchina	1,497,000	1,007,000	N/C	2,183,000
Tudor Road	2,223,000[a]	1,496,000[a]	N/C	3,242,000[a]

N/C= Not considered.

[a] These numbers are unreasonable, engineering judgement needs to be made. The adjusted modulus values may be seen in Table 7.6.

Table 7.6 Modulus Values Used in Overlay Design Analysis

Project Name	Layer Name	Spring	Summer	Seasons Fall	Winter
Rufus-Quinton	AC	872,000	436,000	909,000	1,283,000
	Base	20,000[a]	25,600[a]	27,000[a]	20,000[a]
	Subg	15,000[a]	20,500[a]	21,000[a]	15,000[a]
Centennial Blvd	AC	1,242,000	778,000	1,291,000	1,575,000
	Base	43,900	50,000[a]	45,000[a]	40,000[a]
	Subg	15,300	20,000[a]	21,000[a]	16,000[a]
Nelchina	AC	70,000[b]	70,000[b]	-	70,000[b]
	Base/sub	25,000[c]	55,000[c]	-	60,000[a]
	Subg	11,800[c]	12,200[c]	-	30,000[a]
Tudor	AC	1,500,000[d]	1,000,000[d]	-	2,000,000[d]
	Base	35,000[a]	60,000[a]	-	80,000[a]
	Subg	20,000[a]	25,000[a]	-	60,000[a]

[a] Adjusted modulus based on backcalculated results and experience. Engineering judgement was made in determining these values.

[b] This value is assigned because the existing pavement surface is totally cracked.

[c] Average backcalculated modulus for base and subbase.

[d] Adjusted modulus based on engineering judgement

used in the design analysis. In the case of the Rufus-Quinton and Centennial Blvd projects, the backcalculated values play an important role of reference. The final modulus values determined were primarily based on the backcalculated results. For the Nelchina project, the selection of the design resilient moduli was also based on the backcalculated results. Considering the effect of the badly cracked surface, the modulus, used in the overlay design analysis (for the existing asphalt concrete layer) is assigned a value of 70,000 psi. This is done to consider that the severely cracked surface layer would perform as a granular material layer.

Engineering judgement was made in selecting the moduli for the Tudor project. The backcalculated AC moduli seemed to be in the right range; however, the backcalculated results for the base and subgrade provided unreasonable numbers. In many cases, the subgrade modulus values are much higher than the base modulus values. It is generally expected that the modulus for the base would be higher than that for the subgrade (except in the spring season when base layer material thawed while the subgrade is still frozen).

7.1.4 Traffic Analysis

Traffic repetitions are expressed in terms of 18 kip equivalent axial loads (EAL's). Mixed traffic can be converted to repetitions of the 18 kip EAL using the AASHTO equivalency factors.

It is ideal if the historical traffic data are available. This data helps the designer evaluate the remaining life of an existing pavement prior to an overlay. However, the historic traffic data are usually difficult to obtain which makes the analysis of remaining pavement life extremely difficult. In this study, only one project (Nelchina) had an estimate of the historic traffic applications. Future traffic application data are also needed for overlay design. In the following evaluation, all traffic applications before the year 1989 are considered as historical traffic repetitions.

Traffic data for the Rufus-Quinton project was furnished by the Oregon State Highway Division (OSHD) traffic section. The data came from a 16-hour manual count taken in 1988. For the Centennial Boulevard project, the traffic data were provided by the city of Eugene. Traffic data for the Alaska projects were developed by the Alaska Department of Transportation and Public Facilities (ADOT&PF).

Table 7.7 summarizes both historical traffic data (if they are available) and projected 20-year traffic applications. The traffic distribution for each season is presented in Table 7.8, and as can be seen it varies with the season. For the projects evaluated, a large percentage of the traffic applications are in the summer season. A fifty percent reliability factor, meaning no modification on traffic applications, was used for the overlay design. The same reliability level was also used in the analysis using the AASHTO design procedure, as is seen in a later section.

7.1.5 Overlay Design

After establishing the necessary inputs for overlay design, the MECHOD program was used to determine the thickness of overlay. The inputs required to run MECHOD included design load, load radius, moduli and Poisson ratios for each pavement layer and season, historical and projected traffic applications for each season,

Table 7.7 Traffic Data for Overlay Design (ESAL's)

Project Name	Historical Traffic	Future Traffic
Rufus-Quinton	N/A	27,104,357[a]
Centennial Blvd	N/A	4,604,526[b]
Nelchina	501,840[c]	1,056,000[d]
Tudor	N/A	1,812,000[e]

[a] Estimated using a five percent growth rate for the first fifteen years and a three percent growth rate for the last five years.

[b] Estimated using a five percent truck and a three percent growth rate for twenty years design.

[c] Calculated as 1,230 EAL/month/way * 12 month/yr * 17 yr * 2 ways

[d] Calculated as 2,200 EAL/month/way * 12 month/yr * 20 yr * 2 ways

[e] Provided by Alaska DOT&PF.

Table 7.8 Traffic Distribution for Each Season (ESAL's)

Project Name	Seasons Spring	Summer	Fall	Winter
Rufus-Quinton	4,526,428	11,275,413	4,526,428	6,776,089
	2[a]	5	2	3
	16.7[b]	41.6	16.7	25.0
Centennial Blvd	1,151,132	1,533,307	768,956	1,151,132
	3	4	2	3
	25.0	33.3	16.7	25.0
Nelchina	87,648	528,000	-	440,352
	(41,653)[c]	(250,920)	-	(209,267)
	1	6	-	5
	8.3	50.0	-	41.7
Tudor	154,020	947,676	-	710,304
	1	6	-	5
	8.5	52.3	-	39.2

[a] Length of the season in month.

[b] Percent distribution of the total traffic for the season.

[c] Historical traffic for the season.

reliability factor, and standard deviation. Since a fifty percent reliability level was selected for the analysis, this factor had no effect on the overlay design.

The MECHOD program first uses the given data to evaluate the existing pavement. If an overlay is needed, based on total pavement damage, the program would ask for the modulus of overlay material. Table 7.9 presents modulus data for the overlay material. The moduli in the Table 7.9 were estimated using the AMOD program.

Several assumptions were made in using the AMOD program. For the Oregon projects, these include an 8% voids for the asphalt concrete overlay mix, an AC-20 grading of asphalt, a 6% of asphalt content by weight of total mix, a 5% fine passing the No. 200 sieve, and a vehicle travel speed of 35 mph. With the above assumptions, the modulus value at temperature of 70°F was computed to be 1,200,000 psi. This value seems to be high for the Oregon projects. Therefore, a modulus value of 450,000 psi, which is typically used in Oregon for new asphalt material, was selected. By using the representative temperature data shown in Table 7.4, the modulus value of overlay material for each season was determined and presented in Table 7.9. For the Alaska projects, the overlay material modulus was estimated using data from Kodiak Airport runway design (Vinson et al, 1989).

The overlay thickness design is an iterative process. For practical purposes, an initial overlay thickness of one-inch is used in the MECHOD program, with a half-inch increment for each iteration. The process is repeated until the total pavement damage is less than unity. The design results for the four projects are summarized in Table 7.10, while detailed output each project may be found in

Table 7.9 Modulus Data (psi) for Overlay Material[a]

Project Name	Seasons Spring	Summer	Fall	Winter
Rufus-Quinton	900,000	450,000	937,500	1,324,000
Centennial Blvd	865,400	542,200	900,000	1,097,600
Nelchina	1,360,000	915,400	N/C	1,983,000
Tudor	1,360,000	915,400	N/C	1,983,000

[a] Poisson's ratio is assumed to equal 0.35 for all seasons.

N/C = Not Considered

Table 7.10 Overlay Design from MECHOD

Project Name	Overlay Thickness (in)	Total Pavement Damage (%) Surface	Subgrade
Rufus-Quinton	4.0	96.5	2.2
Centennial Blvd	2.0	98.3	11.3
Nelchina	3.0	85.7	0.6
Tudor	1.0	45.4	9.3

Appendix G. Total pavement damage is also presented in the table. This value indicates that after 20 years of service, the design overlay would use up certain percentage of its design life. For all the projects evaluated, the results seem to indicate that fatigue damage in the asphalt concrete layer is a major concern in these projects, while the rutting in the subgrade is not significant. The rutting problems, as indicated in Table 7.2, very likely occurred in the asphalt concrete and/or base layers. At present, the MECHOD program is not capable of determining rutting for these circumstances.

7.2 Overlay Design Using Standard Procedures

Three standard overlay design procedures were used for the purposes of evaluating the developed procedure. These procedures are currently used in both Oregon and Alaska States. These procedures are the Oregon DOT, 1986 AASHTO, and ADOT&PF methods. The following briefly describe these procedures.

7.2.1 ODOT Design Procedure

The present procedure used to determine overlay requirements in Oregon is based on deflection measurements of the existing pavement. The design procedure is essentially that of the California Division of Highways, with modifications for Oregon's Traffic and Crushed Base Equivalencies. The procedure suggests that tolerable deflection is a function of traffic and pavement thickness, and that additional overlay thickness will reduce measured deflection. The deflections are measured using either a Falling Weight Deflectometer (FWD) or the

Dynaflect test equipment. Deflections are typically measured every 250 ft. within a section. However, different spacings may be specified if requested by the designer. The measured deflections are normalized to an equivalent deflection for a 9,000 pound load at 70°F. For deflections measured using the FWD, the equivalent deflections are determined by interpolating between the deflections measured at loads above and below 9,000 pounds. Once the equivalent deflections have been determined, they must be adjusted to account for the in-place pavement temperature. This adjustment is a function of both the pavement temperature at the time the deflections were measured and the thickness of the existing pavement. Knowing these two factors, Figure 7.3 is used to determine the appropriate temperature correction factor. The equivalent deflections are multiplied by the temperature correction factor to establish the final normalized deflection. For pavements over six inches thick, no temperature correction is required.

The normalized deflection is determined for each location where deflections were measured. Statistical analysis is performed to delineate analysis unit. For each unit, the 80th percentile deflection is calculated and used as design value to determine the overlay requirement. The 80th percentile deflection is computed using the following equation:

$$D_{80} = X + 0.84\ S \qquad (7\text{-}1)$$

where:

D_{80} = design deflection value (80th percentile deflection),

X = mean deflection, and,

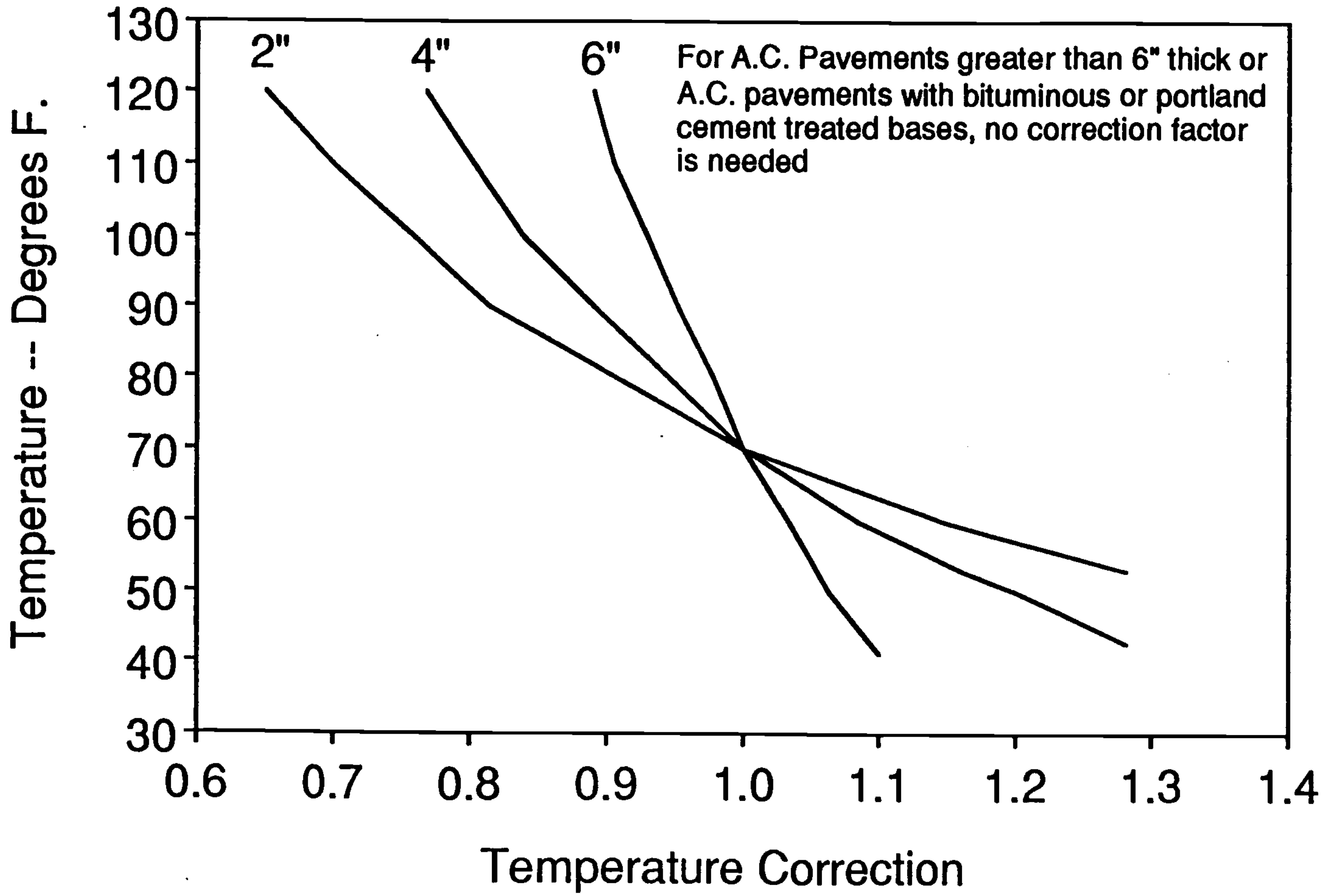


Figure 7.3 Temperature Correction Factors Used in ODOT Overlay Design Procedure (Oregon State Highway Division (OSHD), 1951)

S = standard deviation of the deflections.

The 80th percentile deflection, for a particular project length, is then compared with a tolerable deflection (determined from Figure 7.4), which is a function of future equivalent axle load repetition and the thickness of the in-place pavement which has remaining fatigue life. An iterative procedure is then used to find the overlay thickness. For pavements which are substantially or wholly failed in fatigue, the tolerable deflection is based on the proposed overlay thickness only. If the 80th percentile deflection is less than the tolerable deflection, then an overlay is not needed. If the 80th percentile deflection is greater than the tolerable deflection, then the percent reduction in deflection is calculated as follows:

$$\% \text{ reduction} = 100 * (D_{80} - D_t)/D_{80} \qquad (7\text{-}2)$$

where

D_t = tolerable deflection.

The value of % reduction is used in Figure 7.5 to determine the Crushed Base Equivalence factor, which means one inch thick of asphalt concrete is equivalent to a certain thickness of gravel. The equivalent factor ranges from 1.52 to 2.5. A factor of 2.0 is used by Oregon DOT.

Deflection data used in the overlay design can be found in Appendix H. The final overlay design results are summarized in Table 7.11.

7.2.2 1986 AASHTO Design Procedure

The 1986 AASHTO overlay design procedure (AASHTO, 1986) is based

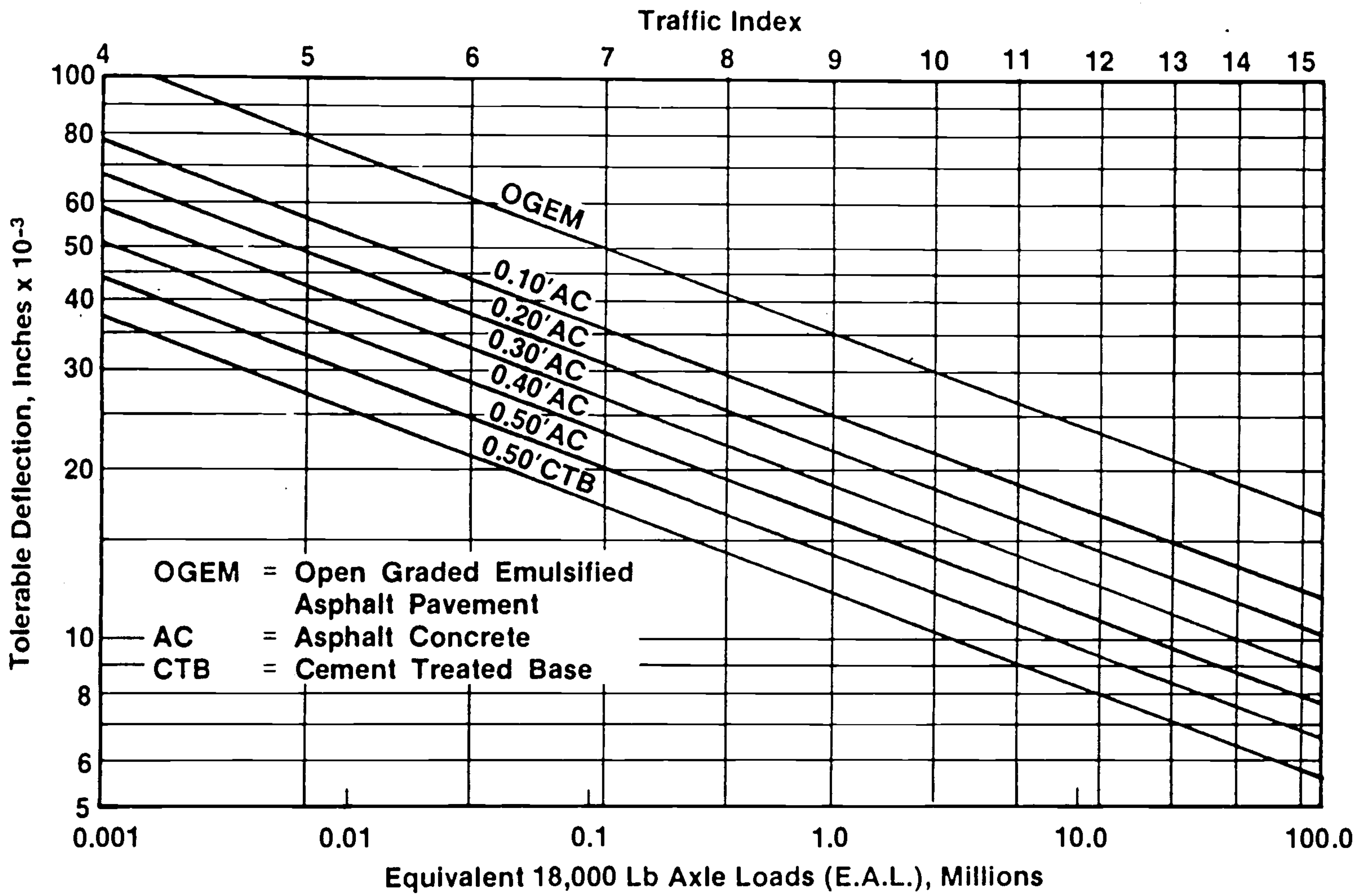


Figure 7.4 Tolerable Deflection Chart Used in ODOT Overlay Design Procedure (OSHD, 1951)

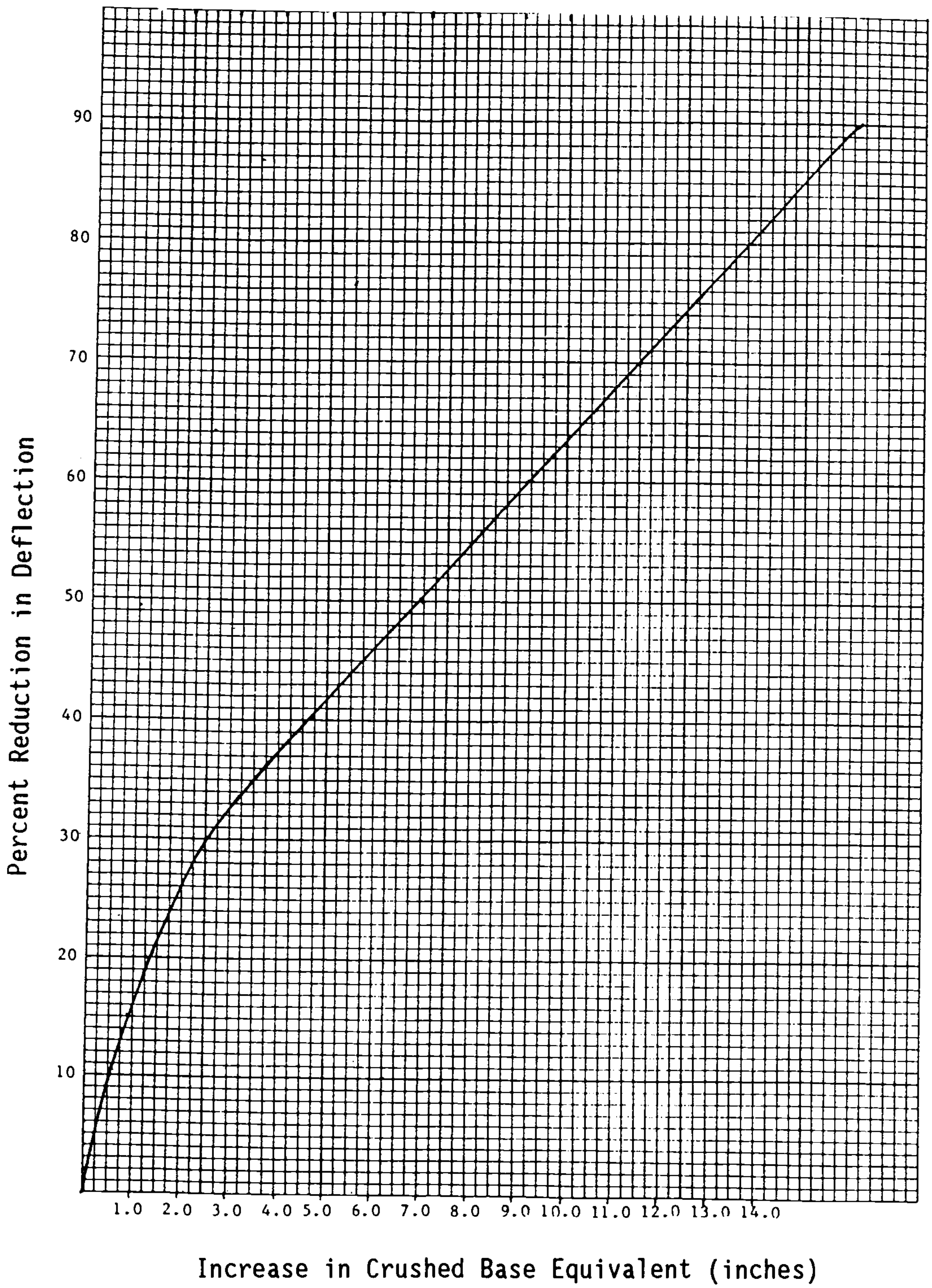


Figure 7.5 Percent Deflection Reduction Chart Used in ODOT Overlay Design Procedure (OSHD, 1951)

Table 7.11 Overlay Thickness Design Using ODOT Procedure

Project Name	TC[a]	D_{80}[b] (mils)	D_t[c] (mils)	Deflection Reduction %	Overlay Thickness (inch)
Rufus-Quinton	13.33	14.12	8.0	43.3	2.8
Centennial Blvd	10.79	22.14	14.0	36.8	2.0
Nelchina	9.06	42.82	24.0	44.0	2.8
Tudor	9.66	16.53	17.0	0.0	0.0

[a] Traffic Coefficient = $9 * (\text{18-kip traffic}/10^{-6})^{0.119}$

[b] 80th percentile deflection

[c] Tolerable deflection

on the serviceability versus traffic and structural capacity versus traffic relationships developed at the AASHO Road Test. Determination of an overlay is accomplished by using a deficiency approach. Figure 7.6 illustrates the basic concepts used in the developing the procedure, while Figure 7.7 lists seven steps that are generally involved in overlay design analysis. Of these steps, materials characterization and effective structural capacity analysis require the most effort. Two nondestructive test methods are presented in the Guide and can be used to analyze the existing pavement structure. They include 1) determination of pavement layer moduli (NDT Method 1) or 2) determination of the total structural capacity (NDT Method 2). Both methods rely upon the use of deflection data generated from a nondestructive testing device.

7.2.2.1 NDT Method 1

NDT Method 1 is a technique used to determine the structural capacity of an existing pavement. This technique uses measured deflection basin data from an NDT device to backcalculate the in-situ layer elastic moduli and is applicable to both flexible and rigid pavements. The fundamental premise of this solution is that a unique set of layer moduli exist such that the theoretically predicted deflection basin is equivalent to the measured deflection basin. To implement this technique, a computer program that backcalculates the elastic modulus for each pavement layer is necessary. The obtained moduli are related to layer coefficients using various charts given in the Guide. The structural number is then determined using the equation:

$$SN = \Sigma a_i h_i \tag{7-3}$$

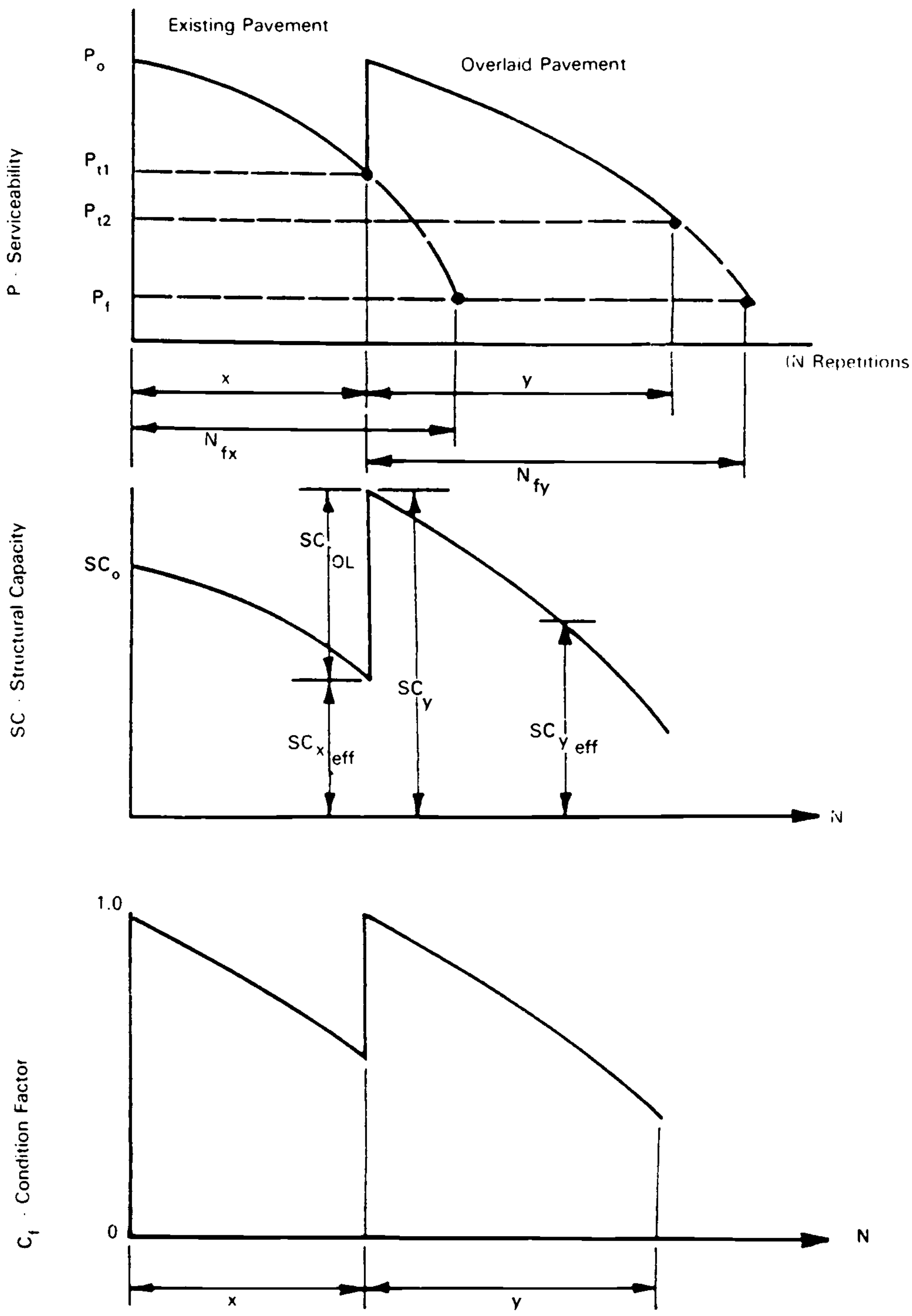


Figure 7.6 Relationship Serviceability-Capacity Condition Factor and Traffic (AASHTO, 1986)

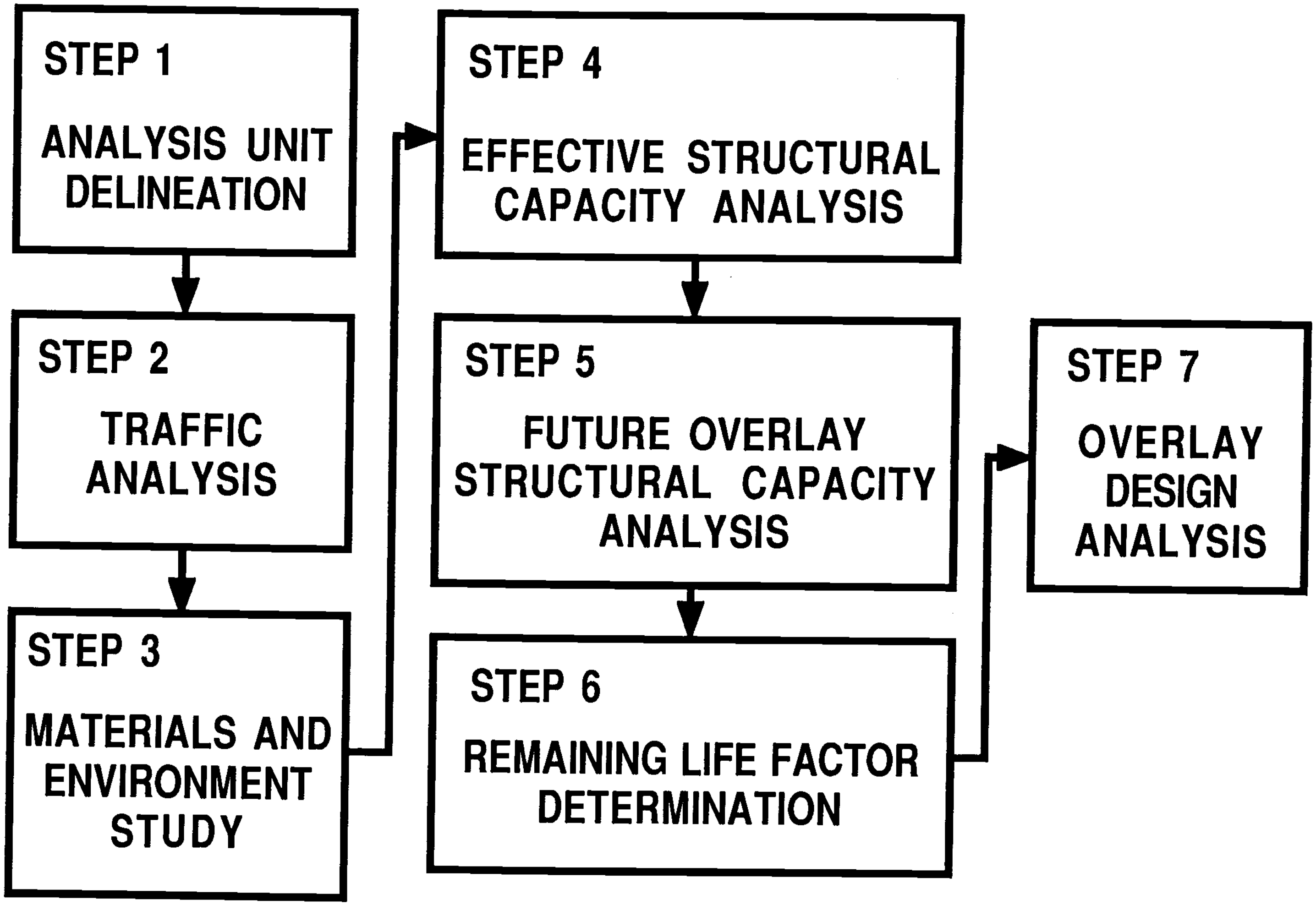


Figure 7.7 AASHTO Overlay Design Steps (AASHTO, 1986)

where:

a_i = layer coefficient for each layer, and,

h_i = thickness of each layer above subgrade.

Figures 7.8 to 7.10 show the layer coefficients versus resilient modulus for asphalt concrete, granular base, and granular subbase, since they will be used in later analysis.

7.2.2.2 NDT Method 2

NDT Method 2 is based upon the maximum measured deflection from the dynamic NDT equipment and, as such, does not require a computerized model to backcalculate layer moduli (E_i). With NDT Method 2, the maximum measured deflection is used to determine S_{Nxeff} from Burmister's two-layer deflection theory. The relationship between deflection and structural number is given by the following equations:

$$d_o = \left[\frac{2P(.0043*h_t)^3}{3.1416\ a_c SN^3}\right]\left[1 + F_b\left[\frac{SN^3(1 - \mu_{sg}^2)}{E_{sg}(.0043*h_t)^3} - 1\right]\right] \qquad (7\text{-}4)$$

where:

d_o = deflection value,

P = NDT device load (lbs),

h_t = total layer thickness (above subgrade),

μ_{sg} = subgrade Poisson's ratio,

E_{sg} = subgrade modulus,

SN = SN_{xeff}, the effective structural number, and,

F_b = Boussinesq one layer deflection factor and is given by

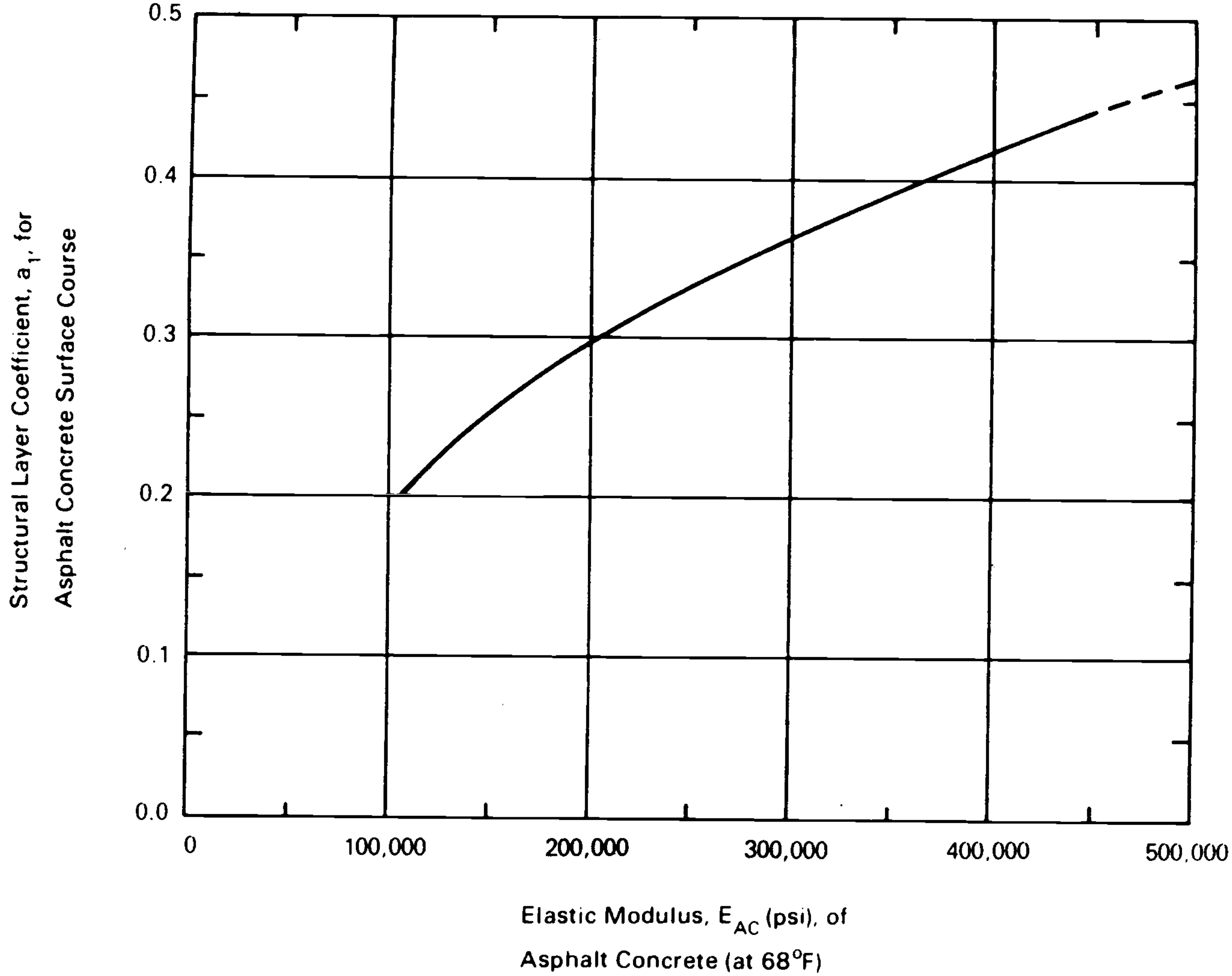
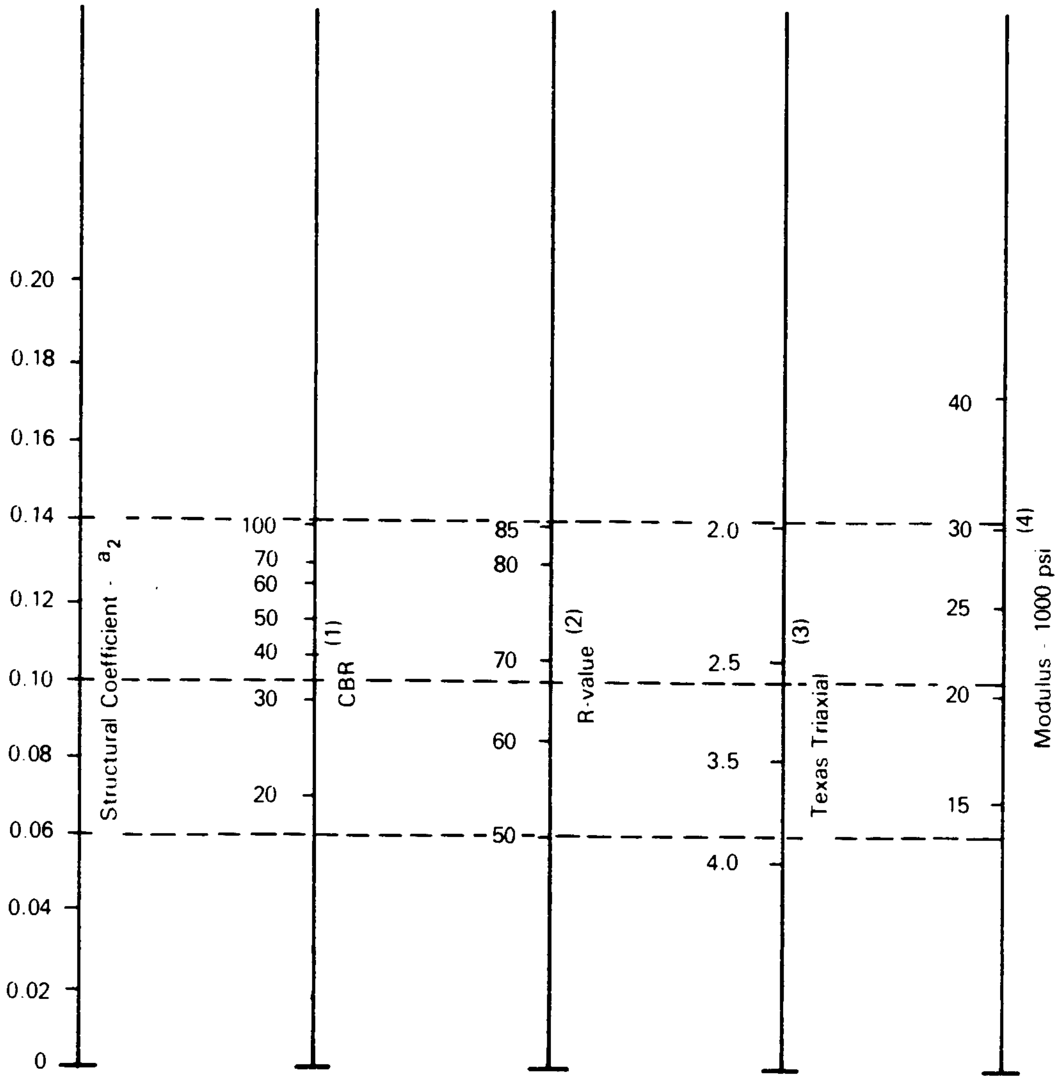
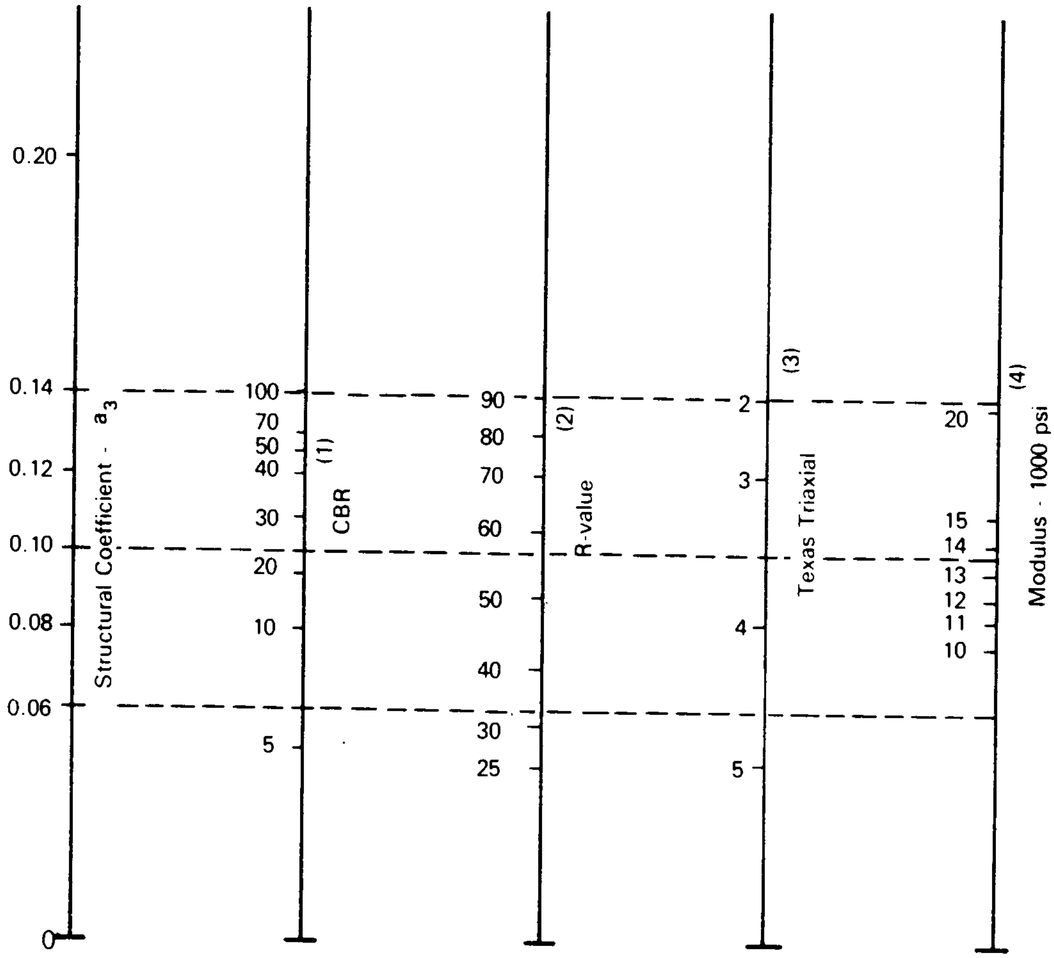


Figure 7.8 Chart for Estimating Structural Layer Coefficient of Dense-graded Asphalt Concrete Based on the Resilient Modulus (AASHTO, 1986)



(1) Scale derived by averaging correlations obtained from Illinois.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project

Figure 7.9 Variation in Granular Base Layer Coefficient (a_2) with Various Base Strength Parameters (AASHTO, 1986)[2]



(1) Scale derived from correlations from Illinois.

(2) Scale derived from correlations obtained from The Asphalt Institute, California, New Mexico and Wyoming.

(3) Scale derived from correlations obtained from Texas.

(4) Scale derived on NCHRP project

Figure 7.10 Variation in Granular Base Layer Coefficient (a_3) with Various Subbase Strength Parameters (AASHTO, 1986)

$$F_b = \left\{\left[1 + \left[\frac{h_e}{a_c}\right]^2\right]^{.5} - \frac{h_e}{a_c}\right\}\left\{1 + \frac{(h_e/a_c)}{2(1-\mu_{sg})\left[1 + \left[\frac{h_e}{a_c}\right]^2\right]^{.5}}\right\} \quad (7\text{-}5)$$

and

$$\frac{h_e}{a_c} = \frac{209.3*SN}{a_c}\left[\frac{(1 - \mu_{sg}^2)}{E_{sg}}\right]^{1/3} \quad (7\text{-}6)$$

where:

h_e = equivalent transformed thickness, and,

a_c = radius of load plate.

The SN_{xeff} value for a particular pavement structure can be determined by a trial-and-error process. This is done by assuming an SN_{xeff} and computing the deflection d_0. If the calculated d_0 does not agree with the maximum measured deflection (temperature adjusted), a new SN_{xeff} is assigned. The process is repeated until the calculated deflection matches the maximum measured deflection. A computer program has been developed to solve these equations (Zhou, 1987).

For this study, the NDT method 1 was used, because the resilient modulus for each pavement layer could be determined using backcalculation procedures. Therefore, the structural number (SN_{xeff}) was easily calculated.

With the knowledge of reliability and overall standard deviation (a function of traffic, project location), design serviceability loss, resilient modulus of the subgrade, and projected traffic applications, the structural number for the future traffic loadings (SN_y) was determined using Figure 7.11.

NOMOGRAPH SOLVES:

$$\log_{10} W_{18} = Z_R * S_o + 9.36*\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32*\log_{10} M_R - 8.07$$

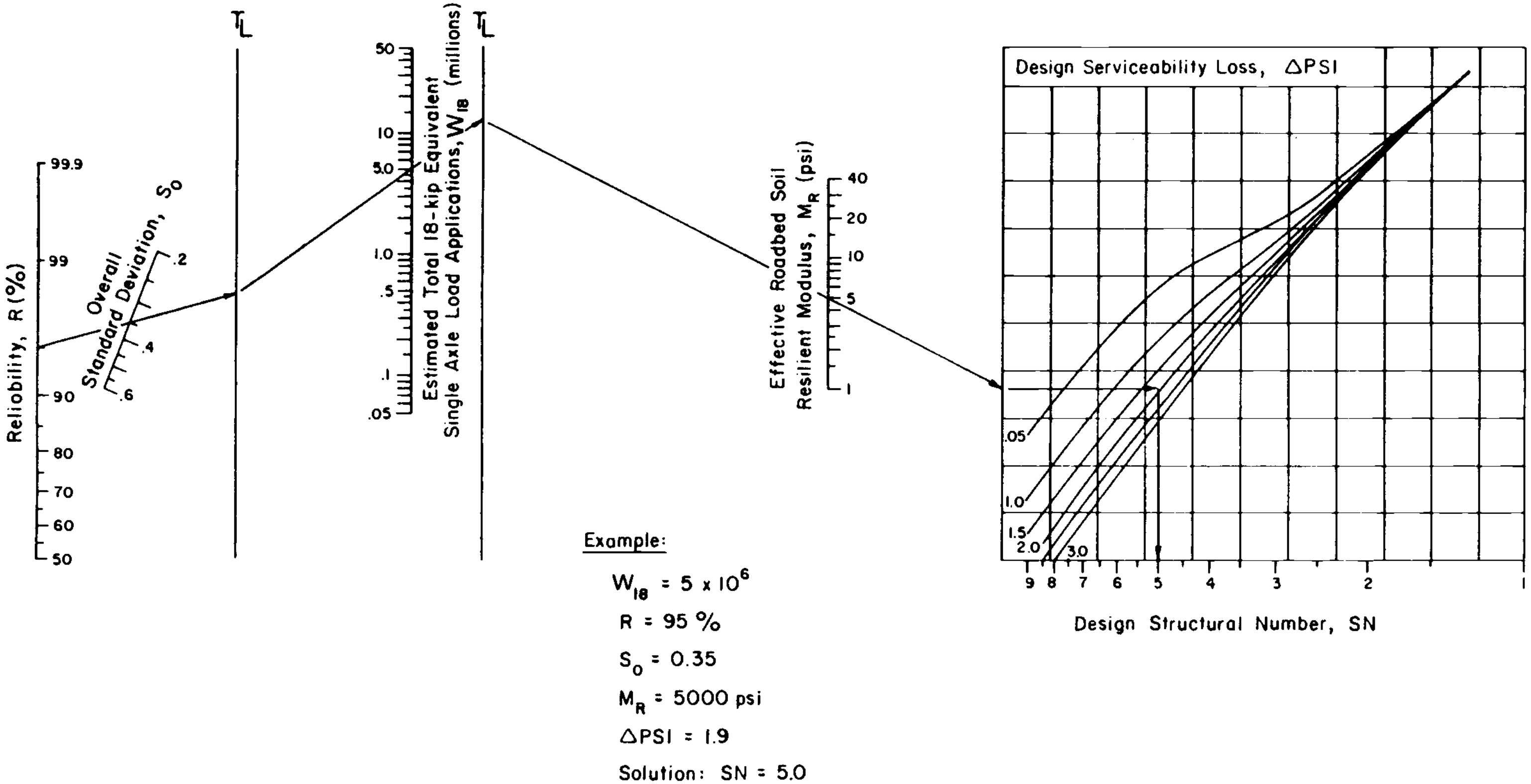


Figure 7.11 Design Chart for Flexible Pavements Based on Using Mean Values for Each Input (AASHTO, 1986)

The remaining life factor (F_{RL}) is a function of remaining life of the existing pavement (R_{LX}) and the remaining life of the overlaid pavement (R_{LY}). The R_{LX} may be determined using one of five approaches: NDT approach, traffic approach, time approach, serviceability approach, or visual condition survey approach. In this study, the NDT approach was used. The R_{LY} can be determined using Figure 7.11 and projected traffic applications. The F_{RL} can then be estimated using Figure 7.12.

The following equation is used to determine structural capacity required by an overlay:

$$SN_{OL} = SN_y - F_{RL} * SN_{xeff} \qquad (7\text{-}8)$$

where:

SN_{OL} = structural number required by an overlay, and

SN_y, F_{RL}, and SN_{exff} are defined in text.

Table 7.12 summarizes the overlay design results for the four projects using the AASHTO NDT Method 1. Calculations of the structural numbers (SN_{OL} and SN_{xeff}) may be found in Appendix I. The layer coefficient for the overlay material was assumed to be 0.42, a value typically used in Oregon.

7.2.3 The Asphalt Institute Design Procedure

The Asphalt Institute design procedure was used (prior to 1987) by the Alaska Department of Transportation and Public Facilities (ADOT&PF) as the official approach for flexible overlay design. This approach is a deflection-based method. In Alaska, pavement deflections are measured using FWD equipment. The recorded pavement deflections are used to determine a Representative Rebound Deflection

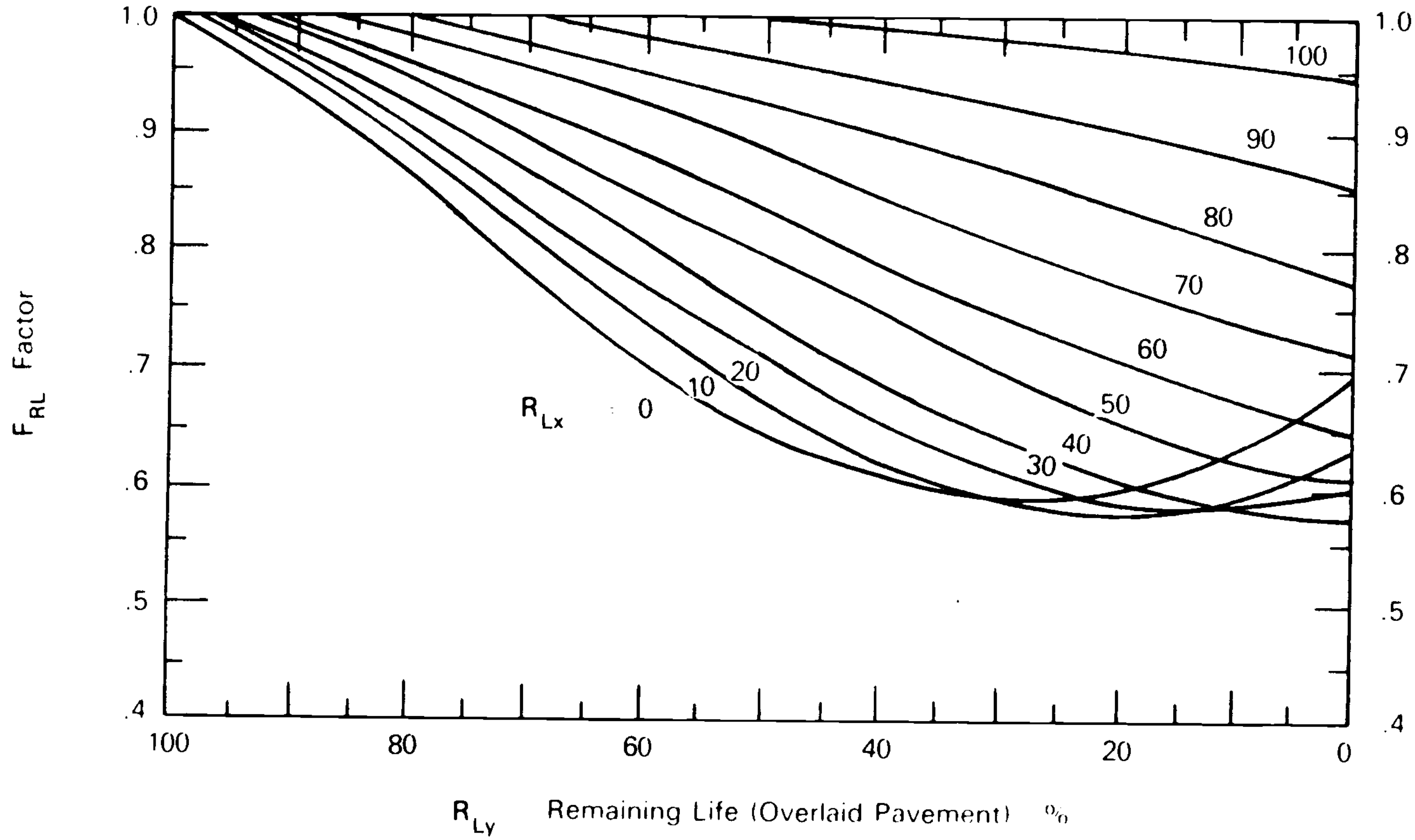


Figure 7.12 Remaining Life Factor (AASHTO, 1986)

Table 7.12 Overlay Thickness Design Using AASHTO Procedure

Project Name	SN_{xeff}	SN_y	SN_{OL}	Overlay Thickness
Rufus-Quinton	4.20	3.69	1.11	2.6
Centennial Blvd	3.24	2.75	0.78	1.9
Nelchina	2.19	2.57	1.21	2.9
Tudor	2.96	2.11	0.00	0.0

(RRD) for the design section. This value is the mean of the measured deflections which have been multiplied by a temperature adjustment factor for reference to 70°F and if necessary, a critical period adjustment factor, plus two standard deviations. The RRD is calculated using the following equation:

$$RRD = (X + 2S)*f*c \tag{7-9}$$

where:

X = mean deflection adjusted for temperature,

S = Standard deviation,

f = temperature adjustment factor (Figure 7.13), and

c = critical period adjustment factor.

With the knowledge of the RRD and projected traffic applications, Figure 7.14 is used to determine required overlay thickness. Table 7.13 summarizes the overlay designs for the four projects. Detailed deflection data used in this procedure may be found in Appendix H.

7.3 Comparison of Design Results

The results of overlay design from four procedures are summarized and presented in Table 7.14. It appears that the results from MECHOD, ODOT, and AASHTO procedures are very compatible. Overlay thicknesses from The Asphalt Institute Method seem to be consistently less than the other procedures. Although there is no conclusion as to which method provides the best solution, the results from MECHOD for the four projects evaluated are compared favorably with those standard procedures. This indicates that the improved procedure has the capability of determining the overlay design thickness, which compares reasonably well to those using the standard procedures. The

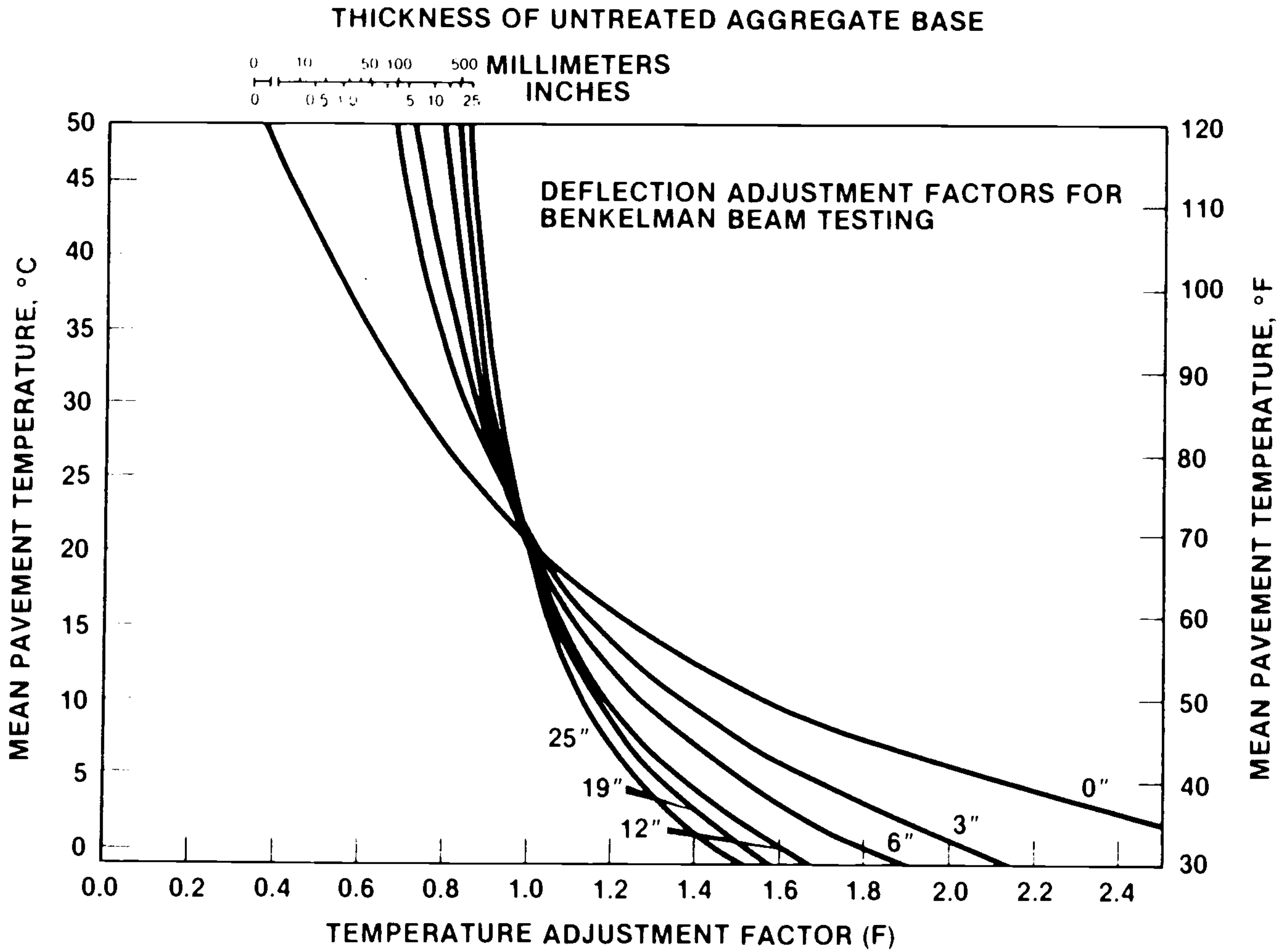


Figure 7.13 Temperature Correction Factors Used in The Asphalt Institute Procedure (TAI, 1983)

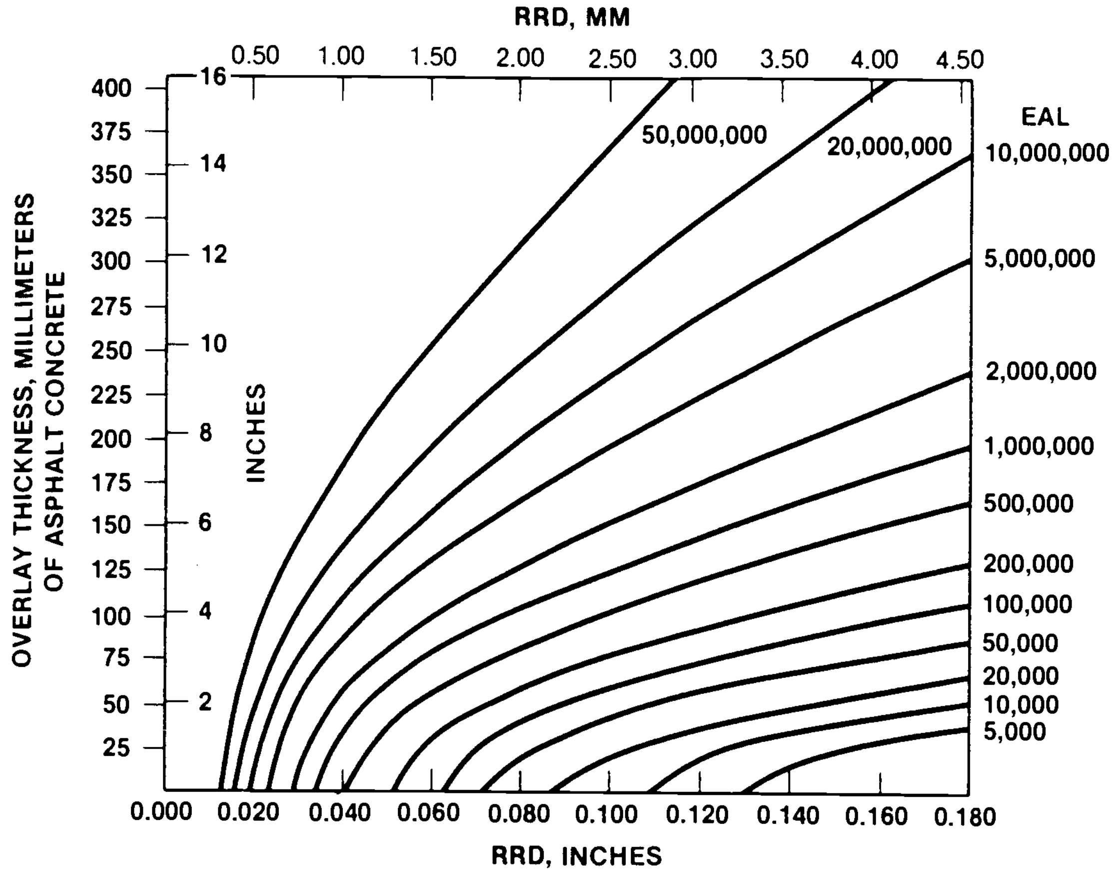


Figure 7.14 Asphalt Concrete Overlay Thickness Required to Reduce Pavement Deflections from a Measured to a Design Deflection Value (Rebound Test) (TAI, 1983)

Table 7.13 Overlay Thickness Design Using TAI Procedure

Project Name	X	S	f	RRD	Overlay
Rufus-Quinton	12.06	2.46	0.98	16.63	1.5
Centennial Blvd	18.67	4.12	0.99	26.65	1.0
Nelchina	27.79	5.89	1.30	51.44	2.5
Tudor	11.11	3.14	1.30	22.62	0.0

Table 7.14 Comparison of Overlay Design Results

Project Name	Overlay Thickness (in)			
	MECHOD	ODOT	AASHTO	TAI
Rufus-Quinton	4.0	2.8	2.6	1.5
Centennial Blvd	2.0	2.0	1.9	1.0
Nelchina	3.0	2.8	2.9	2.5
Tudor	1.0	0.0	0.0	0.0

results also indicate that the failure criteria used in MECHOD are appropriate for the projects evaluated.

7.4 Summary

This chapter accomplished an initial evaluation of the improved mechanistic overlay design procedure using actual pavement data from the states of Oregon and Alaska. All pavements evaluated are conventional pavements consisting of an AC surface, an aggregate base and/or a subbase, and subgrade. The overlay design results from the improved procedure are compared with three standard procedures developed by ODOT, AASHTO, and The Asphalt Institute. The results show that the improved method provides results very close to those of the standard procedures.

However, the advantages or benefits of using mechanistic type of analysis is not just limited to the conventional overlay thickness design. As indicated in Chapter 1, the mechanistic approach allows the designer to consider the fundamental properties of pavement materials used, to consider changes in loading and tire pressure, to consider the environmental impact on material properties as well as to consider pavement structural performance in terms of stresses and strains. These characteristics of mechanistic approach provide the designer with better means to address pavement structural design more realistically and rationally. The standard overlay design procedures are not able to address these issues fully.

8.0 CONCLUSIONS AND RECOMMENDATIONS

As stated at the beginning of this dissertation, the major objectives of the research are to develop a mechanistic overlay design procedure for flexible pavements and to computerize the procedure for routine design work. These objectives have been successfully accomplished. The work completed in this study includes the following:

1. A through review of some fundamental concepts and techniques used in this research (Chapter 2).
2. An extensive review of backcalculation methods for determining pavement layer moduli using NDT methods (Chapter 3).
3. Development of an improved backcalculation program (Chapter 4).
4. Determination of pavement moduli using laboratory tests and developed correlations (Chapter 5).
5. Review of existing mechanistic overlay design methods and development of an improved mechanistic overlay design procedure (Chapter 6).
6. Evaluation of the improved mechanistic overlay design procedure (Chapter 7).

Two microcomputer programs have been developed as a result of this study, 1) BOUSDEF, a backcalculation program for determining pavement layer moduli, and 2) MECHOD, a computerized mechanistic overlay design procedure. Copies of these are available from the author for a nominal charge.

Based on the research performed, the following conclusions, recommendations for implementation, and recommendations for further study appear warranted.

8.1 Conclusions

Specific conclusions resulting from this study include:

1. The multi-layered elastic theory has been successfully used to model a flexible pavement structure for many years, and it will still be used as a primary model for the flexible pavements. An on-going research effort (NCHRP project 1-26), suggests that this pavement model will be used in the future editions of the AASHTO Pavement Design Guide.

2. The use of method of equivalent thicknesses (MET) simplifies a multi-layer pavement system. A representative modulus is used to convert the multi-layer system into a half-space system so that Boussinesq theory can be applied to calculate stresses, strains, and deformations for the pavement structure under the action of loads. Initial comparisons on ten pavement structures indicate that both the multi-layer elastic and Boussinesq theories provide very similar results in conventional and PCC pavements. This comparison provides a solid indication that Boussinesq theory can be used for calculating pavement stresses, strains, and deformations.

3. From the above conclusion, an improved backcalculation program (BOUSDEF) has been developed. It includes the use of the method

of equivalent thicknesses and Boussinesq theory. Significant improvements of this backcalculation procedure over other backcalculation methods include the consideration of non-linearity of pavement materials and consideration of overburden pressure on stress calculation, particularly the computing speed. Evaluation of the program was performed using three approaches: 1) comparing with hypothesized theoretical moduli, 2) comparing with other developed backcalculation programs, and 3) comparing with laboratory tested modulus values. The evaluation shows that the moduli backcalculated using the BOUSDEF program compare very well with the theoretical moduli and also are very comparable to results from other developed programs. The backcalculated results on selected projects also compare favorably with the laboratory test results. The BOUSDEF program is very fast when compared to other backcalculation programs. Therefore, the program can be effectively used as a tool to make initial evaluation of deflection testing data for determining pavement layer moduli.

4. An improved mechanistic overlay design procedure has been developed. The developed procedure uses a linear elastic program (ELSYM5) as its subroutine to calculate pavement stresses and strains, and fatigue criteria developed by the Asphalt Institute to evaluate pavement life. Significant improvement of this design procedure is in the consideration of seasonal effects which have substantial influence on pavement structural performance. This improvement allows practicing engineers to

analyze, design, and evaluate a pavement structure more realistically and closer to the actual environmental condition. Design results from this procedure were compared with the results from standard methods: Oregon DOT's, AASHTO's, and the Asphalt Institute's. A favorable comparison was observed.

8.2 Recommendations for Implementation

Much of the work accomplished appears ready for implementation. This includes:

1. For deflection tests, at least four deflection sensors should be used to measure the pavement deflection, and at least one sensor should be located far enough away to obtain the response purely from the subgrade. A procedure, as described by Hicks, et al (1988), can be used for determining the location of the last sensor. The use of four sensors is to ensure that the deflection response from all pavement layers is obtained and a better deflection basin is defined.

2. Deflection tests should be carefully performed. Deflections should be measured as accurately as possible. Specifically, the deflections should be measured to the 100th of a mil (±0.00001"). Also, pavement thickness should be measured as accurately as possible, specifically, to the 10th of an inch. Since these two factors are crucial in the backcalculation analysis. The output cannot be good if the input is not good.

3. Although in the initial evaluation stage, the BOUSDEF program

provided favorable results as compared to those of theoretical values, other developed programs, and laboratory tests, caution should still be exercised. At present time, the BOUSDEF program is recommended to make initial evaluation of the NDT test data. Other developed programs (e.g., BISDEF and ELSDEF) are suggested for verification.

4. Laboratory tests on resilient modulus of pavement materials should be performed, particularly the subgrade soils. The number of samples to be tested may be determined based on project size. The tests are used primarily for verification purposes. Correlations described in Chapter 5 may also be used as a reference in case neither backcalculation nor laboratory test results are available.

5. The BOUSDEF and MECHOD programs can be used together as a pavement evaluation and overlay design system. The use of these two programs provides engineers with a better means to evaluate existing pavements and to perform overlay designs. The procedures to use the programs are as follows:
    a. Once the deflection data are obtained, one may use the BOUSDEF program to backcalculate pavement layer moduli.
    b. Traffic data and design load, and the backcalculated moduli (after engineering judgement or modification), can be used as inputs to the MECHOD program to perform overlay design.

6. The MECHOD program can be used for several purposes. By selecting the number of season(s), pavement damage incurred in a particular period of the year may be determined. By considering overlay material properties, evaluation of the use of different paving materials becomes possible. By equating the materials properties for the overlay and existing pavement, the program may also be used for new pavement structural design.

8.3 Recommendations for Further Research

Based on the studies to date, it appears additional study is needed in the following areas:

1. Further verification of the backcalculation with laboratory test results should be conducted, and on a relatively large scale. The purpose of this verification is to gain experience or confidence in using the backcalculation technique to determine pavement layer moduli. The verification can be conducted by selecting more pavement projects and following the procedures used in this study. On the same project, both deflection and laboratory tests should be performed for each season, if possible. This is done to evaluate the seasonal effects on pavement material properties determined through both backcalculation and laboratory tests. It is not expected that the backcalculated results will perfectly match the laboratory results, however, a correlation between the two might be developed.

2. The selection of design criteria seems to be a major issue in mechanistic pavement design. It is encouraged that agencies develop their own fatigue criteria for the materials they use. The criteria may be developed in the laboratory where an accelerated field simulation can be conducted. However, the laboratory results must be calibrated to the field condition so that a more reasonable prediction of pavement performance can be obtained. In recent years, Accelerated Loading Facility (ALF) is used to evaluate in-service pavement performance. The ALF test is expected to be very useful for developing design criteria, which can be used in a mechanistic design procedure.

3. For BOUSDEF, the nonlinear analysis of granular base should consider the average base stress rather than stress at a specific location. An algorithm needs to be developed to resolve this issue. Also, it would be ideal if the program would be able to determine the rock depth based on NDT deflection test data, since the pressure of a rock layer has considerable influence on the backcalculated results. The determination of the rock depth may improve the backcalculated results.

4. For MECHOD, the program at present time accepts only one design load (e.g. use one 9,000 lb wheel load to represent two 4,500 lb dual wheel loads). It is recommended that the program be improved to accept at least two loads so that dual wheel loads can be analyzed.

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APPENDICES

APPENDIX A BOUSDEF USER'S GUIDE

A-1 Introduction

BOUSDEF was developed at Oregon State University to determine in-situ pavement layer moduli using deflection data through backcalculation technique. The program is based on the method of equivalent thicknesses and Boussinesq theory. The backcalculated moduli may be used for evaluating the existing pavement and/or mechanistic overlay design.

BOUSDEF can be operated on any IBM or compatible microcomputers with a DOS version 3.1 or higher. BOUSDEF is an integrated program which includes creating, editing, and analyzing a data file functions. A menu screen of the program is shown in Figure A-1. Three selections can be made and each of them is discussed in the following.

A-2 Create Data File

This option allows the user to create a data file for later analysis. By pressing key C (Create) or 2 in the main menu, the program will ask for a file name and display a data input screen as shown in Figure A-2. The data input screen provides a friendly environment for data entry. The user may use cursor keys to move the cursor to any fields and enter required data. If the [F1] key is pressed, the program will display a brief explanation of what information is required for the field. After entering all necessary information, the user may press function key [F8] to run the data right away. The analysis results will be displayed and the program will return to the data input screen for possible edit. Function key [F10] allows the user to save a data file under same filename or under a new filename. If the data is not going be saved, press Esc key.

The following information are needed to create a file:

1. Number of layer (required) - total pavement layers, including subgrade.
2. Number of layer for modulus (required).

```
This program allows user to backcalculate pavement
layer moduli from deflection basin data. The program
was developed for use with Falling Weight Deflecto-
meter (FWD) data. However, other NDT data may also
be used with some modification of the data.

            [1].  Edit a Data File

            [2].  Create a Data File

            [3].  Analyze a Data File

            Enter your selection

                 Press Esc to Exit
```

Figure A-1 BOUSDEF Menu Screen

Pavement Structure Data
Number of Layers: 0 File Name: EXAMPLE

Layer No.	Layer for M	Thickness (inch.)	Poisson Ratio	Minimum Modulus	Maximum Modulus	Initial Modulus	Density (pcf)
1.	1	0.00	0.00	0	0	0	0.0
2.	1	0.00	0.00	0	0	0	0.0
3.	1	0.00	0.00	0	0	0	0.0
4.	0	0.00	0.00	0	0	0	0.0
5.	0	0.00	0.00	0	0	0	0.0

Deflection Measurement Data
Load Plate Radius: 0.00
Number of Sensors: 0

	Load (lb)	Deflection Readings at Corresponding Sensor Locations						
Sensor Locations :		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Test 1:	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test 2:	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test 3:	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Test 4:	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Tolerance (%): 10 Number of Iterations: 3

F1=Help F8=Run F10=Save Esc=Exit (No save)

Figure A-2 BOUSDEF Data Input/Edit Screen

3. Tolerance (required) - deflection error tolerance to stop program execution. Usually set at 5-10 percent.
4. Number of iterations (required) - usually set at three iterations.
5. Layer for modulus (required) - 1 for calculating modulus for the layer. In this case, minimum, maximum, and initial modulus must be provided. 0 for not calculating modulus for the layer. In this case, minimum and maximum moduli are not required. Initial modulus must be given and is treated as fixed value for the layer.
6. Layer thickness (required, except subgrade) - in inches.
7. Poisson's ratio (required) - for asphalt concrete, Poisson's ratio = 0.35.
8. Minimum and maximum modulus (required if modulus for the layer needs to be calculated) - in psi. These values are used to set up the range of possible modulus.
9. Initial modulus (required) - if layer for modulus is set at 0, this value will be used as a fixed modulus for the layer.
10. Number of sensors (required) - maximum 7.
11. Sensor spacings (required) - in inches. Starts from load center line.
12. Test (required) - Four tests can be entered. Load in pounds, deflection in mils. Maximum 7 deflections allowed.

The input data are saved in a text file in ASCII form and can be accessed and edited be the program or by other word processor software.

A-3 <u>Edit Data File</u>

This option allows the user to edit a data file that has been created previously. By pressing key E (Edit) or 1 in the menu screen (Figure A-1) and providing a file name to be edited, the same screen used to create the data file will be displayed. The information saved in the existing data file will be shown in corresponding fields. The user may use cursor keys to move to each filed and edit. After editing all necessary information, the user may press function key [F8] to run the data right away. The analysis results will be displayed and the program will return to the data edit screen for further edit. Function key [F10] allows the user to save a data file under same filename or under a new filename. If the edited data is not going be saved, press Esc key.

A-4 Analyze Data File

This option allows the user to analyze a data file created previously. By pressing key A (Analyze) or 3 and giving the file name to be analyzed, the calculation will begin.

A-5 Output

The output will be displayed on the screen. The output include pavement modulus for each layer, bulk stress (BSTRS) and deviator stress (DSTRS), NDT load, and material coefficient k_1 and k_2.

APPENDIX B

DEFLECTION TEST RESULTS FOR SELECTED PROJECTS

This appendix presents detailed deflection data used in this study. These data include:

- B-1 Rufus - Quinton Project
- B-2 Centennial Boulevard Project
- B-3 Nelchina Project
- B-4 Tudor Project

The deflection data on the Rufus-Quinton project were provided by Oregon Department of Transportation (ODOT). The Centennial Project data were provided by Pavement Services, Inc. of Portland. Alaska Department of Transportation and Public Facilities (ADOT&PF) furnished deflection data test data for both Nelchina and Tudor projects.

Appendix B-1 Rufus - Quinton Project

DISK FILE: RUFUS1.DAT

SITE DATA:

Date	08-01-89
Time	07:42
Dist. No.	4
County Name	GILLIAM
Roadway No.	4
Lane desig.	2
Dist. from Rt. edge	OWT
Begin Mile Post	115.00
Offset	EB RTLN
End Mile Post	116.00
Offset	250' INT
Surface Type	AC
Operator	DOUG H.

SENSOR LOCATIONS:

Sensor#	Location
1	0B
2	8B
3	12B
4	24B
5	36B
6	58F

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	1	N	N	N	N
2	1	Y	Y	N	Y
3	2	Y	Y	N	Y
4	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
45.	8396.8500	.516	.464	.511	.219	.217	.297

TIME SERIES SCALE FACTOR (LOAD) : 1.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	115.000	1	*****	3199.	4.38	3.65	2.79	2.30	.57	.24
1	115.000	2	*****	6398.	7.81	7.49	5.78	3.45	1.31	.54
1	115.000	3	*****	11934.	12.61	11.43	9.08	5.97	2.32	1.08
2	115.051	1	*****	3158.	4.06	3.56	2.27	1.59	.53	.24
2	115.051	2	*****	6685.	9.17	8.24	5.57	3.40	1.66	.90
2	115.051	3	*****	11811.	19.38	13.86	10.32	6.99	3.55	1.86
3	115.101	1	*****	3199.	3.44	3.09	1.86	1.24	.48	.36
3	115.101	2	*****	6726.	7.50	6.74	4.85	2.96	1.58	1.08
3	115.101	3	*****	11852.	11.25	11.43	8.36	5.26	3.15	2.16
4	115.150	1	*****	2953.	4.58	3.37	2.27	1.24	.39	.24
4	115.150	2	*****	6603.	9.69	7.31	5.16	3.14	1.10	.48
4	115.150	3	*****	11852.	15.21	11.05	8.15	4.55	2.28	1.08
5	115.200	1	*****	3158.	4.90	4.22	2.89	1.72	.66	.42
5	115.200	2	*****	6603.	10.73	9.37	6.81	3.76	1.71	1.20
5	115.200	3	*****	11811.	16.67	14.05	11.04	6.37	3.33	2.40
6	115.250	1	*****	2830.	6.77	5.06	3.40	1.37	.35	.18
6	115.250	2	*****	6521.	13.02	9.65	6.91	3.05	.96	.42
6	115.250	3	*****	12057.	18.02	13.86	10.01	4.51	1.66	.78
7	115.300	1	*****	2830.	5.94	4.12	2.79	1.46	.26	.24
7	115.300	2	*****	6439.	10.31	8.34	5.67	2.56	.88	.60
7	115.300	3	*****	11893.	15.42	12.18	8.77	5.57	1.75	1.02
8	115.351	1	*****	3117.	6.04	4.87	2.99	1.24	.35	.18
8	115.351	2	*****	6439.	11.77	9.46	6.71	4.78	1.01	.42
8	115.351	3	*****	12016.	17.19	13.96	10.21	5.17	1.71	1.08
9	115.400	1	*****	3076.	4.90	3.93	2.27	1.15	.35	.18
9	115.400	2	*****	6480.	9.79	7.78	4.95	2.61	1.23	.60

9	115.400	3	*****	11852.	13.33	11.90	7.84	3.94	1.97	1.02
10	115.451	1	*****	3076.	5.94	4.97	2.68	1.41	.48	.18
10	115.451	2	*****	6480.	11.88	9.93	6.60	3.23	1.40	.60
10	115.451	3	*****	11770.	17.61	15.27	10.52	6.41	2.94	1.26
11	115.500	1	*****	2871.	6.67	5.43	3.71	1.64	.53	.36
11	115.500	2	*****	6439.	14.27	11.62	8.56	4.38	1.62	.66
11	115.500	3	*****	11893.	21.88	18.17	13.93	7.38	3.24	1.26
12	115.551	1	*****	3076.	5.73	4.31	2.89	1.41	.48	.24
12	115.551	2	*****	6398.	12.40	9.84	7.22	3.58	1.62	.66
12	115.551	3	*****	11975.	19.79	15.93	12.48	6.85	3.42	1.38
13	115.600	1	*****	3035.	6.35	5.06	3.61	1.99	.70	.06
13	115.600	2	*****	6357.	13.13	10.49	7.94	3.94	1.75	.60
13	115.600	3	*****	11852.	18.96	15.27	10.83	6.63	3.15	.72
14	115.651	1	*****	2871.	7.19	5.62	3.92	2.30	.96	.66
14	115.651	2	*****	6357.	13.75	11.34	8.46	4.91	2.37	1.20
14	115.651	3	*****	11893.	19.90	16.58	12.90	7.65	4.07	2.22
15	115.700	1	*****	2912.	4.38	3.09	1.86	.84	.00	.12
15	115.700	2	*****	6439.	8.86	6.46	4.13	1.86	.57	.60
15	115.700	3	*****	12016.	13.33	9.56	6.60	3.14	1.27	.96
16	115.751	1	*****	3117.	5.00	3.65	2.06	1.24	.31	.36
16	115.751	2	*****	6644.	9.69	7.31	4.95	2.34	1.01	.66
16	115.751	3	*****	12139.	14.79	11.71	8.36	4.20	2.23	1.44
17	115.802	1	*****	3035.	5.00	4.31	2.27	.88	.35	.30
17	115.802	2	*****	6398.	9.90	7.96	5.06	2.12	1.14	.84
17	115.802	3	*****	12180.	15.11	12.46	8.77	4.29	2.54	1.80
18	115.851	1	*****	3076.	2.71	2.81	1.86	1.33	.44	.66
18	115.851	2	*****	6685.	7.81	6.56	4.54	2.96	1.66	1.26
18	115.851	3	*****	11975.	12.50	10.77	8.36	5.39	3.29	2.46
19	115.904	1	*****	3117.	3.44	3.00	1.86	1.19	.31	.36
19	115.904	2	*****	6644.	8.23	6.93	4.64	2.56	1.05	.84
19	115.904	3	*****	12221.	11.46	11.15	8.25	4.69	2.41	1.62
20	115.958	1	*****	3117.	5.00	3.75	2.48	1.28	.35	.12
20	115.958	2	*****	6726.	10.52	8.34	5.78	2.92	1.27	.60
20	115.958	3	*****	12221.	16.36	12.93	9.90	5.22	2.54	1.32
21	116.000	1	*****	3035.	4.58	3.93	2.89	1.64	.70	.48
21	116.000	2	*****	6685.	10.11	8.99	6.91	5.22	2.06	1.44
21	116.000	3	*****	12016.	16.15	14.15	11.45	10.08	4.07	2.34

TEST ..LOC. HT COMMENTS ====>

1	115.0000	3	PAVEMENT TEMPERATURE IS 66 DEGREES.
21	116.0000	3	END TEST SECTION.

DISK FILE: RUFUS2.DAT

SITE DATA:

Date	08-01-89
Time	09:08
Dist. No.	4
County Name	GILLIAM
Roadway No.	2
Lane desig.	2
Dist. from Rt. edge	OWT
Begin Mile Post	116.00
Offset	WB. RTLN
End Mile Post	115.00
Offset	250' INT
Surface Type	AC
Operator	DOUG H.

SENSOR LOCATIONS:

Sensor#	Location
1	0B
2	8B
3	12B
4	24B
5	36B
6	58F

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	1	N	N	N	N
2	1	Y	Y	N	Y
3	2	Y	Y	N	Y
4	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
45.	8396.8500	.516	.464	.511	.219	.217	.297

TIME SERIES SCALE FACTOR (LOAD) : 1.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	116.000	1	*****	3240.	4.27	4.12	2.99	1.72	.70	.48
1	116.000	2	*****	6521.	9.58	8.81	6.50	3.94	2.15	1.14
1	116.000	3	*****	12057.	15.11	13.58	10.83	6.81	3.90	2.22
2	115.950	1	*****	3158.	5.21	4.50	3.10	1.77	.74	.60
2	115.950	2	*****	6685.	11.15	8.81	6.91	4.07	2.02	1.32
2	115.950	3	*****	11975.	17.40	14.24	11.04	6.81	3.68	2.52
3	115.920	1	*****	3199.	4.38	3.75	2.68	1.64	.70	.60
3	115.920	2	*****	6480.	8.75	7.78	5.88	3.63	1.88	1.20
3	115.920	3	*****	12385.	13.65	11.80	9.70	6.15	3.55	2.04
4	115.850	1	*****	3076.	4.79	4.22	2.79	1.81	.79	.66
4	115.850	2	*****	6808.	10.42	8.62	6.29	4.11	1.97	1.38
4	115.850	3	*****	12262.	16.25	13.49	10.52	6.72	3.81	2.52
5	115.800	1	*****	3199.	3.96	3.19	2.06	1.28	.39	.18
5	115.800	2	*****	6808.	8.23	7.03	5.16	2.96	1.23	.48
5	115.800	3	*****	12057.	12.92	10.59	8.46	4.82	2.23	.84
6	115.750	1	*****	3199.	2.40	2.15	.93	1.19	.44	.30
6	115.750	2	*****	6767.	5.52	4.87	3.51	2.61	1.23	.72
6	115.750	3	*****	12303.	9.58	7.96	6.60	4.73	2.58	1.86
7	115.715	1	*****	3199.	4.17	3.65	2.17	1.24	.35	.00
7	115.715	2	*****	6849.	8.65	7.31	5.26	2.87	1.10	.12
7	115.715	3	*****	12303.	13.33	11.43	8.36	4.69	2.02	.42
8	115.650	1	*****	3117.	5.94	5.15	3.71	2.12	.79	.42
8	115.650	2	*****	6644.	12.61	11.05	8.36	4.86	2.23	1.14
8	115.650	3	*****	12221.	19.90	17.52	13.52	8.14	4.16	2.28
9	115.600	1	*****	3199.	5.00	4.50	3.10	2.03	1.01	.54
9	115.600	2	*****	6767.	10.63	9.65	7.33	4.69	2.28	1.32
9	115.600	3	*****	12098.	16.77	14.99	12.07	7.52	4.03	2.76
10	115.550	1	*****	3076.	3.02	2.53	1.44	.71	.04	.12
10	115.550	2	*****	6808.	6.67	5.25	3.61	1.99	.92	.30
10	115.550	3	*****	12180.	11.25	9.37	6.40	3.58	1.58	.66
11	115.500	1	*****	3117.	3.96	3.19	2.17	.84	.04	-.12
11	115.500	2	*****	6808.	6.77	5.90	4.02	1.86	.39	.24
11	115.500	3	*****	12344.	9.69	8.71	6.29	2.92	1.05	.42
12	115.450	1	*****	3076.	6.25	5.15	3.40	2.08	.74	.36
12	115.450	2	*****	6726.	12.08	10.59	7.63	4.51	2.02	.90
12	115.450	3	*****	12262.	18.02	15.46	12.28	6.94	3.50	1.56
13	115.400	1	*****	3117.	5.63	4.12	2.99	1.86	.70	.36
13	115.400	2	*****	6808.	10.94	8.81	6.50	3.94	1.75	.78
13	115.400	3	*****	12344.	16.36	13.12	10.11	6.46	3.20	1.56
14	115.350	1	*****	3199.	4.06	3.19	2.17	1.28	.31	.06
14	115.350	2	*****	6767.	8.44	6.84	5.06	2.74	1.10	.30
14	115.350	3	*****	12344.	12.81	10.40	7.94	4.33	2.10	.72
15	115.300	1	*****	3199.	4.27	3.37	2.48	1.11	.22	.12
15	115.300	2	*****	6767.	8.33	6.46	4.54	2.12	.88	.12
15	115.300	3	*****	12385.	11.77	9.46	7.33	3.58	1.40	.36
16	115.250	1	*****	3117.	5.52	4.22	2.99	1.37	.39	.24
16	115.250	2	*****	6849.	10.31	8.71	6.50	2.87	1.23	.66
16	115.250	3	*****	12303.	15.31	12.74	10.11	4.91	2.32	1.38
19	115.200	1	*****	3158.	3.65	3.00	1.96	1.19	.48	.42
19	115.200	2	*****	6767.	6.98	6.56	4.64	2.96	1.45	.84
19	115.200	3	*****	12098.	11.46	10.59	8.05	5.13	2.89	1.92
20	115.150	1	*****	3158.	3.13	2.44	1.34	.84	.13	.00
20	115.150	2	*****	6685.	6.67	5.06	3.40	1.95	.74	.36
20	115.150	3	*****	12221.	11.25	8.34	5.98	3.49	1.62	.84
21	115.100	1	*****	3158.	3.75	3.56	1.86	1.46	.57	.24
21	115.100	2	*****	6685.	8.13	7.21	5.06	3.14	1.58	1.02
21	115.100	3	*****	12139.	12.61	10.87	8.36	5.17	2.67	1.92
22	115.100	1	*****	3158.	4.48	3.84	2.58	1.59	.57	.48
22	115.100	2	*****	6726.	9.38	7.78	5.98	3.49	1.66	1.02

22	115.100	3	*****	11852.	14.48	12.37	9.59	5.70	2.94	2.04
23	115.050	1	*****	3117.	4.06	3.84	2.48	1.59	.66	.42
23	115.050	2	*****	6726.	9.27	8.24	5.78	3.45	1.53	.90
23	115.050	3	*****	12139.	14.79	12.93	9.70	5.75	2.98	1.74
24	115.000	1	*****	3117.	4.69	3.65	2.27	1.41	.35	.30
24	115.000	2	*****	6685.	9.90	7.78	5.67	3.01	1.23	.78
24	115.000	3	*****	12180.	14.17	12.18	9.80	5.35	2.72	1.74

TEST ..LOC. HT COMMENTS ====>
1 116.0000 3 PAVEMENT TEMPERATURE IS 78 DEGREES.
24 115.0000 3 END TEST SECTION.

B-2 Centennial Boulevard Project

DISK FILE: CENT3.DAT

SITE DATA:

Date	04-03-89
Time	09:57
Dist. No.	
County Name	
Roadway No.	
Lane desig.	E
Dist. from Rt. edge	
Begin Mile Post	BRIDGE
Offset	
End Mile Post	
Offset	
Surface Type	
Operator	DB

SENSOR LOCATIONS:

Sensor#	Location
1	0F
2	12B
3	24B
4	36B
5	60F
6	99B

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	3	N	N	N	N
2	2	Y	Y	N	Y
3	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
0.	5902.0000	.521	.512	.509	.251	.280	.280

TIME SERIES SCALE FACTOR (LOAD) : 5902.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	200.	2	54.	8821.	16.09	12.09	8.53	6.18	2.88	7.07
1	200.	3	54.	14269.	24.72	18.61	13.57	9.88	4.92	12.21
2	400.	2	53.	8821.	19.35	12.61	7.60	5.88	3.17	5.94
2	400.	3	52.	14297.	28.40	18.81	12.33	9.63	5.77	10.06
3	600.	2	55.	8763.	20.30	13.85	9.25	6.59	2.43	7.63
3	600.	3	55.	14269.	29.98	21.29	14.90	10.69	4.52	13.62
4	800.	2	62.	8705.	18.72	13.13	8.43	6.03	2.71	7.46
4	800.	3	61.	14153.	27.24	20.26	13.57	9.98	4.81	12.38
5	1000.	2	59.	8849.	21.35	14.58	9.15	6.13	2.83	7.18
5	1000.	3	58.	14240.	31.66	22.12	14.49	10.29	4.35	12.72
6	1200.	2	59.	8763.	20.41	12.71	8.02	5.42	2.20	5.88
6	1200.	3	57.	14240.	29.77	19.64	13.05	9.17	3.90	12.04
7	1400.	2	57.	8792.	19.25	12.30	7.60	4.76	1.64	6.16
7	1400.	3	56.	14211.	29.24	19.33	12.64	8.11	3.90	12.49
8	1600.	2	60.	8734.	22.72	14.37	8.63	6.08	2.71	7.80
8	1600.	3	59.	14182.	33.98	21.81	14.18	9.78	4.81	14.25
9	1800.	2	54.	8734.	21.77	14.58	9.87	6.54	2.71	8.31
9	1800.	3	54.	14153.	32.92	22.33	15.31	10.74	4.92	15.77
10	2000.	2	58.	8763.	17.15	12.30	8.63	5.93	2.32	7.18
10	2000.	3	57.	14211.	26.82	19.23	13.87	9.83	4.24	12.78
11	2200.	2	62.	8676.	23.88	15.82	9.87	6.64	2.26	7.46
11	2200.	3	60.	14067.	35.24	24.19	15.83	10.95	4.30	14.30
12	2400.	2	59.	8763.	20.09	13.23	8.22	5.12	2.66	7.18
12	2400.	3	59.	14182.	30.19	20.05	13.15	8.67	4.81	13.68
13	2600.	2	64.	8734.	14.41	8.48	4.73	2.79	1.07	3.22

13	2600.	3	64.	14269.	20.83	12.30	6.89	4.36	1.92	6.50
14	2800.	2	55.	8705.	21.67	12.09	6.27	3.70	1.13	4.13
14	2800.	3	55.	14124.	30.82	17.78	9.56	5.83	2.37	8.59
15	3000.	2	56.	8676.	13.15	7.86	4.52	2.84	1.24	3.11
15	3000.	3	56.	14211.	19.25	11.78	7.50	4.81	2.20	5.94
16	3200.	2	53.	8648.	10.73	6.41	3.39	2.03	.62	2.32
16	3200.	3	53.	14067.	15.67	9.41	5.34	3.29	1.47	4.24
17	3400.	2	52.	8648.	15.67	9.82	5.96	3.85	1.53	3.96
17	3400.	3	52.	13923.	23.46	14.68	9.45	6.54	2.60	7.07
18	3600.	2	60.	8705.	13.88	8.17	4.11	2.64	1.19	3.11
18	3600.	3	61.	14182.	20.83	12.82	6.68	4.21	1.92	6.56
19	3800.	2	62.	8676.	12.83	7.96	4.93	3.40	2.04	3.90
19	3800.	3	60.	14240.	18.72	11.89	7.71	5.63	3.45	7.52
20	4000.	2	61.	8705.	11.15	7.03	4.21	2.69	1.36	3.28
20	4000.	3	60.	14211.	16.94	10.54	6.47	4.56	2.71	5.77

DISK FILE: CENT4.DAT

SITE DATA:

Date	04-03-89
Time	11:03
Dist. No.	
County Name	
Roadway No.	
Lane desig.	
Dist. from Rt. edge	E
Begin Mile Post	
Offset	
End Mile Post	
Offset	
Surface Type	
Operator	DB

SENSOR LOCATIONS:

Sensor#	Location
1	0F
2	12B
3	24B
4	36B
5	60F
6	99B

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	3	N	N	N	N
2	2	Y	Y	N	Y
3	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
0.	5902.0000	.521	.512	.509	.251	.280	.280

TIME SERIES SCALE FACTOR (LOAD) : 5902.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	4200.	2	67.	8648.	12.41	8.17	4.93	3.60	2.04	4.52
1	4200.	3	67.	14124.	17.99	11.99	7.81	5.83	3.39	8.31
2	4400.	2	63.	8648.	13.15	8.48	5.34	3.75	2.04	4.24
2	4400.	3	64.	14096.	19.14	12.61	8.43	6.03	3.34	8.14
3	4600.	2	69.	8532.	16.20	11.68	8.02	6.03	3.11	5.99
3	4600.	3	68.	13951.	24.30	17.88	12.85	9.73	5.26	11.08
4	4800.	2	63.	8561.	11.89	8.06	5.14	3.65	2.04	2.94
4	4800.	3	63.	14009.	17.67	11.68	8.02	5.73	3.39	5.03
5	5000.	2	58.	8561.	12.52	8.99	5.96	4.36	2.09	5.03
5	5000.	3	58.	14038.	18.09	13.13	9.15	6.69	3.67	8.71
6	5200.	2	60.	8619.	11.99	8.68	5.86	4.26	2.04	5.20

6	5200.	3	57.	14096.	17.88	12.92	9.15	6.84	3.62	8.54
7	5400.	2	67.	8792.	15.78	11.27	7.50	4.92	1.70	6.50
7	5400.	3	68.	13980.	24.09	17.26	11.92	8.16	3.22	11.76
8	5600.	2	55.	8676.	14.20	9.82	6.37	4.36	2.09	5.99
8	5600.	3	54.	14096.	21.77	15.20	10.58	7.35	3.73	11.59
9	5800.	2	59.	8590.	16.09	11.78	8.63	6.39	3.34	7.07
9	5800.	3	60.	14038.	24.09	18.09	13.57	10.24	5.71	12.21
10	6000.	2	59.	8561.	15.67	11.89	8.53	6.13	2.88	5.88
10	6000.	3	59.	14009.	24.30	18.61	13.77	9.98	4.86	10.68
11	6200.	2	68.	8705.	15.46	10.03	6.99	4.86	2.26	6.11
11	6200.	3	68.	14124.	23.14	15.82	11.10	8.06	4.18	11.65
12	6400.	2	71.	8648.	15.46	11.06	7.30	5.22	2.43	6.84
12	6400.	3	70.	14096.	23.25	16.85	12.02	8.67	4.47	12.61
13	6600.	2	73.	8619.	18.51	13.96	10.38	7.75	3.96	7.80
13	6600.	3	70.	14009.	27.98	21.09	16.13	12.31	6.56	12.78
14	6801.	2	75.	8763.	10.62	8.79	6.89	5.37	2.83	5.26
14	6801.	3	76.	14240.	16.62	13.75	11.20	8.72	4.58	8.54
15	7000.	2	74.	8734.	15.88	10.75	6.89	4.92	2.20	6.39
15	7000.	3	73.	14124.	24.30	16.85	11.51	8.46	4.13	12.32

DISK FILE: CENT5.DAT

SITE DATA:

Date	04-03-89
Time	11:41
Dist. No.	
County Name	
Roadway No.	
Lane desig.	
Dist. from Rt. edge	W
Begin Mile Post	6900
Offset	
End Mile Post	
Offset	
Surface Type	
Operator	DB

SENSOR LOCATIONS:

Sensor#	Location
1	0F
2	12B
3	24B
4	36B
5	60F
6	99B

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	3	N	N	N	N
2	2	Y	Y	N	Y
3	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
0.	5902.0000	.521	.512	.509	.251	.280	.280

TIME SERIES SCALE FACTOR (LOAD) : 5902.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	6900.	2	74.	8705.	11.04	7.75	5.45	4.16	2.26	4.52
1	6900.	3	75.	14182.	16.72	11.99	8.74	6.74	3.79	8.03
2	6700.	2	77.	8705.	13.67	9.30	6.78	5.02	2.77	5.26
2	6700.	3	76.	14182.	20.62	14.68	10.89	8.21	4.81	8.71
3	6500.	2	74.	8648.	15.57	10.03	6.17	4.16	1.75	5.09
3	6500.	3	72.	14096.	23.77	15.71	10.07	7.09	3.17	10.46
4	6300.	2	78.	8676.	13.25	7.75	4.32	2.79	1.13	2.94
4	6300.	3	77.	14182.	19.35	11.68	6.68	4.56	1.92	6.50
5	6100.	2	77.	8676.	15.15	8.48	4.93	3.14	1.19	4.07

5	6100.	3	76.	14153.	21.98	12.61	7.19	5.17	2.43	7.58
6	5900.	2	72.	8648.	15.36	9.92	6.06	3.90	1.87	4.86
6	5900.	3	71.	14096.	24.09	15.92	10.07	6.79	3.28	9.89
7	5700.	2	73.	8590.	14.62	9.72	6.47	4.61	2.49	5.26
7	5700.	3	73.	14096.	22.51	15.09	10.58	7.65	4.18	9.67
8	5500.	2	75.	8619.	12.31	8.99	5.96	4.05	1.92	5.03
8	5500.	3	74.	14182.	19.04	13.85	9.45	6.79	3.34	10.40
9	5300.	2	76.	8648.	11.04	7.24	4.52	3.09	1.41	3.96
9	5300.	3	76.	14211.	16.41	10.75	7.19	5.07	2.49	7.29
10	5100.	2	75.	8676.	12.10	8.37	5.86	4.05	1.70	4.97
10	5100.	3	75.	14153.	18.41	13.02	9.15	6.69	3.00	9.38
11	4900.	2	78.	8648.	13.04	8.79	5.86	4.05	2.09	4.81
11	4900.	3	77.	14124.	19.57	13.44	9.25	6.74	3.62	8.31
12	4700.	2	77.	8619.	12.10	8.58	5.96	4.36	2.15	5.09
12	4700.	3	76.	14182.	18.41	13.23	9.45	7.09	3.79	9.10
13	4500.	2	72.	8619.	17.04	11.99	7.50	5.17	2.88	6.67
13	4500.	3	72.	14153.	25.46	17.78	11.72	8.26	4.81	11.31
14	4300.	2	69.	8648.	12.52	9.51	6.06	4.26	2.15	4.86
14	4300.	3	69.	14182.	18.93	14.16	9.66	6.94	3.73	8.88
15	4100.	2	85.	8648.	13.04	10.13	6.68	4.51	2.15	5.37
15	4100.	3	84.	14153.	19.57	14.99	10.28	7.45	3.84	10.57
16	3900.	2	86.	8590.	10.83	8.68	6.06	4.31	2.26	4.58
16	3900.	3	85.	14124.	16.72	13.02	9.56	7.04	3.96	8.59
17	3700.	2	83.	8619.	12.83	7.86	5.04	3.19	1.64	3.17
17	3700.	3	82.	14153.	18.83	12.09	7.81	5.12	2.94	6.39
18	3500.	2	90.	8619.	12.20	7.86	4.32	2.53	1.02	2.26
18	3500.	3	89.	14124.	18.72	12.20	6.78	4.36	1.87	5.99
19	3300.	2	90.	8561.	17.25	11.47	7.09	4.21	1.64	4.18
19	3300.	3	89.	14096.	25.56	17.47	10.89	6.79	3.05	8.31
20	3100.	2	90.	8532.	15.78	10.96	6.37	3.90	1.13	4.35
20	3100.	3	88.	14038.	24.51	17.37	10.79	6.64	2.49	10.01
21	2900.	2	85.	8561.	17.67	13.02	8.94	5.93	2.83	6.95
21	2900.	3	85.	14067.	27.45	20.57	14.59	9.93	4.75	12.83
22	2700.	2	85.	8590.	16.09	11.06	7.30	4.56	1.87	5.43
22	2700.	3	84.	14096.	24.61	17.37	11.92	8.01	3.45	11.25

DISK FILE: CENT6.DAT

SITE DATA:

Date	04-03-89
Time	12:34
Dist. No.	
County Name	
Roadway No.	
Lane desig.	W
Dist. from Rt. edge	
Begin Mile Post	2500
Offset	
End Mile Post	
Offset	
Surface Type	
Operator	DB

SENSOR LOCATIONS:

Sensor#	Location
1	0F
2	12B
3	24B
4	36B
5	60F
6	99B

Drop#	Ht. Par.	Measure ?	Save ?	Plot ?	Print ?
1	3	N	N	N	N
2	2	Y	Y	N	Y

3	3	Y	Y	N	Y

PEAK VALUE SCALE FACTORS :

TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
0.	5902.0000	.521	.512	.509	.251	.280	.280

TIME SERIES SCALE FACTOR (LOAD) : 5902.000

TEST	LOC	HT	TEMP	LOAD	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
1	2500.	2	88.	8561.	14.83	9.51	5.75	3.75	1.92	4.81
1	2500.	3	86.	14038.	22.30	14.37	9.35	6.44	3.34	8.93
2	2299.	2	88.	8561.	11.89	9.92	6.27	4.56	2.26	5.20
2	2299.	3	88.	13923.	18.09	15.30	10.17	7.70	3.90	10.06
3	2100.	2	92.	8532.	17.99	11.99	8.22	5.42	2.20	6.56
3	2100.	3	91.	14009.	28.19	19.43	13.57	9.43	3.90	12.72
4	1900.	2	89.	8676.	15.67	11.06	7.30	4.81	2.09	5.82
4	1900.	3	88.	14182.	24.30	17.78	11.92	8.36	3.67	11.02
5	1700.	2	85.	8561.	17.15	12.09	8.53	5.93	2.66	6.67
5	1700.	3	84.	14067.	27.03	18.92	13.77	10.03	4.86	12.49
6	1500.	2	81.	8619.	15.57	10.23	6.58	4.61	2.09	5.37
6	1500.	3	81.	14038.	23.56	15.61	10.89	7.85	3.73	9.72
7	1300.	2	83.	8648.	18.41	11.16	7.09	4.86	1.98	5.37
7	1300.	3	82.	14067.	28.09	17.47	11.61	8.41	3.56	10.85
8	1100.	2	81.	8590.	16.20	10.34	6.47	4.10	1.47	4.58
8	1100.	3	80.	14067.	24.93	16.44	10.89	7.15	3.00	9.38
9	900.	2	76.	8648.	15.99	10.03	6.68	4.46	2.15	4.92
9	900.	3	76.	14096.	24.40	16.02	11.10	7.70	3.56	10.06
10	700.	2	87.	8648.	14.10	9.61	6.06	3.85	1.87	5.03
10	700.	3	84.	14182.	21.98	14.99	9.97	6.74	3.39	10.29
11	500.	2	90.	8648.	16.83	9.61	6.27	4.16	2.49	4.47
11	500.	3	89.	14096.	25.03	14.78	10.28	7.09	4.24	8.20
12	299.	2	92.	8648.	15.46	10.65	7.91	5.68	2.83	6.56
12	299.	3	91.	14067.	24.19	16.85	12.85	9.48	4.92	11.82
13	100.	2	92.	8705.	13.46	9.61	7.19	5.17	2.26	5.14
13	100.	3	89.	14153.	20.83	15.40	11.82	8.36	4.18	9.16

B-3 Nelchina Project

NELCHINA SPRING DATA

```
R32  18  225 890511nelchina29F8*
70001...800-002          .3111  8
150 0   211 300 601 899 11991501
........     100 C:          .FWD
nelchina 89 #2000+0.0 000+0.0 00
S127      1   4.5  100  0  00224
S128      1   4.5  100  0  00226
0'  100'0'  100'0        127
18  15  3.5 5   2   15  2   8
Ld 084    1     87.8
D1 621    1     1.049
D2 622    1     1.004
D3 623    1     1.040
D4 624    1     1.033
D5 625    1     1.085
D6 626    1     1.053
D7 627    1     1.049
D0 628    1     1.018
D0 638    1     1.037
D* *****  1     1
David L. Swaim
11101010......12................
11111111.......*................
................................
................................
................................
................................
................................
                ................
S0.x      1   4.5  000  0  000000
 608 324 257 181  99  47  25   1
S2        1   4.5  000  0  000000
 597 345 263 191 106  51  29   5
S4        1   4.5  100  0  000000
 604 278 220 157  89  46  27   1
S6        1   4.5  100  0  000000
 601 355 276 201 117  59  32   1
S8        1   4.5  100  0  000000
 610 277 173  95  51  29  21   1
S10       1   4.5  100  0  000000
 597 323 202 103  53  31  22   7
S12       1   4.5  100  0  000000
 596 377 227 120  59  35  21   2
S14       1   4.5  100  0  000000
 583 370 205 107  55  30  20   1
S16       1   4.5  100  0  000000
 582 341 213 119  58  31  20   1
S18       1   4.5  100  0  000000
 577 308 186  97  49  27  17   1
S20       1   4.5  100  0  000000
 583 311 207 110  57  30  20   2
S22       1   4.5  100  0  000000
 583 362 219 122  58  31  19   1
S24       1   4.5  100  0  000000
 584 350 191 107  54  29  17   1
S26       1   4.5  100  0  000000
 587 360 232 134  71  38  21   1
S28       1   4.5  100  0  000000
 580 315 181  95  48  26  17   1
S30       1   4.5  100  0  000000
 576 271 167  88  40  22  16   2
S32       1   4.5  100  0  000000
 580 298 206 128  68  38  24   1
S34       1   4.5  100  0  000000
 582 322 207 123  64  34  21   2
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NELCHINA SUMMUR DATA

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R32  18  281 890802neltwo  29F8*
70001...800-002          .3111  8
150 0   211 300 601 899 11991501
........     100 C:          .FWD
nelch 89 #2 aug 2+0.0 000+0.0 00
S127          10   100  0  00280
S128          10   100  0  00282
0'  100'0'  100'0        127
18  15  3.5 5   2   15  2   8
Ld 084    1     87.8
D1 621    1     1.049
D2 622    1     1.004
D3 623    1     1.040
D4 624    1     1.033
D5 625    1     1.085
D6 626    1     1.053
D7 628    1     1.018
D0 627    1     1.049
D0 638    1     1.037
D* *****  1     1
David L. Swaim
11101010......12................
11111111.......*................
................................
................................
................................
................................
................................
                ................
S0.0          10   100  0  000000
 562 273 202 144  79  44  29  23
S2            10   100  0  000000
 570 399 247 164  83  46  33  25
S4            10   100  0  000000
 571 206 154 108  60  35  24  15
S6            10   100  0  000000
 569 442 330 230 130  79  60  48
S8            10   100  0  000000
 579 323 200 115  59  37  27  19
S10           10   100  0  000000
 585 256 157  84  44  29  22  12
S12           10   100  0  000000
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 577 283 134  71  36  21  14  11
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S44      1  4.5  100  0  000000
 571 395 253 136  69  40  27  1
S46      1  4.5  100  0  000000
 577 364 209 114  62  37  23  2
S48      1  4.5  100  0  000000
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 570 418 276 161  87  48  27  1
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 567 517 358 209 112  58  32  1
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 570 494 289 166  87  43  24  1
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 568 407 250 150  84  52  35  1
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 570 455 304 188 108  63  38  3
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 562 642 467 289 148  76  41  2
S56      1  4.5  100  0  000000
 568 487 315 192 104  54  31  1
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 572 409 274 159  88  53  36  1
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 568 338 218 125  71  42  28  3
S59      1  4.5  100  0  000000
 561 338 203 108  57  34  23  1
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 567 314 187 111  56  30  18  1
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 560 467 348 210 102  52  27  1
S62      1  4.5  100  0  000000
 554 506 368 224 122  63  37  2
S63      1  4.5  100  0  000000
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S64      1  4.5  100  0  000000
 561 488 331 201 107  53  31  1
S65      1  4.5  100  0  000000
 550 703 423 260 136  60  24  2
S66      1  4.5  100  0  000000
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 546 680 484 258 133  59  23  2
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S73      1  4.5  100  0  000000
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 54913711143 701 430 206 108  2
S77      1  4.5  100  0  000000
 531 959 693 339 165  71  27  1
S78      1  4.5  100  0  000000
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 574 235 118  59  28  16  12  8
S40          10  100  0  000000
 581 231 142  76  36  20  15  9
S42          10  100  0  000000
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S44          10  100  0  000000
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S46          10  100  0  000000
 570 307 166  98  50  30  23 17
S48          10  100  0  000000
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 513 368 216 111  50  28  21 17
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S55      1   10  100  0  000000
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S56      1   10  100  0  000000
 567 377 243 140  72  44  33 25
S57      1   10  100  0  000000
 575 279 178 101  53  33  26 21
S58      1   10  100  0  000000
 573 313 180 105  56  34  24 19
S59      1   10  100  0  000000
 584 263 154  79  39  26  20 14
S60      1   10  100  0  000000
 568 212 134  72  37  25  21 17
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 572 288 190 130  84  58  41 27
S64      1   10  100  0  000000
 561 359 223 159  97  63  44 34
S65      1   10  100  0  000000
 564 326 176 122  80  53  37 31
S66      1   10  100  0  000000
 551 393 239 158  98  64  44 34
S67      1   10  100  0  000000
 562 385 226 132  77  50  36 26
S68      1   10  100  0  000000
 556 358 181 105  59  39  26 22
S69      1   10  100  0  000000
 556 331 171  98  61  38  27 20
S70      1   10  100  0  000000
 561 257 180 119  71  43  31 22
S71      1   10  100  0  000000
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 552 397 242 142  86  53  39 29
S73      1   10  100  0  000000
 557 433 262 161  93  55  37 27
S74      1   10  100  0  000000
 547 486 314 201 118  69  46 34
S75      1   10  100  0  000000
 541 485 307 191 108  65  43 33
S76      1   10  100  0  000000
 543 511 330 194 113  68  45 33
S77      1   10  100  0  000000
 543 456 293 185 113  68  46 35
S78      1   10  100  0  000000
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S81		1	4.5	100	0	000000	
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S82		1	4.5	100	0	000000	
576	373	243	146	77	39	21	3
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546	273	211	136	76	38	20	5
S84		1	4.5	100	0	000000	
557	592	384	202	91	38	19	3
S85		1	4.5	100	0	000000	
532	765	509	348	200	103	59	3
S86		1	4.5	100	0	000000	
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S87		1	4.5	100	0	000000	
548	544	345	191	103	58	38	4
S88		1	4.5	100	0	000000	
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S89		1	4.5	100	0	000000	
571	308	201	115	61	33	19	3
S90		1	4.5	100	0	000000	
574	317	220	96	57	29	18	3
S91		1	4.5	100	0	000000	
567	345	243	151	87	51	35	1
S92		1	4.5	100	0	000000	
573	286	193	111	57	33	22	1
S93		1	4.5	100	0	000000	
573	304	221	140	75	42	26	1
S94		1	4.5	100	0	000000	
577	287	209	136	79	29	15	1
S98		1	4.5	100	0	000000	
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S99		1	4.5	100	0	000000	
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S100		1	4.5	100	0	000000	
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570	578	401	249	126	54	26	1
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566	478	320	207	125	72	45	1
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S104		1	4.5	100	0	000000	
562	523	378	226	107	41	17	1
S105		1	4.5	100	0	000000	
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S106		1	4.5	100	0	000000	
553	621	432	262	123	51	22	5
S107		1	4.5	100	0	000000	
566	434	282	166	90	46	27	1
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571	290	184	102	54	33	22	1
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558	354	223	125	65	33	20	1
S110		1	4.5	100	0	000000	
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S111		1	4.5	100	0	000000	
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S112		1	4.5	100	0	000000	
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S113		1	4.5	100	0	000000	
555	444	293	179	99	48	26	1
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558	433	298	185	100	49	27	1
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S79		1	10	100	0	000000	
547	406	260	163	100	64	46	35
S80		1	10	100	0	000000	
550	376	242	142	83	48	34	25
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545	495	316	211	129	77	52	39
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552	335	234	138	74	49	34	24
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529	586	399	254	142	89	63	49
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562	517	321	205	108	74	58	48
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552	472	329	204	111	71	48	36
S88		1	10	100	0	000000	
562	368	239	159	87	30	25	19
S89		1	10	100	0	000000	
590	284	167	89	45	27	19	13
S90		1	10	100	0	000000	
593	256	151	85	43	26	19	9
S91		1	10	100	0	000000	
588	320	173	100	53	30	22	17
S92		1	10	100	0	000000	
591	236	172	104	57	38	29	18
S93		1	10	100	0	000000	
581	304	210	133	70	41	28	21
S94		1	10	100	0	000000	
584	325	203	110	51	29	20	15
S98		1	10	100	0	000000	
570	446	334	253	152	88	59	47
S99		1	10	100	0	000000	
582	484	352	237	142	87	61	48
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570	536	381	249	135	76	52	39
S101		1	10	100	0	000000	
578	625	435	282	153	90	64	49
S102		1	10	100	0	000000	
568	492	366	250	157	103	74	58
S103		1	10	100	0	000000	
565	649	437	287	165	98	66	48
S104		1	10	100	0	000000	
580	553	381	231	115	63	43	34
S105		1	10	100	0	000000	
558	557	423	307	186	112	76	50
S106		1	10	100	0	000000	
567	376	285	217	138	82	57	42
S107		1	10	100	0	000000	
566	515	376	237	127	69	47	32
S108		1	10	100	0	000000	
569	395	251	150	84	50	36	25
S109		1	10	100	0	000000	
584	340	150	82	51	34	26	25
S110		1	10	100	0	000000	
557	299	182	112	68	46	35	22
S111		1	10	100	0	000000	
567	337	286	238	169	112	80	60
S112		1	10	100	0	000000	
567	494	344	230	133	80	54	37
S113		1	10	100	0	000000	
564	406	247	157	92	58	39	36
S114		1	10	100	0	000000	
567	468	322	207	112	65	44	30
S115		1	10	100	0	000000	
566	267	186	130	83	54	41	39
S116		1	10	100	0	000000	
561	453	321	216	132	79	57	45

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S117      1  4.5  100  0  000000
 547 426 302 197 117  69  45  1
S118      1  4.5  100  0  000000
 562 388 169 116  95  64  44  1
S121      1  4.5  100  0  000000
 538 377 283 198 105  49  27  1
S122      1  4.5  100  0  000000
 551 457 339 227 136  73  40  1
S123      1  4.5  100  0  000000
 558 180 138 101  60  33  23  1
S124      1  4.5  100  0  000000
 559 409 296 193  97  43  21  1
S125      1  4.5  100  0  000000
 559 366 275 186  95  46  24  2
S126      1  4.5  100  0  000000
 565 187 149 111  70  38  25  1
S127      1  4.5  100  0  000000
 564 189 141  97  55  29  21  1
EOF
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 562 465 230 155  97  65  44 26
S118      1  10   100  0  000000
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S121      1  10   100  0  000000
 577 464 364 249 129  63  42 35
S122      1  10   100  0  000000
 559 380 236 156  98  61  42 34
S123         10   100  0  000000
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S124         10   100  0  000000
 567 358 267 178 107  72  53 38
S125         10   100  0  000000
 560 346 281 209 129  81  59 47
S126         10   100  0  000000
 566 247 179 122  68  42  33 27
S127         10   100  0  000000
 568 312 211 132  73  46  35 23
EOF
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B-4 Tudor Project

Tudor Spring Data

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R32  18   579 800101tudor4  29F8*
70001...800-003           .3111  8
150 0   200 300 450 650 900 1200
........     100 B:           .FWD
00000 SH0000  000+0.0 000+0.0 00
S110      1   13    000  0  00575
S111      1   13    000  0  00580
0'  100'0'  100'1        110
18  15  3.5 6    2   15  2   8
Ld 085   1      87.5
D1 631   1      .9918
D2 632   1      1.011
D3 633   1      1.055
D4 634   1      1.056
D5 635   1      1.033
D6 636   1      1.045
D7 637   1      1.078
D0 638   1      1.037
D0 628   1      1.018
D* ***** 1      1
chip
11110010....1234.......*........
11111223********................
................................
................................
................................
................................
................................
                ................
S1.0      1   11    000  0  000010
 403 212 161 148  97  66  37  20
 564 272 215 189 126  87  49  27
 557 268 211 187 126  86  48  26
 888 407 296 284 189 130  73  40
S2.0      1   11    000  0  000011
 405 157  96  94  56  36  21  13
 561 198 144 120  74  48  27  17
 554 194 142 118  71  48  27  17
 887 290 212 175 108  71  42  26
S3        1   11    000  0  000012
 404 187 136 115  70  42  23  14
 555 235 176 145  88  55  29  17
 551 228 174 143  88  55  29  18
 884 347 257 213 130  83  45  27
S4        1   11    000  0  000016
 398 199 167 121  72  43  27  18
 549 244 197 148  91  53  36  23
 553 244 201 148  92  53  34  23
 868 342 263 204 124  76  50  31
S5        1   11    000  0  000017
 393 210 161 137  88  55  24  10
 545 258 197 169 108  69  32  12
 546 255 199 168 108  69  32  12
 868 375 278 241 151  96  44  14
S6        1   11    000  0  000018
 399 187 160 110  67  39  21  12
 550 234 173 140  83  53  27  16
 547 233 169 139  83  53  28  16
 877 340 251 200 120  76  41  24
S7        1   11    000  0  000019
 398 132 107  90  62  43  25  13
 549 173 130 119  80  60  34  20
 549 170 129 118  80  61  34  20
 875 271 211 186 128  92  54  30
S8        1   11    000  0  000021
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Tudor Summer Data

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R32  18   579 800101tudor7  29F8*
70001...800-003           .3111  8
150 0   200 300 450 650 900 1200
........     100 B:           .FWD
00000 SH0000  000+0.0 000+0.0 00
S110      1   13      0  0  00575
S111      1   13      0  0  00580
0'  100'0'  100'1        110
18  15  3.5 6    2   15  2   8
Ld 085   1      87.5
D1 631   1      .9918
D2 632   1      1.011
D3 633   1      1.055
D4 634   1      1.056
D5 635   1      1.033
D6 636   1      1.045
D7 637   1      1.078
D0 638   1      1.037
D0 628   1      1.018
D* ***** 1      1
chip
11110010....1234.......*........
11111223********................
................................
................................
................................
................................
................................
                ................
S1.0      1   13    000  0  000009
 382 223 181 146  91  60  33  20
 544 294 237 191 120  81  46  29
 550 294 237 191 121  82  46  29
 851 422 335 269 174 118  69  45
S2.0      1   13    000  0  000011
 375 203 149 114  63  39  22  14
 545 262 194 148  84  54  29  19
 552 262 195 150  86  54  30  19
 852 367 272 209 119  76  44  29
S3        1   13    000  0  000012
 382 171 123  93  50  30  17  12
 545 222 160 119  65  42  24  16
 548 221 160 119  67  41  24  16
 842 314 225 170  96  61  37  27
S4        1   13    000  0  000013
 381 189 146 110  62  38  22  15
 551 241 185 139  79  51  30  20
 554 239 185 139  79  52  32  22
 846 327 251 188 109  71  43  30
S5        1   13    000  0  000014
 370 186 131 102  58  37  21  14
 537 242 171 132  77  50  29  19
 540 239 169 131  78  50  29  19
 827 338 237 183 108  71  44  30
S6        1   13    000  0  000015
 371 174 112  81  43  27  16  12
 540 226 148 109  61  40  26  19
 541 223 147 107  60  39  25  18
 834 319 207 153  89  60  39  29
S7        1   13    000  0  000016
 381 142 100  76  50  32  19  13
 546 188 132 104  67  46  29  20
 548 186 132 104  67  46  30  22
 845 276 193 154  99  71  48  34
S8        1   13    000  0  000017
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397	115	90	75	49	32	18	10
541	145	107	97	62	42	24	14
545	145	108	97	62	43	24	14
875	214	163	142	93	64	37	22
S9		1	11	000	0	000022	
394	185	142	119	72	43	21	11
545	231	184	148	90	48	27	14
544	229	173	149	90	55	28	14
867	338	248	217	130	81	42	20
S10		1	11	000	0	000023	
389	218	177	135	84	54	27	14
542	274	205	173	108	69	38	22
539	270	204	172	108	70	38	22
863	404	302	253	159	104	56	32
S11		1	11	000	0	000024	
397	194	170	126	80	50	26	14
545	245	188	160	99	65	34	20
544	243	193	158	99	65	34	19
873	367	284	234	147	96	51	28
S12		1	11	000	0	000025	
399	170	129	112	71	46	25	14
542	211	164	139	89	58	32	17
542	208	159	138	88	59	32	18
873	313	239	203	129	86	47	26
S13		1	11	000	0	000026	
400	134	103	88	55	34	19	11
542	169	127	110	69	44	24	14
542	166	124	109	68	44	25	15
866	251	186	161	101	67	38	22
S14		1	11	000	0	000027	
399	81	76	54	36	24	14	9
558	106	75	71	48	34	19	10
545	102	74	70	46	33	19	10
866	155	126	102	70	48	29	18
S15		1	11	000	0	000029	
388	282	206	159	54	31	15	10
538	329	245	194	68	37	19	12
531	324	236	194	68	38	20	12
841	464	328	266	93	52	25	16
S16		1	11	000	0	000030	
396	230	168	139	81	48	22	12
545	279	200	168	98	58	27	15
541	277	198	166	97	58	27	15
845	384	258	227	129	76	37	20
S17		1	11	000	0	000030	
397	149	120	100	69	45	27	16
547	186	143	128	88	60	36	20
547	184	136	127	87	60	34	20
821	263	201	181	121	85	49	29
S18		1	11	000	0	000031	
381	93	67	59	36	23	11	6
512	119	86	76	46	29	15	9
512	118	93	74	46	28	14	9
834	183	133	117	73	46	24	13
S19		1	11	000	0	000032	
385	173	125	102	61	38	20	11
519	210	155	126	75	46	24	14
519	209	158	123	76	45	24	14
841	308	224	185	112	70	38	22
S20		1	11	000	0	000034	
388	189	129	116	70	43	23	13
513	224	162	139	83	53	27	15
511	221	160	138	82	53	27	14
821	326	229	199	120	77	40	22
S21		1	11	000	0	000035	
372	147	109	88	51	31	16	10
510	183	136	110	65	40	21	13
511	182	134	110	65	40	21	13
823	275	202	161	96	61	32	19
S22		1	11	000	0	000036	
338	195	216	128	86	68	32	24

380	119	88	69	44	29	16	11
550	156	116	93	59	39	25	17
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845	221	164	132	84	60	39	26
S9		1	13	000	0	000018	
374	139	100	76	42	28	16	11
546	181	130	100	59	38	23	16
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840	255	183	142	87	59	37	27
S10		1	13	000	0	000019	
379	201	153	119	74	49	30	23
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548	256	198	157	99	69	45	33
839	362	280	225	147	104	70	52
S11		1	13	000	0	000020	
375	178	139	105	63	40	23	16
546	235	181	141	83	57	34	22
548	233	180	140	84	57	34	23
838	333	256	199	124	85	53	38
S12		1	13	000	0	000021	
369	173	128	100	65	43	26	20
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540	223	166	132	89	62	41	30
834	317	235	188	129	93	63	47
S13		1	13	000	0	000022	
371	130	99	76	48	30	16	14
545	177	133	105	65	45	28	22
552	176	133	107	65	45	29	22
840	258	194	153	98	68	44	33
S14		1	13	000	0	000023	
378	91	69	51	34	22	10	9
550	122	89	73	43	29	21	11
548	121	89	71	44	29	18	11
846	174	125	98	63	44	27	18
S15		1	13	000	0	000023	
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530	305	190	131	60	36	23	17
531	300	188	131	61	36	23	17
823	421	261	183	88	54	36	27
S16		1	13	000	0	000024	
374	179	130	97	53	30	15	11
547	230	170	124	69	40	21	15
543	227	167	122	68	39	22	15
840	319	231	172	94	58	33	24
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372	144	112	88	56	37	23	16
540	195	151	121	78	56	34	24
542	193	151	121	79	57	36	25
836	282	218	177	116	85	54	38
S18		1	13	000	0	000026	
377	102	72	55	29	18	9	5
545	136	96	73	40	25	14	10
550	135	96	72	40	25	14	10
844	196	136	103	58	36	20	14
S19		1	13	000	0	000027	
371	149	102	74	41	25	14	10
538	192	133	99	55	35	20	14
543	191	132	99	56	35	20	14
839	274	187	138	80	52	31	23
S20		1	13	000	0	000028	
384	147	101	73	42	27	16	12
542	186	128	96	55	37	25	18
548	184	128	96	56	38	26	19
840	262	182	137	82	58	40	30
S21		1	13	000	0	000029	
366	152	101	77	39	25	15	11
539	196	132	100	54	35	20	16
540	194	132	99	54	35	21	16
833	276	186	140	79	53	33	25
S22		1	13	000	0	000030	
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491	259	234	173	117	83	47	31
506	261	236	175	119	84	49	32
822	407	343	270	183	129	77	52
S23	1	11	000	0	000037		
346	175	164	116	75	50	26	14
496	238	207	158	103	67	37	20
498	236	209	156	103	68	39	20
817	375	315	249	164	108	61	32
S24	1	11	000	0	000038		
323	160	146	104	68	44	22	12
480	217	181	145	93	60	32	17
485	214	170	145	93	61	33	18
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S25	1	11	000	0	000039		
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467	180	167	118	76	45	23	12
479	180	164	119	75	46	24	13
819	280	231	179	112	69	36	19
S26	1	11	000	0	000040		
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477	246	195	155	96	57	28	13
483	245	189	156	95	58	29	14
820	381	299	236	144	76	43	20
S27	1	11	000	0	000041		
319	145	122	100	64	41	22	12
471	198	169	135	89	58	30	15
475	195	167	135	89	58	30	16
808	318	253	215	138	90	46	24
S28	1	11	000	0	000044		
312	166	132	92	54	31	15	9
467	216	170	121	74	43	21	11
472	214	173	121	74	43	21	12
803	324	243	179	108	63	31	17
S29	1	13	000	0	000046		
316	218	154	122	63	34	16	10
467	285	202	159	84	46	22	14
474	284	198	158	86	46	22	14
797	437	293	235	127	69	32	20
S30	1	13	000	0	000047		
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470	235	181	142	84	52	28	16
469	231	179	140	83	51	28	16
801	358	258	217	130	81	45	29
S31	1	13	000	0	000048		
308	169	123	103	63	37	20	12
464	228	171	146	90	56	31	16
476	229	168	147	91	56	31	17
802	351	257	223	139	87	50	29
S32	1	13	000	0	000049		
320	284	203	169	94	56	29	14
464	374	286	225	127	76	37	20
471	374	284	226	128	79	39	23
814	607	440	362	208	126	62	28
S33	1	13	000	0	000050		
319	209	151	134	82	54	30	19
473	279	220	180	113	73	42	28
471	273	212	177	112	73	43	28
812	430	334	276	177	116	69	42
S34	1	13	000	0	000052		
322	203	177	139	91	59	33	19
474	268	237	188	124	81	47	26
478	268	239	188	124	81	47	26
814	415	361	290	196	130	76	41
S35	1	13	000	0	000053		
335	187	161	109	65	39	22	12
476	244	194	146	88	54	31	19
471	239	188	143	87	55	31	18
811	376	293	226	139	89	52	30
S36	1	13	000	0	000054		
318	217	197	126	77	48	26	18
464	286	242	171	107	66	39	25

532	274	209	166	106	73	46	32
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832	400	302	239	157	111	71	51
S23	1	13	000	0	000031		
372	210	162	132	76	51	29	18
545	276	217	173	107	71	42	26
545	272	214	172	106	71	42	26
835	391	304	242	153	105	63	40
S24	1	13	000	0	000032		
361	185	133	103	61	40	23	15
533	230	177	138	84	56	32	22
535	233	175	138	83	57	32	22
827	322	247	195	121	84	50	33
S25	1	13	000	0	000032		
370	186	143	111	68	43	25	16
548	245	189	148	92	61	36	25
541	237	185	146	91	61	36	25
833	340	261	206	131	90	55	39
S26	1	13	000	0	000033		
371	226	174	137	80	52	30	20
536	294	226	179	107	71	44	28
536	289	223	177	107	71	44	29
826	418	320	252	155	105	67	45
S27	1	13	000	0	000034		
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538	236	184	148	97	73	50	34
531	230	180	145	97	71	49	36
823	354	271	219	148	111	76	58
S28	1	13	000	0	000035		
375	179	120	89	54	35	21	12
539	228	159	121	73	50	32	25
535	224	156	119	72	50	31	23
829	319	219	168	105	73	48	36
S29	1	13	000	0	000036		
374	203	144	104	57	39	27	22
538	268	190	141	79	57	40	30
530	261	187	137	79	56	39	30
816	387	275	205	120	89	64	50
S30	1	13	000	0	000037		
365	194	144	109	59	39	23	15
536	253	190	143	81	55	33	23
532	251	189	143	81	56	36	25
819	355	265	203	117	83	53	38
S31	1	13	000	0	000038		
373	189	134	99	55	36	23	16
525	241	174	130	75	50	32	24
534	240	175	131	77	52	33	24
814	338	249	191	112	81	52	37
S32	1	13	000	0	000038		
388	221	163	123	74	52	32	20
537	285	213	164	100	70	45	29
536	281	213	162	100	70	45	30
827	409	309	239	152	108	70	47
S33	1	13	000	0	000039		
378	206	161	122	76	49	26	19
545	272	210	165	100	67	41	28
543	267	208	164	100	67	42	28
824	375	290	229	144	98	62	43
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388	173	137	108	69	48	29	23
553	226	186	150	94	67	44	27
558	225	186	150	94	68	45	28
847	320	266	216	142	102	68	43
S35	1	13	000	0	000041		
378	227	163	122	71	46	28	19
547	282	210	159	96	64	39	27
550	280	210	159	96	65	40	28
834	378	286	220	136	94	60	42
S36	1	13	000	0	000042		
381	230	161	122	77	53	32	23
540	285	214	168	107	75	49	34

469	285	246	171	107	67	39	26
803	440	346	268	170	108	65	41
S37	1	13	000	0	000055		
303	314	194	148	79	46	24	14
460	402	274	191	105	60	31	16
461	398	274	191	106	61	32	18
805	604	389	287	161	93	48	26
S38	1	13	000	0	000056		
319	164	153	82	45	25	18	13
473	214	166	113	65	37	24	15
474	209	169	112	65	35	24	15
806	328	238	176	103	62	38	25
S39	1	13	000	0	000057		
313	154	106	88	46	30	16	13
464	198	145	112	63	38	23	18
472	195	147	112	64	41	23	19
806	307	224	174	103	66	44	33
S40	1	13	000	0	000058		
318	187	148	119	68	43	27	22
469	246	195	157	94	63	42	31
471	245	190	157	92	64	42	32
809	378	294	241	150	104	72	55
S41	1	13	000	0	000059		
315	276	217	189	128	88	60	39
463	375	301	260	178	125	85	56
468	373	298	260	180	127	86	57
807	582	451	401	281	201	140	93
S42	1	13	000	0	000101		
321	182	166	119	76	43	25	14
478	246	218	161	103	63	36	20
475	243	208	161	102	63	36	20
817	376	312	245	155	98	57	34
S43	1	13	000	0	000102		
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467	250	209	167	113	77	51	39
466	249	205	166	112	77	53	39
806	397	306	264	182	129	93	68
S44	1	13	000	0	000103		
318	144	112	88	51	31	17	12
474	191	153	116	70	42	25	17
474	189	159	115	70	42	25	17
807	291	229	174	106	66	41	26
S45	1	13	000	0	000104		
312	201	160	134	87	54	34	23
467	278	244	186	125	76	49	32
469	276	237	185	124	77	49	32
803	445	364	301	202	131	85	56
S46	1	13	000	0	000105		
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468	266	224	178	118	79	48	31
470	264	210	178	117	81	49	32
811	429	339	287	191	132	84	56
S47	1	13	000	0	000106		
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464	267	212	179	116	76	48	30
467	264	207	177	114	77	47	30
807	422	320	281	184	125	78	53
S48	1	13	000	0	000107		
313	192	155	133	84	55	32	19
472	260	229	178	118	76	46	29
470	258	225	176	117	76	46	30
808	398	327	271	180	120	75	47
S49	1	13	000	0	000108		
310	202	159	129	82	58	38	28
465	283	239	180	119	88	57	44
465	277	232	179	118	88	57	43
800	457	352	295	200	145	100	73
S50	1	13	000	0	000109		
316	186	126	119	72	49	31	19
467	264	202	169	108	73	47	30
469	261	187	170	109	74	48	31

526	277	208	166	103	73	50	37
825	406	304	243	161	117	78	57
S37	1	13	000	0	000043		
373	277	182	134	88	68	43	36
534	349	240	181	120	95	71	51
545	349	243	184	124	96	70	52
826	500	350	269	186	148	108	81
S38	1	13	000	0	000044		
387	164	125	93	54	34	19	14
551	205	162	124	72	49	31	22
550	204	161	126	72	50	37	23
838	283	223	174	105	73	50	34
S39	1	13	000	0	000045		
389	181	125	97	61	45	34	29
529	223	163	128	83	64	50	43
528	219	162	127	83	64	50	43
823	307	234	187	128	100	79	68
S40	1	13	000	0	000045		
375	207	147	113	69	48	31	24
539	264	194	153	96	68	46	34
525	259	190	150	95	67	46	34
819	361	273	218	145	105	74	57
S41	1	13	000	0	000046		
370	301	248	202	137	99	64	42
538	391	330	272	188	138	93	64
535	386	326	269	187	138	93	64
820	545	457	380	266	202	140	97
S42	1	13	000	0	000047		
379	191	150	116	70	46	26	17
543	241	192	151	93	63	37	25
544	238	192	151	93	64	39	27
838	341	269	211	133	92	56	40
S43	1	13	000	0	000048		
385	190	144	113	73	53	36	28
548	245	193	153	101	75	55	42
550	243	194	154	101	76	55	42
836	352	279	224	153	117	87	67
S44	1	13	000	0	000049		
375	174	132	100	62	42	25	18
540	222	171	135	84	59	39	27
533	219	169	134	84	59	39	27
833	312	238	190	121	88	60	42
S45	1	13	0	0	000050		
377	231	182	146	94	66	41	30
543	302	246	199	131	95	65	46
544	298	245	199	131	96	66	47
827	432	356	291	199	146	99	74
S46	1	13	0	0	000051		
384	235	190	154	102	71	44	30
544	306	253	207	138	100	65	46
528	299	247	202	136	98	65	46
823	437	362	296	204	151	101	73
S47	1	13	0	0	000052		
383	263	198	159	102	70	41	27
541	329	258	207	136	94	60	40
542	326	256	206	135	95	60	41
819	446	352	285	190	135	87	61
S48	1	13	0	0	000053		
375	232	177	140	90	63	38	26
551	302	233	186	121	85	54	37
540	294	226	181	118	83	52	34
832	416	318	255	169	120	77	53
S49	1	13	0	0	000054		
374	280	220	177	116	84	56	41
538	357	286	232	155	114	78	57
540	354	284	231	155	114	78	57
829	495	396	322	220	163	114	84
S50	1	13	0	0	000054		
373	223	170	134	83	59	37	25
531	296	232	185	119	84	52	36
534	293	231	183	119	84	53	37

806	433	321	284	186	128	83	52
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310	188	135	132	90	65	40	27
468	268	219	190	132	92	60	40
467	264	219	188	131	91	60	40
808	444	359	316	222	156	103	69
S52		1	13	000	0	000112	
319	196	128	130	78	52	27	16
474	267	209	174	111	72	39	24
474	265	214	174	111	72	41	24
813	415	328	269	171	113	63	38
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320	208	163	139	86	56	30	18
480	287	227	193	121	79	44	26
478	283	229	192	121	79	45	27
820	444	376	299	191	123	70	41
S54		1	13	000	0	000115	
317	169	101	97	54	37	23	17
473	227	171	134	81	55	37	27
474	226	172	133	80	55	37	27
811	364	273	215	136	95	65	49
S55		1	13	000	0	000116	
313	189	119	110	60	40	25	22
473	245	192	149	88	62	40	30
472	244	186	148	89	61	41	32
809	365	296	226	145	104	73	52
S56		1	13	000	0	000117	
316	199	136	108	59	37	22	16
473	268	191	147	83	54	33	23
472	264	184	146	84	55	33	24
808	407	294	225	135	90	59	42
S57		1	13	000	0	000118	
316	179	139	117	73	52	32	23
476	249	210	166	109	76	50	33
474	247	204	164	108	76	49	33
809	397	320	265	177	129	86	58
S58		1	13	000	0	000119	
312	212	141	145	95	77	48	37
472	307	252	212	148	108	72	51
470	302	253	209	147	106	72	51
796	518	392	359	250	187	125	87
S59		1	13	000	0	000120	
309	175	144	105	64	41	24	16
466	242	179	150	94	61	37	24
461	238	189	148	93	59	36	24
793	401	294	244	155	103	64	42
S60		1	13	000	0	000121	
301	179	129	127	79	55	31	16
452	251	206	174	116	77	43	23
452	247	205	173	116	77	43	23
780	421	341	291	196	133	75	40
S61		1	13	000	0	000123	
298	150	111	90	53	32	17	11
455	207	158	126	76	46	26	17
443	203	155	123	75	46	27	17
804	332	251	198	121	77	46	32
S62		1	13	000	0	000124	
290	228	160	111	60	36	21	15
451	310	232	154	88	53	32	23
449	304	214	153	87	54	32	23
789	481	335	239	142	91	57	41
S63		1	13	000	0	000125	
291	123	89	63	33	24	13	10
448	168	113	90	50	33	20	15
444	168	116	91	51	33	20	15
795	260	186	143	83	55	36	26
S64		1	13	000	0	000126	
299	171	124	96	52	31	16	11
456	228	180	131	74	42	23	15
459	226	179	131	73	42	24	15
792	348	268	197	113	69	40	28

814	418	335	269	178	128	82	56
S51		1	13	0	0	000055	
376	218	172	145	91	67	43	29
538	280	231	193	125	91	60	41
542	279	229	192	125	91	60	41
831	401	333	276	186	136	89	63
S52		1	13	0	0	000056	
372	231	174	140	89	60	37	26
513	292	224	183	116	81	52	36
535	296	228	186	118	84	53	37
819	418	326	264	173	124	80	57
S53		1	13	0	0	000057	
378	254	209	169	106	71	44	29
542	332	280	225	144	98	61	40
546	330	279	225	145	99	62	41
833	475	399	322	211	148	93	64
S54		1	13	0	0	000058	
382	182	120	84	50	33	22	18
544	228	157	116	68	49	34	25
541	227	157	116	68	50	34	25
822	317	223	167	103	75	52	40
S55		1	13	0	0	000059	
376	221	156	111	61	41	27	22
525	273	199	149	83	60	42	31
539	274	203	151	86	61	43	32
829	380	284	215	130	95	67	50
S56		1	13	0	0	000059	
370	216	130	89	46	32	22	16
535	272	173	120	67	45	31	24
523	265	168	118	64	44	31	23
823	373	244	173	100	71	49	37
S57		1	13	0	0	000100	
378	191	139	105	65	46	31	23
537	252	188	146	93	68	46	32
531	248	185	143	91	67	46	32
827	366	275	217	142	105	73	52
S58		1	13	0	0	000101	
351	237	186	151	96	69	44	30
533	329	264	216	143	104	66	45
536	326	263	216	143	104	66	45
827	463	378	312	211	158	101	71
S59		1	13	0	0	000102	
379	173	120	90	52	35	22	16
542	223	162	121	73	50	32	24
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834	323	236	181	109	79	53	39
S60		1	13	0	0	000103	
344	194	150	121	77	57	34	26
527	280	221	179	117	87	59	42
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813	417	336	275	184	138	93	68
S61		1	13	0	0	000104	
374	188	131	101	58	39	26	20
538	242	175	138	75	56	38	29
521	234	170	131	76	54	38	29
819	342	250	197	113	85	59	45
S62		1	13	0	0	000008	
404	245	186	136	83	58	40	31
567	300	235	176	108	79	55	41
556	294	231	172	107	79	55	40
852	408	323	246	158	119	85	66
S63		1	13	0	0	000008	
382	150	97	70	35	25	18	14
559	192	128	94	50	35	26	20
559	192	129	94	51	35	26	20
854	262	182	133	78	55	40	31
S64		1	13	0	0	000009	
387	188	132	95	52	31	21	17
557	242	172	127	70	45	29	23
557	240	171	124	69	45	29	23
847	338	242	178	102	69	47	38

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S65       1  13   000  0  000127
 299 303 228 164  91  59  36  26
 456 387 293 216 127  82  54  39
 455 384 294 215 127  83  54  39
 788 568 425 325 200 134  94  71
S66       1  13   000  0  000128
 305 156 120 101  59  40  24  17
 460 211 172 136  84  55  34  25
 458 208 166 135  82  54  33  24
 799 335 263 217 138  93  62  46
S67       1  13   000  0  000129
 298 186 159 113  71  45  27  18
 457 268 207 169 103  69  44  28
 456 264 214 165 103  69  44  29
 792 437 352 271 173 116  72  50
S68       1  13   000  0  000130
 299 166  86 101  54  39  24  15
 456 233 220 131  88  54  38  30
 459 230 198 133  84  55  38  28
 795 373 339 215 145  95  69  53
S69       1  13   000  0  000131
 294 166 121 121  84  65  41  25
 449 234 178 169 122  91  60  37
 452 232 183 166 121  90  60  37
 780 377 311 270 200 148 100  66
S70       1  13   000  0  000132
 301 268 190 179 112  81  46  32
 456 391 314 263 170 117  70  46
 458 385 309 261 169 116  70  46
 791 670 543 449 299 200 126  80
S71       1  13   000  0  000133
 298 211 139 135  89  67  45  30
 456 317 246 209 140  98  67  46
 457 311 250 207 139  95  65  45
 789 562 432 372 256 179 122  84
S72       1  13   000  0  000134
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 463 332 263 223 151 103  70  50
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 451 351 281 252 177 127  89  64
 453 345 285 249 177 126  89  64
 791 563 441 407 294 218 158 112
S74       1  13   000  0  000136
 289 302 254 205 136  92  61  42
 443 438 381 302 206 138  92  63
 444 431 372 294 203 136  92  63
 778 744 618 511 353 242 166 113
S75       1  13   000  0  000137
 291 252 177 112  53  33  21  19
 454 326 235 151  76  44  30  24
 450 322 235 150  78  46  32  26
 790 483 334 226 122  74  52  41
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 440 301 246 199 130  85  52  28
 442 297 237 197 128  85  49  28
 782 448 349 302 201 135  83  47
S77       1  13   000  0  000139
 292 218 162 137  83  51  27  16
 456 302 233 193 120  73  41  25
 458 299 235 191 120  74  42  26
 811 478 363 304 192 121  70  45
S78       1  13   000  0  000140
 285 195 128 119  75  55  37  28
 448 284 221 180 122  85  60  42
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 791 481 376 316 221 160 113  82
S79       1  13   000  0  000141
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S65       1  13     0  0  000010
 377 355 247 177 106  76  52  40
 547 448 320 235 146 106  75  58
 545 441 316 232 145 105  75  58
 833 605 442 330 211 160 116  91
S66       1  13     0  0  000011
 389 201 158 120  75  52  34  27
 559 261 204 159 100  71  49  38
 560 259 203 158 100  71  49  38
 854 366 288 228 150 109  78  61
S67       1  13     0  0  000011
 385 284 213 168 102  71  47  36
 554 366 281 224 140 100  68  51
 558 364 281 224 142 101  69  51
 845 512 399 320 209 155 110  82
S68       1  13     0  0  000012
 389 241 176 137  83  59  40  30
 559 309 233 181 114  82  54  41
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 842 430 332 261 171 125  88  68
S69       1  13     0  0  000013
 373 217 178 153 111  82  52  34
 539 285 236 202 148 111  72  51
 539 281 233 199 147 111  72  51
 833 410 337 290 214 163 111  79
S70       1  13     0  0  000014
 384 270 209 167 108  77  49  36
 552 364 287 233 153 112  77  55
 551 361 285 233 154 113  79  56
 839 544 430 352 237 177 122  86
S71       1  13     0  0  000015
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 546 352 272 216 139 101  69  53
 552 349 271 216 140 102  70  54
 842 530 413 328 219 160 112  86
S72       1  13     0  0  000015
 379 243 186 149  94  69  48  39
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 841 489 394 315 212 160 115  89
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 538 452 367 304 208 154 105  74
 541 451 366 305 209 156 107  78
 831 629 521 435 305 232 162 118
S74       1  13     0  0  000017
 365 416 334 274 181 128  83  57
 533 551 451 373 252 183 120  85
 536 545 449 372 253 185 122  87
 824 781 639 532 366 272 182 132
S75       1  13     0  0  000018
 368 303 194 131  71  49  32  24
 537 379 248 172  94  65  44  32
 537 372 246 172  95  66  47  33
 826 518 347 244 142 100  68  52
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 550 378 305 250 159 113  69  42
 539 373 300 245 157 109  68  42
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 548 371 296 237 145  94  53  34
 552 366 294 238 145  95  57  38
 838 497 403 322 203 134  80  55
S78       1  13     0  0  000021
 374 237 182 140  99  74  53  42
 544 317 255 211 144 114  83  61
 544 315 256 212 146 116  86  65
 833 480 392 327 232 184 136 102
S79       1  13     0  0  000022
```

289	151	232	89	48	39	25	24
448	212	157	128	81	54	41	29
449	209	154	127	79	53	40	29
794	348	270	218	147	99	76	57
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457	195	153	98	57	34	24	16
453	193	162	97	57	33	24	16
797	280	219	150	91	58	41	28
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448	211	151	114	68	41	27	19
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793	313	209	178	109	73	51	34
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288	184	118	90	46	32	20	15
451	248	182	129	74	46	29	20
454	246	175	128	74	46	29	20
797	370	267	203	122	81	52	38
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289	184	119	96	50	35	19	15
450	252	182	136	78	52	30	22
452	250	169	135	78	51	31	20
802	389	254	216	130	87	54	36
S84	1	13		000	0	000147	
274	167	99	87	42	36	19	16
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445	242	171	131	77	49	32	22
793	382	271	211	129	83	54	37
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448	273	204	143	83	53	31	22
450	272	200	143	84	54	33	24
791	422	294	230	137	90	59	38
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449	245	178	126	68	41	28	22
448	241	177	124	67	41	28	22
789	363	258	195	112	72	52	40
S87	1	13		000	0	000150	
277	172	91	74	36	24	15	12
447	226	167	104	56	35	20	15
447	223	161	104	56	34	21	15
791	332	217	161	90	60	38	26
S88	1	13		000	0	000151	
278	188	114	105	43	33	15	14
450	257	193	136	72	41	23	16
446	253	191	134	72	41	22	15
796	381	269	211	114	72	43	30
S89	1	13		000	0	000152	
280	242	167	128	57	32	15	11
447	333	239	179	86	50	27	18
448	330	244	176	86	48	25	19
788	504	351	258	129	74	41	31
S90	1	13		000	0	000153	
276	104	82	66	41	25	13	8
441	152	115	96	59	37	19	10
439	150	113	94	59	36	19	10
785	254	193	156	97	61	31	16
S91	1	13		000	0	000156	
267	98	50	91	50	45	45	12
425	146	113	114	79	60	37	20
421	143	113	112	79	62	37	20
772	246	190	188	136	107	71	41
S92	1	13		000	0	000157	
271	73	49	53	27	21	10	6
434	105	89	66	44	28	16	10
432	104	85	68	44	28	17	11
776	176	150	113	76	51	29	19
S93	1	13		000	0	000158	
276	74	50	49	32	26	10	9

374	169	123	92	60	43	31	26
551	224	169	131	87	66	50	40
550	222	169	131	87	66	50	40
850	334	260	209	144	113	87	67
S80	1	13		0	0	000023	
379	171	109	72	40	28	19	15
549	206	141	97	55	41	28	18
550	204	140	96	55	41	28	18
851	276	195	139	84	63	44	32
S81	1	13		0	0	000024	
382	182	122	88	50	35	24	17
551	227	159	118	69	52	36	27
552	225	159	118	70	51	36	26
847	307	221	168	106	79	55	41
S82	1	13		0	0	000025	
390	227	149	104	59	40	26	19
549	278	193	140	81	57	39	28
549	275	192	140	81	57	38	28
847	371	271	203	124	89	61	45
S83	1	13		0	0	000025	
378	224	158	112	65	44	29	22
549	284	209	155	92	66	45	34
547	279	206	153	90	64	45	32
850	389	291	222	138	101	70	52
S84	1	13		0	0	000026	
383	214	145	102	62	41	27	17
546	269	191	140	86	60	39	27
544	265	189	139	86	59	38	27
846	374	271	205	129	92	61	42
S85	1	13		0	0	000027	
392	216	151	109	69	51	32	24
549	268	197	148	94	70	50	37
546	263	193	143	92	68	47	33
855	380	284	218	147	113	77	57
S86	1	13		0	0	000028	
378	210	139	96	54	38	27	22
543	258	179	129	74	54	40	31
557	258	182	131	76	56	40	31
853	346	254	189	117	86	63	50
S87	1	13		0	0	000028	
397	208	133	89	48	31	18	14
556	252	172	119	65	44	30	22
557	248	171	119	65	44	30	22
852	321	234	168	98	68	46	33
S88	1	13		0	0	000029	
385	229	155	107	54	32	19	12
557	275	193	138	72	44	25	19
544	268	188	134	70	42	25	18
837	353	254	186	100	65	39	29
S89	1	13		0	0	000030	
393	291	206	141	68	38	22	16
541	352	255	176	86	51	30	22
554	354	258	179	88	51	30	22
850	479	350	245	121	74	45	34
S90	1	13		0	0	000031	
387	145	97	74	43	26	13	8
531	180	125	96	56	36	21	16
529	177	122	96	55	37	21	16
830	265	181	137	81	52	30	20
S91	1	13		0	0	000032	
363	137	112	96	67	49	32	23
543	188	158	134	95	71	49	36
548	188	158	134	96	72	49	37
833	276	231	195	143	107	75	56
S92	1	13		0	0	000033	
389	103	72	55	34	21	8	8
553	133	96	74	45	30	21	14
556	131	95	74	45	30	20	14
846	193	139	109	68	46	31	23
S93	1	13		0	0	000034	
402	111	81	64	39	26	15	12

438	108	77	73	49	33	17	12
439	108	82	74	50	34	19	13
789	187	141	127	84	57	34	24
S94		1	13	000	0	000200	
274	87	63	69	42	57	19	15
434	127	113	89	62	42	27	19
435	125	108	88	62	43	28	19
771	201	159	140	99	71	47	32
S95		1	13	000	0	000201	
275	127	94	81	48	33	17	8
433	183	162	113	75	49	28	16
436	181	153	112	72	48	27	15
775	299	253	178	118	76	45	26
S96		1	13	000	0	000202	
275	88	58	71	42	31	19	11
439	129	107	95	65	44	28	17
441	128	109	94	65	44	28	17
785	207	162	151	105	73	47	28
S97		1	13	000	0	000203	
274	77	50	52	36	25	14	10
444	121	113	84	57	36	22	14
440	118	104	82	56	36	22	14
785	201	158	137	95	63	40	24
S98		1	13	000	0	000204	
274	85	57	61	39	28	15	9
439	129	120	91	64	40	24	15
437	126	123	88	62	39	23	13
786	213	180	148	103	68	42	24
S99		1	13	000	0	000205	
273	181	123	78	40	28	18	13
439	250	181	119	67	45	32	23
437	248	173	118	68	46	33	25
781	395	283	199	121	84	61	43
S100		1	13	000	0	000208	
273	158	91	83	43	34	24	18
431	221	159	124	74	51	37	28
433	220	150	124	73	52	38	28
772	355	250	214	134	98	72	53
S101		1	13	000	0	000209	
275	141	82	74	37	30	18	14
440	196	137	103	60	39	27	20
441	195	130	104	60	42	29	23
779	311	219	172	103	74	51	39
S102		1	13	000	0	000210	
277	164	109	68	32	24	15	12
438	218	144	98	50	34	23	18
437	216	141	96	50	33	23	18
781	328	215	154	86	60	43	33
S103		1	13	000	0	000211	
274	194	125	98	48	38	23	17
433	269	197	141	79	52	34	26
433	265	192	139	78	53	36	27
781	419	293	233	136	94	65	46
S104		1	13	000	0	000211	
271	234	140	91	38	23	17	14
433	309	188	129	59	37	28	23
432	302	184	127	57	36	26	20
776	465	287	198	98	66	49	40
S105		1	13	000	0	000212	
275	206	112	93	50	35	23	17
434	295	197	141	79	54	39	29
437	288	191	139	78	54	39	29
782	481	329	247	147	102	74	55
S106		1	13	000	0	000213	
280	152	88	77	44	33	24	16
445	211	148	113	72	52	39	27
444	210	151	112	72	52	40	28
789	337	244	194	131	96	73	51
S107		1	13	000	0	000214	
288	153	125	62	33	20	16	13
440	198	191	84	50	28	21	18

563	142	105	85	51	34	23	18
565	140	105	85	51	35	23	17
856	206	155	122	76	51	31	25
S94		1	13	0	0	000036	
353	130	95	77	53	36	22	16
546	174	130	110	72	54	37	25
521	168	125	103	69	51	32	23
813	243	180	148	101	74	49	36
S95		1	13	0	0	000037	
382	170	140	100	64	42	24	15
546	218	180	132	82	55	31	19
549	216	179	131	83	56	31	19
835	305	250	184	116	77	46	29
S96		1	13	0	0	000037	
381	149	108	89	58	40	23	16
546	187	141	116	76	54	32	20
547	184	140	114	76	54	32	22
822	257	193	157	107	76	47	31
S97		1	13	0	0	000038	
384	144	108	87	58	39	22	14
557	181	143	117	74	52	31	19
554	179	140	114	73	50	30	18
828	250	194	158	103	71	42	26
S98		1	13	0	0	000039	
360	115	90	73	48	32	18	11
549	159	126	103	67	46	27	16
535	156	122	99	65	44	27	16
834	224	179	147	97	67	40	25
S99		1	13	0	0	000040	
363	226	148	96	52	38	28	22
535	286	195	134	74	55	41	29
527	281	193	133	74	56	42	30
822	387	278	197	116	90	67	50
S100		1	13	0	0	000041	
380	183	120	85	54	41	31	27
523	220	156	116	73	58	46	38
521	215	154	113	71	55	44	36
833	313	234	179	120	95	74	60
S101		1	13	0	0	000042	
390	191	126	88	51	36	27	20
556	238	162	117	69	52	41	34
558	235	163	117	69	51	40	33
825	324	225	165	101	77	60	47
S102		1	13	0	0	000043	
383	179	109	72	41	34	26	22
552	219	144	98	60	49	40	33
532	212	139	94	56	46	37	31
841	300	202	142	92	75	61	51
S103		1	13	0	0	000044	
385	190	126	89	53	39	27	22
536	233	164	117	72	54	40	31
550	234	167	119	74	56	41	31
844	328	239	176	112	86	63	47
S104		1	13	0	0	000045	
375	227	157	103	53	37	28	23
551	286	208	140	75	53	41	32
530	277	200	137	73	53	40	32
841	390	288	200	114	83	62	50
S105		1	13	0	0	000045	
393	329	220	154	84	60	41	29
553	407	285	204	117	84	57	42
546	398	281	202	116	85	60	42
846	542	392	288	173	129	91	67
S106		1	13	0	0	000046	
392	218	144	104	61	45	33	26
549	270	190	140	87	65	48	37
553	268	190	140	87	65	48	37
844	368	270	207	134	103	76	57
S107		1	13	0	0	000047	
393	189	115	76	43	33	26	23
543	226	148	101	59	44	36	29

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 437 197 161  89  50  31  23  19
 778 301 268 140  88  55  42  34
S108       1  13   000  0  000216
 279 246 177 131  70  43  27  18
 436 334 248 179 102  64  41  28
 439 328 246 176 102  63  41  28
 774 540 388 295 175 114  75  52
S109       1  13   000  0  000217
 283 253 196 168 103  67  38  20
 436 338 276 227 148  94  53  29
 416 323 264 220 145  94  54  31
 772 532 440 359 241 156  91  53
S110       1  13   000  0  000218
 274 206 129 126  74  55  39  31
 437 299 209 181 113  81  57  45
 435 293 207 177 110  80  57  45
 785 503 363 310 200 145 107  82
EOF
```

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 542 223 147  99  58  44  34  28
 826 302 206 148  90  69  53  43
S108       1  13     0  0  000048
 362 319 233 181 113  80  51  36
 553 420 314 249 161 122  84  56
 551 417 314 249 163 123  86  58
 820 562 428 340 227 173 120  83
S109       1  13     0  0  000049
 350 268 213 173 112  83  55  38
 517 348 282 232 156 118  82  53
 518 343 278 229 155 117  78  55
 826 501 415 345 241 186 130  88
S110       1  13     0  0  000050
 380 306 236 185 117  84  53  41
 521 376 297 235 153 111  78  57
 545 383 305 244 159 117  82  60
 833 545 441 350 238 175 120  92
EOF
```

APPENDIX C AMOD USER'S GUIDE

C-1 Introduction

AMOD is a computer program developed by Alaska DOT&PF. AMOD computes the modulus of asphalt concrete mix for the given properties of the asphalt and aggregate using a relationship developed by the Asphalt Institute. The computed modulus can be used for the following purpose:

1. provide reference information for estimating asphalt concrete layer modulus,
2. provide input to mechanistic pavement design.

C-2 Program Input

The program inputs include the following:

1. void ratio (%),
2. asphalt penetration,
3. percent of asphalt by weight,
4. percent aggregate passing the 200 sieve,
5. temperature at time of test (F), and
6. frequency of loading (Hz).

The program includes a set of default data. These are:

1. void ratio = 3%,
2. asphalt penetration = 200,
3. asphalt content = 6%,
4. percent aggregate passing the 200 sieve = 5%,
5. temperature at time of test (F) = 50%, and
6. frequency of loading (Hz) = 40 Hz.

C-3 Program Output

The output of this program is modulus of an asphalt concrete mix. For the above default data, the modulus is calculated to 1,371,823 (psi). By changing any of these parameters, a corresponding modulus will be calculated and displayed on the computer screen.

C-4 Program Execution

To execute the program, type AMOD and press ENTER key; the following screen will then be displayed.

```
PRESS APPROPRIATE NUMBER TO CHANGE DEFAULT VARIABLES

    1.  VOID RATIO                        =  3
    2.  PENETRATION                       =  200
    3.  ABSOLUTE VISCOSITY @ 70 DEG F.    =  .2640662
    4.  % ASPHALT BY WT. OF TOTAL MIX     =  6
    5.  PERCENT PASSING THE 200 SIEVE     =  5
    6.  TEMPERATURE AT TIME OF TEST (F)   =  50
    7.  FREQUENCY OF LOADING IN HZ.       =  40
    8.  END



THE MODULUS FOR THE ASPHALTIC CONCRETE MIX IS: 1,371,823 (PSI)
```

By pressing an appropriate number to change default variables (for example, press 1 to change void ratio), the corresponding modulus for the asphalt concrete mix will be calculated and displayed.

APPENDIX D FWD DATA DELINEATION PROGRAM USER'S GUIDE

This appendix describes a statistical procedure (cumulative difference) for delineating pavement response measurements. A computer program, which was developed by using the cumulative difference, is also described.

D-1 Approach Fundamentals

The cumulative difference approach (AASHTO, 1986) is a relatively straightforward and powerful analytical method for delineating statistically homogenous units from pavement response measurements along a highway system. The methodology is fundamentally easy, however, the manual implementation for large data bases becomes very time consuming and cumbersome.

The cumulative difference approach can be used for a wide variety of measured pavement response variables such as deflection, serviceability, skid resistance, pavement distress-severity index, etc.

Figure D-1 illustrates the overall approach concept using the initial assumptions of a continuous and constant responses value (r_i) within various intervals (0 to x_1; x_1 to x_2; $x_2$to x_3) along a project length. Form this figure, it is obvious that three unique units having different response magnitudes (r_1, r_2, and r_3) exist along the project. Figure D-1(a) illustrates such a response-distance result. The solid line in Figure D-1(b) indicates the results of actual response curves. Because the functions are continuous and constant within a unit, the cumulative area, at and x, is simply the integral or

$$A_x = \int_0^{x_1} r_1 dx + \int_{x_1}^{x} r_2 dx \quad \text{(D-1)}$$

with each integral being continuous within the respective intervals:

$(0 \leq x \leq x_1)$ and $(x_1 \leq x \leq x_2)$

In Figure D-1(b), the dashed line represents the cumulative area

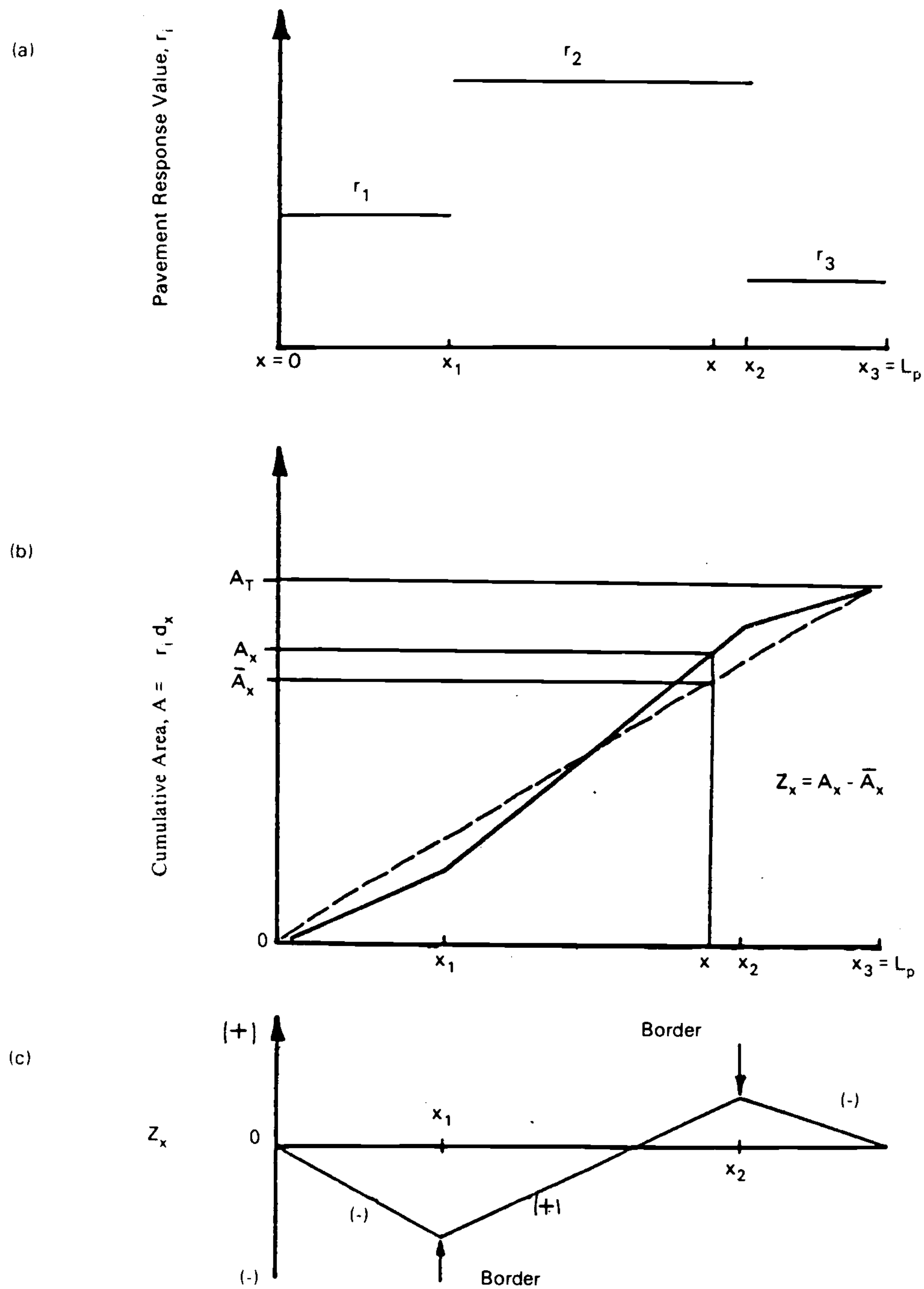

Figure D-1 Concepts of Cumulative Difference Approach to Analysis Unit Delineation (AASHTO, 1986) caused by the overall average project response. It should be recognized that the slope (derivatives) of the cumulative area curves are simply the response value for each unit (r_1, r_2, and r_3) while the slope of the dashed line is the overall average response value of the entire project length considered. At the distance, x, the cumulative area of the average project response is:

$$\bar{A}_x = \int_0^x \bar{r}dx \qquad \text{(D-2)}$$

with

$$\bar{r} = \frac{\int_0^{x_1} r_1 dx + \int_{x_1}^{x_2} r_2 dx + \int_{x_2}^{x_3} r_3 dx}{L_p} \qquad \text{(D-3)}$$

$$= \frac{A_T}{L_p}$$

Knowing both $\bar{A}_x$ and A_x, the cumulative difference variable Z_x can be determined from:

$$Z_x = A_x - \bar{A}_x \qquad \text{(D-4)}$$

As noted in Figure D-1(b), Z_x is the difference in cumulative areas, at given x, between the actual and project average lines. If the Z_x value is, in turn, plotted against distance, x, Figure D-1(c) results. An examination of this plot illustrates that the location of unit boundaries always coincides with the location (along x) where the slope of the Z_x function change algebraic signs (i.e., from negative to positive or vice versa). This fundamental concept is the basis used to analytically determine the boundary location for the analysis units.

D-2 <u>Application to Discontinuous Variables</u>

The schematic figures shown in Figure D-1 are obviously highly idealized. In practice, measurements are normally discontinuous (point measurements), frequently obtained at unequal intervals and never constant, even within a unit. In order to apply the foregoing principles into a solution methodology capable of dealing with these conditions, a numerical difference approach must be used. The form of the Z_x function is:

$$Z_x = \sum_{i=1}^{n} a_i - \frac{\sum_{i=1}^{n} a_i}{L_p} \sum_{i=1}^{n} x_i \qquad \text{(D-5)}$$

$$a_i = \frac{(r_{i-1} + r_i) * x_i}{2} = \bar{r}_i * x_i \qquad \text{(D-6)}$$

(note: let $r_0 = r_1$ for first interval)

where:

- n = the n^{th} pavement response measurement,
- n_t = total number of pavement response measurements taken in project,
- r_i = pavement response value of the i^{th} measurement,
- r_{i-1} = average of the pavement response values between the (i-1) and i^{th} tests, and
- L_p = total project length.

If equal pavement testing intervals are used, then:

$$Z_x = \sum_{i=1}^{n} a_i - \frac{n}{n_t} \sum_{i=1}^{n_t} a_i \qquad \text{(D-7)}$$

D-3 <u>Tabulation Solution Sequence</u>

Table D-1 is a table illustrating how the solution sequence progresses and the necessary computational steps required for an unequal interval analysis.

D-4 <u>Program Description</u>

FWD is a program developed for analyzing deflection data collected from Falling Weight Deflectometer (FWD). The purpose of analyzing the deflection data is to define delineation units so that pavement sections have similar response may be characterized by

Table D-1 Tabular Solution Sequence - Cumulative Difference Approach (AASHTO, 1986)

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 $F^* = \bar{r}$	

representative values. Specifically, the FWD program has the following functions:

1. Convert deflection data collected at different load level to that of 9000-lb load.
2. Delineate analysis unit based on area function.
3. Delineate analysis unit based on maximum deflection.
4. Delineate analysis unit based on subgrade modulus.
5. Display normalized deflection basin area, or maximum deflection, or subgrade modulus at each test location in a bar chart form.

The FWD program can be used to analyze deflection data for any length of a project. This allows delineation to be performed in a single analysis.

D-5 Program Execution

To execute the program, type FWD and press Enter key. A screen as shown in Figure D-2 will be displayed. By pressing any key, the program will prompt for a file to be analyzed as shown in Figure D-3. The following shows an example file named TEST.DAT is being analyzed.

Figure D-4 illustrates a title screen for the file TEST.DAT, showing information related to test date, location, milepost, surface type, and operator. Pavement thickness data need to be input manually. The program will ask for this information for each test section (not each test spot, e.g. a test section contains 21 test spots). Deflection data are corrected for temperature effect for those asphalt pavements with less than 6-inch thick of surface using method recommended by ODOT and converted to a 9,000-lb load level.

Figure D-5 shows the program main menu which includes five options: delineation on area function; delineation on maximum deflection; delineation on subgrade modulus; operating system; and quit.

1) Delineation on area function: This method considers the entire deflection basin area as an indicator of the pavement response.

FWD DEFLECTION DATA DELINEATION PROGRAM

Developed for
Oregon State Highway Division
Oregon Department of Transportation
Oregon State University

Version 1.0 Oct. 1988

Press any key to continue

Figure D-2 Title Screen

FWD DEFLECTION DATA DELINEATION PROGRAM

Developed for
Oregon State Highway Division
Oregon Department of Transportation
Oregon State University

File name:

Press ↵ or Esc to Exit

Figure D-3 Asking for File Name

```
Test Date: 10-17-88      Dist. No: 04
County: KLAMATH          Roadway No: 4
Lane Desig: 2            Dist from Edge: OWT
Begin MP: 204.00         Offset: S.B.
End MP: 207.00           Offset:
Surface: AC              Operator: DOUG H.

File name: TEST.DAT
Pavement Thickness:
```

Figure D-4 Heading for TEST.DAT

```
P R O G R A M   M A I N   M E N U

1. DELINEATION ON AREA FUNCTION
2. delineation on Maximum deflection
3. delineation on Subgrade modulus
4. Operating System (DOS)
5. Quit

File name: TEST.DAT
```

Use ↑ or ↓ to Select   ◄┘ to Activate   Esc to Exit

Figure D-5 Program Main Menu

2) Delineation on maximum deflection: This method considers the maximum deflection as an indicator of the pavement response.

3) Delineation on subgrade modulus: This method considers the subgrade modulus as an indicator of the pavement response.

All three delineation methods are based on the cumulative difference technique described above.

4) Operating System: This option allows a user to leave the program temporarily and work on something else while still keep the program in computer memory. To return to the program, type EXIT under DOS prompt.

5) Quit: This option terminates the program execution.

To select a delineation method, the user may use cursor keys to highlight a option and press Enter key to activate it or type in a number corresponding to an option to invoke it. For the above example, option 1 (delineation on area function) is selected and a bar chart showing the pavement response variation is displayed as presented in Figure D-6. This bar chart may be printed by using PrintScreen Key on keyboard. This bar chart representation allows the user to look at the pavement response variations along the roadway and also allows to define an analysis unit by user itself. As shown in Figure D-7, two options are provided to select the method for defining the units. Figure D-8 shows a display for option 1 (user defines units). There are a total of 61 tests in the TEST.DAT file, and 6 units have been defined by the user. Based on user defined units, the average deflections at sensor locations 1 to 6, 80th deflection value, standard deviation for the maximum deflection, subgrade modulus at sensor 4, 5, and 6, and average subgrade modulus at those three location are printed as shown in Table D-2.

Table D-3 shows delineation units defined by the program by selecting option 2 as shown in Figure D-7. The delineation method is based the cumulative difference approach as described previously.

There is one file created during the analysis. This file is named as filename with an extension of FWD. For example, to analyze a file named TEST.DAT, a new file will be created as TEST.FWD. This

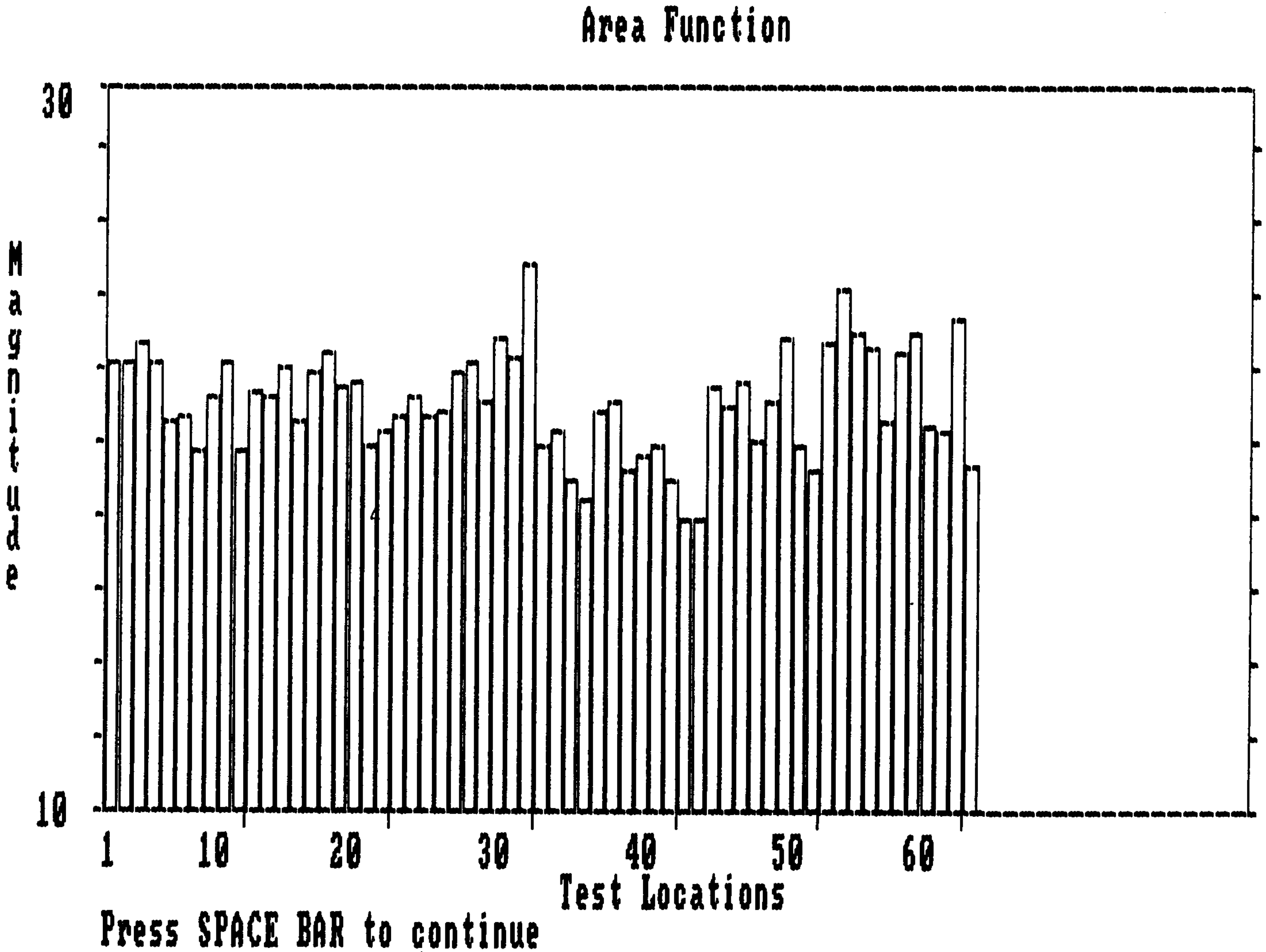

Figure D-6 Bar Chart Representation of Pavement Response

```
Select delineation methods

1. User define delineation units
2. Program define delineation units

Selection ⟹ █
```

Figure D-7   Options for Defining Delineation Units

```
Number of Units: 6                      Total tests =  61
Unit   1     From: 1        To: 10
Unit   2     From: 11       To: 20
Unit   3     From: 21       To: 30
Unit   4     From: 31       To: 40
Unit   5     From: 41       To: 50
Unit   6     From: 51       To: 61
```

Figure D-8   Screen Display for Option 1

Table D-2 Example Output for User Defined Delineation Units

Test No. From	To	Def-1	Average Deflections (@ 9000lb) Def-2	Def-3	Def-4	Def-5	Def-6	80th	STD Def-1	Subgrade Modulus (ksi) S-4	S-5	S-6	Avg
1	10	23.5	17.5	15.5	13.9	10.5	8.7	26.1	3.0	10.1	10.0	8.1	9.4
11	20	28.6	20.9	19.0	16.7	12.8	10.1	33.9	6.3	8.4	8.2	6.9	7.8
21	30	31.8	24.2	22.5	19.2	14.1	11.5	37.5	6.8	7.3	7.4	6.1	6.9
31	40	36.7	25.7	24.1	20.1	13.0	11.8	41.5	5.7	7.0	8.1	5.9	7.0
41	50	33.5	24.2	22.8	19.2	11.7	11.2	40.8	8.6	7.3	9.0	6.2	7.5
51	61	23.7	17.8	16.4	14.5	10.7	9.2	28.5	5.7	9.6	9.8	7.6	9.0

Total of 6 delineation units

Table D-3 Example Output for Program Defined Delineation Units

Test No. From	To	Def-1	Average Deflections (@ 9000lb) Def-2	Def-3	Def-4	Def-5	Def-6	80th	STD Def-1	Subgrade Modulus (ksi) S-4	S-5	S-6	Avg
1	18	24.8	18.5	16.4	14.6	11.2	9.1	28.0	3.8	9.5	9.3	7.6	8.8
19	28	34.3	25.5	23.6	20.1	14.6	11.7	39.3	5.9	6.9	7.2	6.0	6.7
29	30	25.0	19.6	18.6	16.4	13.1	10.8	29.9	5.8	8.5	8.0	6.5	7.7
31	42	36.0	25.2	23.6	19.5	12.0	11.1	40.7	5.6	7.2	8.7	6.3	7.4
43	43	23.3	16.8	16.3	15.2	8.2	11.0	23.3	0.0	9.2	12.7	6.4	9.4
44	47	34.5	25.4	24.1	20.8	12.7	12.8	42.0	8.9	6.7	8.2	5.4	6.8
48	48	22.6	17.4	17.1	15.1	10.3	10.0	22.6	0.0	9.2	10.2	7.0	8.8
49	51	36.0	25.6	23.8	19.9	14.3	11.3	46.4	12.4	7.0	7.3	6.2	6.8
52	58	23.8	17.9	16.8	14.8	11.0	9.5	28.6	5.6	9.4	9.5	7.4	8.8
59	59	33.2	24.8	21.9	18.3	13.1	10.2	33.2	0.0	7.6	8.0	6.9	7.5
60	61	19.7	14.5	12.9	11.6	8.5	7.5	21.9	2.6	12.0	12.4	9.3	11.2
Average		28.4	21.0	19.6	16.9	11.7	10.4	32.3	4.6	8.5	9.2	6.8	8.2

There are total of 11 delineation units

file contains information such as test number, test location (mileage), and deflection values converted to 9,000-lb load at each sensor location. Table D-4 shows a typical output.

D-6 <u>Usage of the Output</u>

Tables D-2 and D-3 shows typical program output. The information contained in these tables may be used in several purposes. The average deflection values may be used for backcalculation analysis. The 80th deflection may used for overlay design using the ODOT procedure. The subgrade modulus may be used in backcalculation as a fixed value or as a reference for checking the backcalculated result.

D-7 <u>Recommendation for Implementation</u>

To obtain a best result from using the program , it is recommended that the user:

1. Obtain pavement surface thickness data before using the program, since the program will need these data for correcting the deflection values.
2. Combine necessary files into one single file (same project). For example, deflections collected at shoulder may be combined to a file, while deflections collected at out wheel track may be saved to another file.
3. Print out the graph. This graph may help the user to define manually the delineation units.
4. Print out the file with an extension FWD. This file includes test number, test location, and deflections that are converted to 9,000-lb load.

Table D-4 Example Output for TEST.FWD File

Test #	Location	Deflection Values					
Sensor	Location:	0	8	12	18	24	36
1,	204.050,	25.89,	19.96,	18.31,	16.42,	11.89,	9.66
2,	204.100,	20.52,	15.23,	14.05,	12.82,	9.62,	8.51
3,	204.151,	24.50,	18.55,	17.04,	15.64,	12.36,	10.20
4,	204.152,	26.54,	19.87,	18.05,	16.51,	13.06,	10.33
5,	204.200,	27.70,	20.40,	17.87,	15.40,	11.67,	9.08
6,	204.251,	23.37,	17.26,	14.98,	13.19,	9.79,	8.32
7,	204.300,	20.65,	15.07,	12.65,	10.87,	8.14,	6.35
8,	204.351,	18.82,	14.65,	12.14,	10.96,	7.92,	6.88
9,	204.400,	21.33,	16.66,	14.64,	13.19,	9.84,	8.76
10,	204.451,	25.88,	17.77,	15.49,	13.69,	10.62,	8.47
11,	204.500,	32.10,	25.90,	21.43,	18.36,	14.14,	10.78
12,	204.550,	24.95,	17.77,	16.13,	14.52,	11.59,	9.26
13,	204.600,	17.73,	12.78,	11.88,	10.86,	8.88,	7.05
14,	204.650,	29.13,	20.97,	18.56,	16.38,	12.29,	9.77
15,	204.700,	27.10,	19.43,	17.86,	16.46,	13.40,	10.79
16,	204.751,	24.23,	18.57,	16.98,	15.25,	11.55,	9.82
17,	204.800,	26.54,	19.89,	17.93,	16.09,	11.81,	9.67
18,	204.850,	28.71,	21.42,	20.07,	16.97,	13.32,	10.52
19,	204.900,	40.87,	28.02,	26.32,	22.37,	16.63,	12.66
20,	204.951,	34.66,	24.34,	22.81,	19.51,	14.25,	10.82
21,	205.000,	34.66,	25.45,	24.54,	19.75,	14.35,	10.38
22,	205.051,	33.29,	25.45,	21.85,	19.29,	14.39,	12.05
23,	205.100,	36.19,	26.58,	24.22,	20.83,	14.92,	12.21
24,	205.150,	34.69,	25.28,	23.41,	20.41,	14.51,	11.80
25,	205.200,	38.81,	29.78,	28.56,	23.53,	17.72,	13.13
26,	205.250,	21.44,	16.74,	15.78,	14.05,	8.65,	8.54
27,	205.304,	40.68,	31.08,	28.79,	23.79,	16.73,	13.48
28,	205.350,	28.11,	22.52,	20.18,	17.76,	13.87,	11.70
29,	205.400,	29.16,	22.13,	20.85,	17.78,	14.35,	11.41
30,	205.450,	20.94,	17.05,	16.41,	14.92,	11.76,	10.20
31,	205.500,	41.02,	28.26,	26.28,	21.65,	17.30,	12.26
32,	205.550,	33.15,	23.18,	21.94,	18.48,	13.18,	11.42
33,	205.600,	32.24,	21.59,	19.84,	17.30,	10.21,	10.50
34,	205.653,	48.24,	33.01,	30.50,	24.35,	14.54,	12.83
35,	205.702,	34.76,	25.88,	24.28,	20.60,	13.09,	12.22
36,	205.751,	35.61,	25.94,	24.69,	20.81,	14.66,	13.36
37,	205.800,	36.54,	24.89,	23.61,	19.72,	11.92,	11.77
38,	205.859,	43.04,	30.06,	28.48,	23.39,	15.75,	12.58
39,	205.900,	31.76,	22.50,	21.13,	18.17,	10.19,	11.60
40,	205.950,	30.34,	21.49,	19.86,	16.15,	8.69,	9.50

APPENDIX E MECHOD USER'S GUIDE

E-1 Introduction

The MECHOD program is a computerized procedure for MECHanistic Overlay Design. The MECHOD program consists of two parts: one is for determining pavement damage and the other named MECHSUB is for calculating pavement strains. MECHSUB is a modified ELSYM5 program. The main program MECHOD uses the strains determined using MECHSUB program to calculate failure repetitions and total pavement damage. For existing pavements with remaining life less than 80 %, an overlay is requested and the modulus for the overlay is needed as an input. The MECHOD program then calculates automatically the pavement strains and determines the pavement damage after overlay. This procedure is repeated until an overlay thickness that provides pavement with damage less than unity is determined.

Seasonal variations in traffic and pavement materials properties are also considered in this program. This is done by breaking traffic applications and pavement layer properties into four seasons and considering the pavement damage separately for each season. The total pavement damage is then the sum of damage within each season.

The MECHOD program was developed considering the use of an FWD loading condition; therefore, only one load is required. Figure E-1 shows the program main menu. Four selections can be made and each of them is discussed in the following.

E-2 Create Data File

This selection allows the user to create a data file for later analysis. By pressing key C (Create) or 2 in the main menu, the program will ask for a file name and display a data input screen as shown in Figure E-2. The data input screen provides an easy data entry environment. The user may use cursor keys to move the cursor to any field and enter required data. After entering all necessary information, the user may press function key [F10] to save the data, or [F8] key to analyze the data right away, or [Esc] key to exit without saving the data. The following information is needed.

PROGRAM MAIN MENU

1. EDIT A DATA FILE
2. Create a data file
3. Analyze a data file
4. Operating system (DOS)

Figure E-1 MECHOD Program Main Menu

Load Data:
Load Force (lbs): 0 Load Radius (in.): 0.00

File in Use
EXAMPLE

Layer Properties:
Number of Layers: 0

		Season(s) for Analysis							
Layer	Thickness	Spring (Y)		Summer (N)		Fall (N)		Winter (N)	
No.	(inch.)	Modulus	Pois	Modulus	Pois	Modulus	Pois	Modulus	Pois
1.	0.0	1000000	0.35	0	0.00	0	0.00	0	0.00
2.	0.0	12500	0.45	0	0.00	0	0.00	0	0.00
3.	0.0	500000	0.40	0	0.00	0	0.00	0	0.00
4.	0.0	0	0.00	0	0.00	0	0.00	0	0.00
5.	0.0	0	0.00	0	0.00	0	0.00	0	0.00

Traffic Data:

Hist. Repetitions:	0	0	0	0
Future Repetitions:	0	0	0	0
Reliability Level (%):	50	(Optional, default @ 50 %)		
Standard Deviation:	0.45	(Optional, default @ 0.45)		

[F10] = Save & Exit [F8] = Run [Esc] = Exit (No save)

Figure E-2 MECHOD Screen Data Input/Edit

1. Load force (required) - in lbs.
2. Load radius (required) - in inches.
3. Number of layer (required) - total pavement layers, including subgrade.
4. Seasons for analysis (required) - can be one season or all seasons. Y stands for yes and N for no.
5. Layer thickness (required, except subgrade) - in inches.
6. Modulus and Poisson's ratio (required) - for seasons that will be analyzed, the modulus and Poisson's ratio are required.
7. Traffic data (required) - both historical and future traffic repetitions. If the historical data is not given, the program may also be used for new pavement design.
8. Reliability level (optional) - percent, default is set at 50%.
9. Standard deviation (optional) - for flexible pavement, it ranges from 0.4 to 0.5.

E-3 <u>Edit Data File</u>

This option allows the user to edit a data file that has been created previously. By pressing key E (Edit) or 1 in the main menu and giving a file name to be edited, the same screen (Figure E-2) used for creating a data file will be displayed. The information saved in the existing data file will be shown in corresponding fields. The user may use cursor keys to move to any field and edit the existing information. Again, follow the bottom menu for next step.

E-4 <u>Analyze Data File</u>

This option allows the user to analyze a data file that has been created previously. By pressing key A (Analyze) or 3 and giving the file name to be analyzed, a message "Computing ..." will be shown on screen (Figure E-3). Analysis results will be displayed. An example is shown in Figure E-4. If an overlay is needed, the program will assume an one-inch overlay and ask the user for modulus of overlay materials for the season(s) being analyzed (Figure E-5). This allows different paving materials to be considered for overlay designs.

The overlay design procedure is a repeated process with an increment of 0.5 inch. This procedure is carried out by the program automatically until the total pavement damage is less than unity and the recommended overlay thickness will then be displayed. The output will be saved in a file with an extension OUT. For example, if a file has name TEST.DAT, the output will be saved to TEST.OUT. An example output is shown in Figure E-6.

E-5 Operating System (DOS)

This option allows the user to leave the MECHOD program temporarily and work in the DOS environment. To return to the MECHOD program, type EXIT in DOS and press ENTER key.

```
PROGRAM   MAIN   MENU

 1.  Edit a data file
 2.  Create a data file
 3.  ANALYZE A DATA FILE
 4.  Operating system (DOS)
```

```
File name: example
```

Computing .....

Figure E-3 Screen for Data Analysis

Reliability = 50 Standard Dev. = 0.45
Layer Thickness (inches): 5.0 12.0

Seasons	Surface Modulus (ksi)	Calculated Starins AC.	Calculated Starins Subg.	Traffic Repetitions Past	Traffic Repetitions Future	Failure Repetitions Surface	Failure Repetitions Subgrade	Damage Ratio% AC	Damage Ratio% Subg
Spring	400	324	-603	500000	1000000	4.00E+05	3.61E+05	375	415

Total damage = 375.4 % for surface, 415.3 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %
OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SUBGRADE IS LESS THAN 20 %

Figure E-4 Example Output Showing Overlay Is Needed

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Modulus of Overlay Material for season(s)
being analyzed is required and should be
input in the following (in psi).
-----------------------------------------
For Spring < 400000 > ? 600000
```

Figure E-5 Modulus of Overlay Material Can Be Considered

Reliability = 50 Standard Dev. = 0.45
Layer Thickness (inches): 5.0 12.0

Seasons	Surface Modulus (ksi)	Calculated Starins AC.	Subg.	Traffic Repetitions Past	Future	Failure Repetitions Surface	Subgrade	Damage Ratio% AC	Subg
Spring	400	324	-603	500000	1000000	4.00E+05	3.61E+05	375	415

Total damage = 375.4 % for surface, 415.3 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %
OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SUBGRADE IS LESS THAN 20 %

Overlay thickness = 1.0 in.

Spring	400	261	-468	500000	1000000	8.14E+05	1.12E+06	184	133

Total damage = 184.3 % for surface, 133.4 % for subgrade

Overlay thickness = 1.5 in.

Spring	400	237	-421	500000	1000000	1.12E+06	1.81E+06	134	83

Total damage = 134.1 % for surface, 83.0 % for subgrade

Overlay thickness = 2.0 in.

Spring	400	216	-381	500000	1000000	1.52E+06	2.82E+06	99	53

Total damage = 98.8 % for surface, 53.1 % for subgrade

Recommendation: use 2.0 in. overlay.

Figure E-6 Example Output

APPENDIX F

BACKCALCULATION RESULTS

This appendix presents detailed output from backcalculation analysis for the following projects:

F-1 Rufus - Quinton Project

F-2 Centennial Boulevard Project

F-3 Nelchina Project

F-4 Tudor Road Project

F-1 Rufus - Quinton Project (Eastbound)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk stress	Deviator stress
1	3,199	302,658	87,337	14,847	8.42	4.27
1	6,398	1,257,591	14,555	23,882	6.07	7.03
1	11,934	1,268,846	30,659	22,929	12.67	9.21
2	3,158	509,816	34,371	24,822	6.11	5.13
2	11,811	173,076	48,314	19,659	25.80	11.51
3	3,199	610,269	33,422	33,890	5.86	5.48
3	6,726	492,083	28,512	30,505	10.41	8.63
4	2,953	259,183	26,058	30,547	6.39	5.93
4	6,603	267,678	35,667	25,531	12.86	8.48
4	11,852	324,543	36,048	31,620	20.52	13.67
5	3,158	353,341	20,003	25,054	5.86	5.80
5	6,603	709,493	11,538	24,949	6.92	8.53
5	11,811	176,235	10,351	29,877	16.93	19.86
6	6,521	266,598	12,658	31,552	9.58	11.15
7	2,830	161,216	20,294	24,605	6.51	6.02
7	11,893	363,088	40,729	25,635	20.65	11.89
8	6,439	243,075	36,564	15,768	12.97	7.09
8	12,016	386,336	17,561	31,867	15.83	15.70
9	3,076	287,092	17,354	39,274	5.85	6.82
9	6,480	267,245	27,931	29,528	11.89	9.30
10	3,076	244,209	13,748	32,867	5.75	6.86
10	6,480	332,561	13,664	28,046	9.13	10.04
10	11,770	153,986	13,075	30,703	18.88	19.57
11	6,439	326,903	11,389	20,418	8.64	9.20
11	11,893	526,235	11,665	22,739	12.26	13.54
12	3,076	253,026	16,343	29,930	5.94	6.48
12	6,398	329,310	14,050	24,271	9.14	9.40
12	11,975	346,906	19,621	22,916	16.93	13.58
13	3,035	254,005	18,565	18,566	6.06	5.53
13	6,357	376,159	10,805	23,589	8.06	9.43
13	11,852	329,116	28,234	21,706	19.06	12.27
14	2,871	195,491	16,824	15,610	6.05	5.39
14	6,357	319,128	16,976	15,848	9.70	7.80
14	11,893	503,199	21,622	18,842	15.40	11.20
16	3,117	193,967	26,817	33,926	7.12	6.49
16	12,139	571,760	21,556	35,889	15.01	14.61
17	12,180	620,775	17,300	37,613	13.56	15.31
18	3,076	230,240	35,813	32,091	7.23	5.93
18	6,685	497,033	39,748	27,553	11.35	7.77
18	11,975	809,831	40,781	25,952	16.32	10.19
19	3,117	572,716	32,391	34,328	5.80	5.50
19	6,644	680,060	19,775	33,094	8.37	8.83
20	3,117	269,346	21,742	32,117	6.31	6.33
20	6,726	473,480	15,311	29,783	8.73	9.63
21	3,035	924,348	13,054	24,918	4.06	5.18
21	6,685	570,617	44,089	13,831	11.24	5.90
21	12,016	380,178	126,956	11,562	27.26	6.57
Average		424,767	27,060	26,278		
STD		248,301	20,108	6,585		

F-1 Rufus - Quinton Project (Westbound)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk stress	Deviator stress
1	3,240	340,993	12,043	31,568	4.94	6.51
1	6,521	666,413	13,607	24,690	6.59	7.68
1	12,057	882,720	18,052	24,040	10.29	9.94
2	3,158	399,510	15,647	25,811	4.98	5.83
2	6,685	359,843	22,021	20,414	9.06	7.49
2	11,975	450,584	25,414	21,510	14.10	10.12
3	3,199	491,324	22,562	25,731	5.19	5.49
3	6,480	657,531	19,015	23,906	7.23	7.23
3	12,385	885,645	26,625	24,856	11.92	9.54
4	3,076	396,075	21,830	22,061	5.27	5.38
4	6,808	377,011	27,770	19,762	9.64	7.14
4	12,262	516,346	29,416	21,705	14.42	9.76
5	3,199	365,477	31,656	32,607	5.91	5.72
5	6,808	601,823	21,182	32,505	7.90	8.17
5	12,057	706,802	25,741	33,820	12.39	11.13
6	6,767	810,309	63,150	28,590	9.73	6.29
6	12,303	869,746	77,331	26,934	16.46	7.98
7	3,199	401,272	20,879	39,374	5.32	6.25
7	6,849	546,094	18,504	36,591	7.85	8.87
7	12,303	691,963	21,264	39,325	11.94	12.53
8	6,644	467,614	11,154	20,492	6.97	8.00
8	12,221	569,319	14,296	20,966	11.12	10.88
9	3,199	464,359	20,343	20,264	5.14	5.31
9	6,767	617,598	16,485	18,818	7.29	7.09
9	12,098	806,569	15,690	22,057	10.14	10.06
12	3,076	244,263	18,082	19,262	5.59	5.59
12	6,726	428,882	13,792	21,249	7.64	8.00
12	12,262	637,104	13,400	27,265	10.52	11.97
13	3,117	209,438	28,711	19,979	6.37	5.42
13	6,808	351,754	23,308	21,679	9.38	7.65
13	12,344	426,199	33,843	22,354	15.99	9.94
14	3,199	366,653	29,561	32,745	5.83	5.77
14	6,767	503,474	21,672	35,231	8.32	8.58
14	12,344	652,950	25,325	40,620	12.89	12.43
19	3,158	419,703	31,587	34,765	5.70	5.70
21	3,158	400,430	37,071	27,611	5.95	5.34
21	6,685	594,077	23,851	28,384	8.09	7.61
21	12,139	785,417	28,260	30,241	12.41	10.28
22	3,158	643,400	15,778	25,774	4.52	5.52
22	6,726	513,236	20,965	25,605	8.16	7.72
22	11,852	674,652	21,580	28,103	11.73	10.68
23	3,117	588,250	19,544	27,662	4.78	5.51
23	6,726	555,988	17,631	28,134	7.61	8.08
23	12,139	690,632	19,644	29,886	11.52	11.28
24	3,117	257,551	28,055	28,818	6.09	5.78
24	6,685	374,314	19,633	31,491	8.69	8.75
	Average	536,115	23,978	27,071		
	STD	172,033	11,600	5,792		

F-2 Centennial Boulevard Project
(Eastbound from location 200 to 4000)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
200	8,821	1,192,686	35,389	10,619	13.2	6.3
200	14,269	1,074,783	44,632	10,656	22.3	8.1
400	8,821	383,337	33,174	12,131	17.3	7.9
400	14,297	280,833	50,940	11,598	31.6	9.9
600	8,763	446,242	33,644	10,133	16.7	7.2
600	14,269	498,348	44,397	10,037	27.1	9.0
800	8,705	524,632	37,849	10,832	16.4	7.0
800	14,153	1,140,917	30,466	10,620	19.5	8.7
1000	8,849	677,562	21,917	10,991	13.6	7.7
1000	14,240	647,469	29,774	10,578	22.9	9.8
1200	8,763	339,800	29,463	12,337	17.2	8.3
1200	14,240	395,530	38,190	11,842	27.6	10.4
1400	8,792	576,179	23,206	13,901	14.3	8.5
1400	14,211	625,636	28,086	13,105	22.7	10.9
1600	8,734	364,318	24,634	11,208	16.2	8.2
1600	14,182	315,199	32,533	11,030	27.9	10.9
1800	8,734	429,492	28,801	9,912	16.2	7.4
1800	14,153	380,923	36,522	9,931	27.4	9.8
2000	8,763	898,118	32,653	10,838	13.9	6.7
2000	14,211	656,243	44,998	10,683	25.3	8.8
2200	8,676	476,446	20,870	9,959	14.4	7.8
2200	14,067	537,890	25,928	9,760	22.9	10.0
2400	8,763	676,194	20,354	12,914	13.2	8.3
2400	14,182	564,264	29,181	12,294	23.5	10.7
2600	8,734	666,228	25,826	23,487	14.1	9.9
2600	14,269	648,552	33,947	25,003	23.7	13.8
2800	8,705	383,872	16,507	17,944	14.4	10.8
2800	14,124	458,096	19,922	18,146	22.4	14.5
3000	8,676	641,011	33,459	23,180	15.1	9.3
3000	14,211	568,411	49,657	22,162	26.9	12.0
3200	8,648	982,052	31,485	32,579	13.3	10.0
3200	14,067	964,432	42,288	32,492	22.3	13.4
3400	8,648	583,606	30,334	17,083	15.1	8.5
3400	13,923	382,669	46,799	16,351	28.4	11.1
3600	8,705	666,593	26,030	25,630	14.1	10.2
3600	14,182	851,510	27,606	25,665	20.7	13.9
3800	8,676	502,722	47,255	19,749	17.4	8.3
3800	14,240	413,078	68,918	19,793	30.9	10.8
4000	8,705	904,828	40,382	24,621	14.6	8.6
4000	14,211	609,647	60,128	24,355	27.6	11.7
	AVERAGE	608,259	34,454	15,904		
	STD	229,872	11,032	6,581		

F-2 Centennial Boulevard Project
(Eastbound from location 4200 to 7000)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
4200	8,648	733,522	44,104	19,073	15.6	7.9
4200	14,124	604,680	67,282	19,012	28.2	10.1
4400	8,648	578,668	45,958	17,889	16.7	7.9
4400	14,096	524,224	64,597	17,972	28.8	10.2
4600	8,532	676,229	42,831	10,781	15.6	6.5
4600	13,951	680,957	56,206	10,770	26.1	8.2
4800	8,561	858,319	47,075	18,196	15.1	7.4
4800	14,009	479,265	77,869	18,668	30.3	9.9
5000	8,561	1,054,069	45,675	15,151	14.3	6.8
5000	14,038	1,102,778	60,950	15,907	23.7	8.8
5200	8,619	1,154,214	48,720	15,489	14.2	6.7
5200	14,096	872,094	74,352	15,633	26.5	8.6
5400	8,792	1,185,558	26,500	13,516	12.1	7.2
5400	13,980	995,197	36,552	12,831	21.1	9.2
5600	8,676	918,746	35,486	15,219	14.0	7.4
5600	14,096	777,984	49,862	14,379	24.7	9.4
5800	8,590	623,626	54,045	9,928	16.9	6.1
5800	14,038	758,515	64,979	10,062	26.4	7.6
6000	8,561	1,287,120	34,744	10,354	12.5	6.1
6000	14,009	1,256,945	42,694	10,303	20.7	7.8
6200	8,705	274,332	57,679	13,491	20.5	7.4
6200	14,124	420,490	61,997	13,297	29.9	9.4
6400	8,648	917,159	34,679	12,716	13.9	6.9
6400	14,096	868,758	48,870	11,850	23.9	8.5
6600	8,619	648,294	46,532	8,220	16.2	5.9
6600	14,009	528,858	56,056	8,724	27.7	7.8
7000	8,734	633,344	36,933	13,752	15.6	7.5
7000	14,124	547,457	50,960	12,784	27.1	9.4
	AVERAGE	784,336	50,507	13,785		
	STD	259,845	12,384	3,177		

F-2 Centennial Boulevard Project
(Westbound from location 6900 to 2700)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
6900	8,705	549,293	86,849	16,120	19.4	6.6
6900	14,182	505,870	110,433	16,033	32.4	8.4
6700	8,705	311,068	82,928	13,055	21.3	6.6
6700	14,182	393,500	93,740	12,641	33.0	8.2
6500	8,648	604,949	32,495	16,002	15.2	8.1
6500	14,096	588,483	41,301	15,352	25.3	10.6
6300	8,676	567,289	33,848	23,922	15.6	9.5
6300	14,182	620,694	42,163	24,353	25.2	12.8
6100	8,676	361,100	34,291	20,897	17.4	9.6
6100	14,153	351,517	43,914	21,888	29.0	13.2
5900	8,648	720,605	28,884	16,867	14.1	8.3
5900	14,096	703,185	34,819	15,889	23.1	10.9
5700	8,590	484,190	48,198	14,289	17.4	7.3
5700	14,096	338,452	67,074	14,020	31.7	9.6
5500	8,648	874,525	48,054	21,573	15.3	7.9
5500	14,211	624,465	74,903	21,459	28.9	10.3
5100	8,676	774,804	57,989	16,033	16.5	6.9
5100	14,153	776,411	70,602	16,035	27.0	9.0
4900	8,648	706,615	47,964	16,225	16.1	7.3
4900	14,124	604,709	66,351	16,016	28.1	9.4
4700	8,619	795,417	61,138	15,027	16.5	6.6
4700	14,182	724,053	78,649	15,175	28.2	8.6
4500	8,619	902,274	25,244	12,929	12.7	7.4
4500	14,153	786,905	35,892	13,110	22.7	9.8
3700	8,619	530,502	44,536	20,145	16.8	8.4
3700	14,153	736,687	49,111	20,853	25.1	11.2
3500	8,619	1,263,788	22,439	26,557	11.1	9.4
3500	14,124	1,182,953	29,387	25,427	19.0	12.7
3300	8,561	920,650	18,988	15,307	11.6	8.3
3300	14,096	1,080,032	22,397	15,850	17.9	11.2
3100	8,532	1,277,277	16,303	17,317	10.0	8.4
3100	14,038	1,418,923	21,726	15,827	16.2	10.6
2900	8,561	1,202,374	22,991	10,836	11.3	6.8
2900	14,067	1,388,525	25,879	10,491	17.3	8.6
2700	8,590	983,678	25,082	14,033	12.3	7.5
2700	14,096	938,722	35,231	13,158	21.4	9.5
	AVERAGE	766,513	46,716	16,964		
	STD	298,557	23,418	4,008		

F-2 Centennial Boulevard Project
(Westbound from location 2500 to 100)

Station	Load (lb)	AC (psi)	Base (psi)	Subgrade (psi)	Bulk Stress	Deviator Stress
2500	8,561	696,691	30,281	17,457	14.3	8.3
2500	14,038	508,317	47,227	16,663	26.9	10.8
2100	8,532	485,466	34,521	11,670	16.1	7.3
2100	14,009	512,793	40,242	10,969	25.9	9.4
1900	8,676	1,070,951	27,632	13,658	12.5	7.3
1900	14,182	1,192,106	32,396	12,922	19.6	9.3
1700	8,561	640,110	37,988	10,675	15.4	6.7
1700	14,067	337,358	59,504	10,487	30.9	8.8
1500	8,619	525,731	39,137	14,395	16.4	7.6
1500	14,038	295,918	64,070	13,622	32.1	9.8
1300	8,648	201,822	38,022	13,687	19.9	8.5
1300	14,067	201,950	51,226	12,949	33.1	10.7
1100	8,590	618,645	28,924	15,765	14.6	8.3
1100	14,067	625,296	36,771	14,750	24.1	10.6
900	8,648	337,715	44,163	14,580	18.6	7.9
900	14,096	353,862	54,817	13,782	30.2	10.1
700	8,648	1,102,055	27,453	17,099	12.3	7.9
700	14,182	840,150	41,470	15,911	23.2	10.2
500	8,648	142,658	49,225	15,638	22.1	8.7
500	14,096	226,980	65,390	14,904	33.9	10.4
299	8,648	271,970	70,620	11,342	21.1	6.6
299	14,067	306,764	85,021	10,933	33.6	8.2
100	8,705	522,935	74,902	12,136	19.0	6.2
100	14,153	871,873	69,792	12,004	26.2	7.9
	AVERAGE	537,088	47,950	13,667		
	STD	293,206	16,195	2,061		

F-3 Nelchina Project

(Spring)

Station	Load	AC MR	Base MR	Subbs MR	Subgrade	Average	
8	9,699	1,200,000	90,477	54,622	27,841	Base	67,355
10	9,492	1,200,000	69,206	48,598	26,060	Subbase	37,030
12	9,476	1,200,000	56,414	43,701	23,125	Subgrade	22,054
14	9,270	1,200,000	51,100	54,185	24,716		
16	9,254	1,200,000	69,246	36,032	25,111		
18	9,174	1,200,000	69,633	48,772	28,461		
20	9,270	1,200,000	86,932	26,905	32,904		
22	9,270	1,200,000	62,007	36,358	25,064		
24	9,286	1,200,000	57,088	53,025	25,556		
26	9,333	1,200,000	59,863	46,651	14,825		
28	9,222	1,200,000	64,998	53,655	29,286		
30	9,158	1,200,000	83,972	46,612	37,407		
32	9,222	1,200,000	112,928	22,173	26,130		
34	9,254	1,200,000	87,553	25,857	28,010		
36	9,174	1,200,000	112,259	23,243	31,221		
38	9,206	1,200,000	103,689	22,173	25,360		
40	9,222	1,200,000	72,201	46,324	22,510		
42	9,079	1,200,000	62,941	39,103	22,786		
44	9,079	1,200,000	55,439	34,195	19,168		
46	9,174	1,200,000	54,026	55,616	19,959		
48	9,079	1,200,000	65,104	44,797	25,722		
50	9,063	1,200,000	58,499	28,141	15,348		
51	9,015	1,200,000	48,894	18,656	12,964		
52	9,063	1,200,000	40,966	30,029	16,252		
53	9,031	1,200,000	54,068	40,556	13,847		
54	9,063	1,200,000	56,348	26,816	11,617		
55	8,936	1,200,000	42,671	11,225	10,491		
56	9,031	1,200,000	49,824	23,139	13,312		
57	9,095	1,200,000	59,849	31,616	14,139		
58	9,031	1,200,000	70,092	42,525	17,444		
59	8,920	1,200,000	59,369	50,114	21,818		
60	9,015	1,200,000	73,265	42,123	24,611		
61	8,904	1,200,000	61,782	14,446	14,716		
62	8,809	1,200,000	55,382	15,403	11,981	Base	35,425
63	8,745	1,200,000	43,817	10,692	11,562	Subbase	14,439
64	8,920	1,200,000	54,479	16,777	15,152	Subgrade	11,831
65	8,745	1,200,000	28,565	16,216	11,037		
66	8,745	1,200,000	23,633	12,344	15,864		8,401
67	8,681	1,200,000	32,259	11,999	12,495		4,145
68	8,729	1,200,000	33,851	14,794	13,161		1,969
69	8,809	1,200,000	36,678	22,196	11,714		
70	8,586	1,200,000	21,417	7,826	11,942		
71	8,920	1,200,000	31,852	16,008	9,923		
72	8,777	1,200,000	25,081	14,238	8,660		

73	8,904	1,200,000	30,647	10,846	9,293		
74	8,761	1,200,000	24,969	10,595	9,885		
79	8,856	1,200,000	29,255	14,766	11,127		
80	8,872	1,200,000	42,219	11,875	11,065		
81	8,968	1,200,000	52,698	24,441	14,432		
82	9,158	1,200,000	74,213	22,604	22,359	Base	67,288
83	8,681	1,200,000	122,536	30,442	16,323	Subbase	22,757
84	8,856	1,200,000	34,604	15,626	19,404	Subgrade	15,762
85	8,459	1,200,000	31,527	11,820	6,381		
86	8,888	1,200,000	46,323	23,300	6,119		
87	8,713	1,200,000	35,989	26,454	12,008		
88	8,681	1,200,000	67,508	25,010	16,626		
89	9,079	1,200,000	88,825	26,766	29,010		
90	9,127	1,200,000	68,044	45,318	25,353		
91	9,015	1,200,000	72,271	46,141	11,177		
92	9,111	1,200,000	103,066	24,787	31,933		
93	9,111	1,200,000	116,148	21,914	21,351		
98	8,952	1,200,000	42,413	17,518	13,628		
99	8,872	1,200,000	70,519	14,051	11,841		
100	9,063	1,200,000	60,855	14,755	13,448		
101	9,063	1,200,000	48,202	11,732	14,995		
102	8,999	1,200,000	55,360	25,704	9,642		
103	8,936	1,200,000	59,370	9,989	14,989		
104	8,936	1,200,000	55,157	9,981	20,877		
105	8,697	1,200,000	62,051	15,747	9,025		
106	8,793	1,200,000	41,403	9,823	16,477		
107	8,999	1,200,000	55,715	25,868	15,612		
108	9,079	1,200,000	80,372	49,585	23,297		
109	8,872	1,200,000	64,261	33,597	21,669		
110	8,522	1,200,000	66,321	20,585	10,598		
112	8,793	1,200,000	59,382	11,254	6,841		
115	8,777	1,200,000	98,082	54,434	15,452		
116	8,697	1,200,000	52,118	14,892	11,025		
117	8,697	1,200,000	67,733	23,360	10,045		
122	8,761	1,200,000	73,164	16,148	9,858		
124	8,888	1,200,000	73,245	16,973	16,328		
125	8,888	1,200,000	106,439	12,044	20,702		
AVERAGE	8,982	1,200,000	61,021	26,929	17,549		
STD	225	0	22,687	14,191	7,109		

(Summer)

2	9,063	1,000,000	66,692	28,045	16,396	Base	80,469
6	9,047	1,000,000	83,500	17,706	9,647	Subbase	56,117
8	9,206	1,000,000	74,866	44,610	21,670	Subgrade	29,991
10	9,302	1,000,000	91,169	66,077	28,567		
12	9,158	1,000,000	64,502	61,209	35,326		
14	9,190	1,000,000	79,336	44,289	30,985		
16	9,174	1,000,000	75,913	48,008	33,680		
18	9,127	1,000,000	61,591	58,348	28,982		
20	9,143	1,000,000	99,593	53,249	39,988		
22	9,286	1,000,000	77,788	68,052	43,553		
24	9,127	1,000,000	91,263	66,744	35,484		
26	8,968	1,000,000	70,326	56,823	29,152		
28	8,952	1,000,000	94,668	52,638	29,260		
30	9,047	1,000,000	72,884	56,068	36,056		
32	9,158	1,000,000	65,364	75,796	37,230		
36	9,174	1,000,000	150,640	55,138	31,303		
38	9,127	1,000,000	78,718	95,621	48,974		
40	9,238	1,000,000	107,945	53,657	42,078		
42	9,079	1,000,000	77,562	92,412	41,533		
44	9,127	1,000,000	74,140	40,680	22,401		
46	9,063	1,000,000	67,605	61,756	24,998		
48	9,095	1,000,000	85,747	35,016	65,758		
50	8,840	1,000,000	80,433	58,654	26,539		
51	8,157	1,000,000	49,560	35,094	25,671		
52	9,206	1,000,000	70,484	70,472	26,333		
53	9,270	1,000,000	81,202	66,837	23,304		
54	9,222	1,000,000	70,634	78,799	22,623		
55	8,984	1,000,000	75,056	49,868	17,888		
56	9,015	1,000,000	63,899	34,282	17,579		
57	9,143	1,000,000	91,109	48,203	24,314		
58	9,111	1,000,000	70,404	56,370	22,181		
59	9,286	1,000,000	81,283	70,371	32,434		
60	9,031	1,000,000	113,806	70,769	33,230		
61	8,968	1,000,000	76,277	36,312	14,583		
62	8,904	1,000,000	54,472	32,283	10,091	Base	63,982
63	9,095	1,000,000	102,870	58,233	11,781	Subbase	46,088
64	8,920	1,000,000	75,264	44,453	10,647	Subgrade	12,167
65	8,968	1,000,000	64,743	87,635	11,971		
66	8,761	1,000,000	59,229	46,776	10,290		20,994
67	8,936	1,000,000	53,718	53,268	14,202		20,216
68	8,840	1,000,000	48,071	84,302	17,825		2,675
69	8,840	1,000,000	53,324	93,451	17,445		
70	8,920	1,000,000	129,296	41,040	16,814		
71	8,872	1,000,000	61,289	55,248	13,238		
72	8,777	1,000,000	53,930	45,740	12,831		
73	8,856	1,000,000	51,509	37,241	12,522		
74	8,697	1,000,000	50,507	26,455	9,796		
75	8,602	1,000,000	46,647	28,111	10,489		
76	8,634	1,000,000	42,675	28,223	9,990		

77	8,634	1,000,000	52,039	31,525	9,689		
78	8,681	1,000,000	91,713	25,228	10,159		
79	8,697	1,000,000	58,755	38,749	10,506		
80	8,745	1,000,000	63,549	35,882	14,569		
81	8,666	1,000,000	49,937	27,920	8,476		
82	8,777	1,000,000	80,085	33,632	15,742	Base	75,951
83	8,300	1,000,000	62,972	13,126	10,035	Subbase	31,061
84	8,300	1,000,000	56,711	14,443	9,806	Subgrade	13,369
85	8,411	1,000,000	40,874	18,970	7,656		
86	8,936	1,000,000	43,869	29,532	10,056		
87	8,777	1,000,000	56,159	23,126	10,393		
89	9,381	1,000,000	79,070	59,525	30,189		
90	9,429	1,000,000	93,884	62,501	31,636		
91	9,349	1,000,000	66,228	62,038	25,035		
92	9,397	1,000,000	142,564	45,900	22,055		
93	9,238	1,000,000	104,324	31,793	19,835		
94	9,286	1,000,000	73,523	38,605	28,568		
98	9,063	1,000,000	97,435	15,352	8,428		
99	9,254	1,000,000	69,816	20,653	8,460		
100	9,063	1,000,000	56,970	15,979	10,097		
101	9,190	1,000,000	45,373	15,853	8,490		
102	9,031	1,000,000	69,463	21,501	6,761		
103	8,984	1,000,000	40,380	17,812	7,209		
104	9,222	1,000,000	49,092	16,728	12,792		
105	8,872	1,000,000	69,182	13,178	6,373		
106	9,015	1,000,000	122,605	19,625	8,572		
107	8,999	1,000,000	59,812	15,100	11,334		
108	9,047	1,000,000	62,145	35,040	14,743		
110	8,856	1,000,000	77,261	64,403	15,232		
112	9,015	1,000,000	60,892	21,036	9,027		
113	8,968	1,000,000	57,590	41,832	12,079		
114	9,015	1,000,000	61,337	21,120	11,580		
115	8,999	1,000,000	129,238	46,707	12,704		
116	8,920	1,000,000	69,473	22,969	8,832		
117	8,936	1,000,000	36,842	82,673	9,579		
121	9,174	1,000,000	90,303	9,523	15,756		
122	8,888	1,000,000	65,507	44,251	10,905		
123	9,079	1,000,000	107,804	39,194	15,659		
124	9,015	1,000,000	97,435	28,708	10,149		
125	8,904	1,000,000	146,257	17,790	9,067		
127	9,031	1,000,000	91,758	37,995	16,466		
AVERAGE	8,992	1,000,000	74,819	43,866	19,381		
STD	238	0	23,803	21,119	11,435		

F-4 Tudor Road Project

Spring (TUDOR4)

STATION	LOAD	E1	E2	E3
2	8,809	2,522,758	25,914	69,821
3	8,761	1,627,281	16,591	69,186
4	8,793	1,802,737	21,365	53,422
6	8,697	1,485,981	17,608	71,213
7	8,729	1,366,869	18,885	64,758
8	8,666	1,265,272	24,362	88,533
9	8,650	1,905,893	12,374	88,809
10	8,570	1,394,032	13,408	53,943
12	8,618	2,357,785	15,916	67,794
13	8,618	1,678,070	22,906	80,988
16	8,602	1,437,052	12,180	77,800
17	8,697	1,187,702	11,161	69,539
18	8,141	2,449,590	19,715	68,919
19	8,252	2,506,592	13,038	78,964
20	8,125	1,732,664	10,403	77,357
21	8,125	2,549,027	15,457	85,380
22	8,045	1,807,402	11,171	36,362
23	7,918	1,959,808	8,278	56,016
26	7,680	2,764,867	7,409	76,514
28	7,505	1,449,724	10,594	82,566
29	7,537	1,091,509	8,999	71,703
30	7,457	1,854,921	10,668	61,970
33	7,489	2,716,261	10,895	38,138
35	7,489	1,617,430	11,240	55,032
36	7,457	1,544,495	10,318	40,658
37	7,330	1,068,741	8,028	47,326
38	7,537	1,661,123	17,013	64,646
39	7,505	1,605,133	20,135	60,620
40	7,489	1,687,449	23,511	34,042
41	7,441	2,409,085	11,976	18,490
42	7,553	2,657,302	8,244	53,629
43	7,409	1,808,887	21,091	28,534
45	7,457	1,890,126	10,158	34,054
46	7,473	1,489,547	11,772	33,356
47	7,425	2,049,189	11,448	34,961
48	7,473	2,005,324	8,642	36,261
49	7,394	1,545,986	20,542	25,917
52	7,537	2,510,644	8,688	44,481
53	7,600	2,250,639	8,002	40,759
54	7,537	1,430,387	24,028	41,114
55	7,505	1,196,969	23,146	36,235
56	7,505	1,125,882	17,316	44,038
57	7,537	2,643,775	16,693	32,346
58	7,473	2,921,515	17,909	21,401
61	7,044	2,685,954	13,843	56,750
62	7,139	944,906	13,344	42,865
63	7,060	1,461,267	26,235	67,467
64	7,298	1,575,921	11,720	66,785
65	7,235	685,008	11,552	26,972
67	7,250	1,887,403	13,865	35,010
68	7,298	2,022,767	22,641	37,842
71	7,266	2,095,090	15,263	23,311

Summer (TUDOR7)

STATION	LOAD	E1	E2	E3
2	8,777	1,483,581	18,283	62,272
3	8,713	822,610	23,977	76,780
4	8,809	1,384,514	23,791	57,356
5	8,586	932,227	23,897	60,314
6	8,602	430,447	32,590	68,167
7	8,713	446,591	39,512	59,121
8	8,761	636,704	39,332	72,664
9	8,745	936,550	35,129	74,918
10	8,713	802,435	27,164	39,389
11	8,713	800,108	23,056	53,973
12	8,586	769,889	37,622	41,823
13	8,777	834,381	38,911	61,102
16	8,634	983,233	21,164	80,775
17	8,618	667,208	25,094	49,993
18	8,745	658,243	70,153	28,188
19	8,634	1,478,342	24,300	83,335
20	8,713	699,197	37,517	67,749
21	8,586	1,038,107	27,573	77,308
22	8,554	1,020,985	19,615	37,506
23	8,666	1,623,364	16,142	39,698
24	8,507	1,793,133	18,258	53,261
25	8,602	572,325	16,327	49,889
26	8,522	1,865,138	14,807	40,680
27	8,443	1,255,065	36,887	34,738
28	8,507	749,118	29,615	52,845
29	8,427	577,615	28,125	43,459
30	8,459	1,093,926	21,263	47,783
31	8,491	1,232,821	24,043	50,715
33	8,634	2,284,115	16,921	42,966
35	8,745	1,052,558	18,911	43,713
36	8,363	1,060,087	26,306	33,655
39	8,395	400,962	67,906	35,565
40	8,348	1,001,495	30,987	36,265
41	8,507	2,427,190	15,138	19,087
42	8,650	2,292,126	18,815	45,435
43	8,745	1,058,242	42,985	32,530
44	8,475	1,632,499	42,600	37,781
45	8,650	1,423,907	23,370	26,978
47	8,618	1,372,367	16,126	29,499
48	8,586	1,208,240	17,396	34,309
49	8,586	1,263,911	22,332	22,283
50	8,491	2,672,311	18,752	32,343
51	8,618	2,441,484	19,147	30,183
52	8,507	1,611,574	18,999	32,388
53	8,681	2,071,876	11,089	30,596
54	8,602	652,180	36,092	51,032
55	8,570	812,480	25,184	40,988
57	8,443	1,053,473	33,550	37,554
58	8,522	2,766,370	16,034	26,701
59	8,618	2,255,674	30,188	51,877
60	8,459	1,679,145	24,010	30,261
61	8,284	1,040,752	31,667	44,123
62	8,840	1,330,767	27,295	33,061
63	8,888	692,090	40,016	70,821
64	8,856	931,207	24,605	59,301
65	8,666	298,004	21,556	23,432
66	8,904	2,024,227	30,748	36,255
67	8,872	1,114,934	20,803	25,913
68	8,793	1,365,438	28,150	31,066
70	8,761	2,284,900	23,617	22,762
71	8,777	1,123,460	25,379	24,946

72	7,362	2,211,743	14,847	21,535	72	8,713	1,078,698	31,617	24,399
					73	8,602	2,308,693	18,636	16,261
74	7,060	1,825,387	8,384	16,427	74	8,522	1,512,029	11,036	14,258
75	7,155	1,290,507	13,386	44,097	75	8,538	719,268	19,581	37,256
77	7,282	2,602,516	9,129	39,681	77	8,777	2,320,696	11,070	33,040
78	7,235	2,360,181	24,855	24,301	78	8,650	1,706,427	44,185	20,862
79	7,139	2,541,853	34,492	37,214	79	8,745	561,242	70,967	36,157
80	7,203	2,790,473	22,027	64,968	80	8,745	1,213,308	39,649	65,558
81	7,123	2,557,446	24,894	51,407	81	8,777	1,300,460	40,932	50,015
82	7,219	2,250,358	19,165	49,662	82	8,729	1,301,419	28,725	45,618
83	7,187	1,577,923	19,399	46,356	83	8,697	1,226,260	28,047	40,058
84	7,076	2,013,220	20,719	44,438	84	8,650	1,650,895	28,037	44,846
85	7,155	1,633,844	17,145	42,417	85	8,681	1,066,652	37,085	37,790
86	7,123	1,907,352	19,783	50,927	86	8,856	869,683	36,340	45,360
87	7,107	1,823,650	19,502	66,589	87	8,856	1,369,885	29,012	59,302
88	7,091	2,385,923	12,738	64,685	88	8,650	1,967,969	18,576	67,588
89	7,123	1,453,364	9,651	55,153	89	8,809	1,328,289	12,991	57,769
					91	8,713	915,164	36,619	35,948
93	6,980	1,554,789	23,859	81,886	93	8,984	739,475	42,926	79,981
94	6,917	1,614,053	27,362	53,781	94	8,284	724,144	41,649	51,375
95	6,932	745,912	13,094	63,566	95	8,729	716,071	15,743	64,296
96	7,012	1,886,152	17,296	62,599	96	8,697	860,502	28,018	55,683
97	6,996	1,526,651	19,546	76,068	97	8,809	973,691	21,397	66,962
					98	8,507	1,382,052	26,577	70,101
99	6,948	928,742	25,511	42,842	99	8,379	513,774	30,720	42,964
100	6,885	727,055	37,580	36,932	100	8,284	371,029	56,885	41,364
101	7,012	1,281,148	39,651	47,049	101	8,872	813,162	46,196	47,634
102	6,948	1,352,291	26,481	59,627	103	8,745	354,199	51,655	44,177
104	6,869	499,520	16,639	53,095	104	8,427	873,424	28,898	44,225
105	6,948	623,102	23,732	36,168	105	8,681	893,421	21,595	29,988
106	7,060	639,732	43,769	37,865	106	8,793	590,042	41,952	38,166
107	6,948	1,313,258	24,670	62,887					
108	6,980	1,607,984	13,172	34,879	108	8,761	1,105,127	24,935	21,122
110	6,917	490,209	32,783	24,102					
AVERAGE	7,520	1,751,905	17,505	51,419	AVERAGE	8,642	1,200,162	28,850	44,856

STATION	TUDOR4	TUDOR7	TUDOR4	TUDOR7	AVERAGE	THICKNESS	EXISTING PAVEMENT SPRING	SUMMER	WINTER
	0.45	0.64	MODULUS CONVERTED TO 70F			(INCH)	0.35	0.52	0.24
2	1,135,241	949,492	2-6	2-6					
3	732,276	526,470	836,860	646,833	741,846	3.69	2,119,561	1,426,628	3,091,026
4	811,232	886,089							
5		596,625							
6	668,691	275,486							
7	615,091	285,818	7-8	7-8					
8	569,372	407,491	615,091	285,818	450,455	5.88	1,287,013	866,259	1,876,894
9	857,652	599,392	9-12	9-12		4.16			
10	627,314	513,558	848,657	529,437	689,047		1,968,705	1,325,090	2,871,028
11		512,069							
12	1,061,003	492,729							
13	755,132	534,004	755,132	534,004	644,568	5.13	1,841,622	1,239,553	2,685,699
16	646,673	629,269	646,673	629,269	637,971	3.44	1,822,775	1,226,868	2,658,214
17	534,466	427,013	818,391	424,144	621,268	5.75	1,775,050	1,194,745	2,588,615
18	1,102,316	421,276							
19	1,127,966	946,139	19-24	19-24		3.73			
20	779,699	447,486	949,994	816,334	883,164		2,523,326	1,698,392	3,679,850
21	1,147,062	664,388							
22	813,331	653,430							
23	881,914	1,038,953							
24		1,147,605							
25		366,288		366,288	366,288	5.63	1,046,537	704,400	1,526,200
26	1,244,190	1,193,688	26-50	26-50					
27		803,242	826,984	893,558	860,271	3.38	2,457,917	1,654,367	3,584,463
28	652,376	479,436							
29	491,179	369,674							
30	834,714	700,113							
31		789,005							
33	1,222,317	1,461,834							
35	727,844	673,637							
36	695,023	678,456							
37	480,933								

38	747,505								
39	722,310	256,616							
40	759,352	640,957							
41	1,084,088	1,553,402							
42	1,195,786	1,466,961							
43	813,999	677,275							
45	850,557	1,044,799							
46	670,296	911,300							
47	922,135	878,315							
48	902,396	773,274							
49	695,694	808,903							
50		1,710,279							
51		1,562,550	51-76	51-76					
52	1,129,790	1,031,407	819,144	893,883	856,514	3.1	2,447,182	1,647,142	3,568,807
53	1,012,788	1,326,001							
54	643,674	417,395							
55	538,636	519,987							
56	506,647								
57	1,189,699	674,223							
58	1,314,682	1,770,477							
59		1,443,631							
60		1,074,653							
61	1,208,679	666,081							
62	425,208	851,691							
63	657,570	442,938							
64	709,164	595,972							
65	308,254	190,723							
66		1,295,505							
67	849,331	713,558							
68	910,245	873,880							
70		1,462,336							
71	942,791	719,014							
72	995,284	690,367							
73		1,477,564							
74	821,424	967,699							
75	580,728	460,332							
77	1,171,132	1,485,245	77-90	77-90					
78	1,062,081	1,092,113	965,704	880,403	923,053	2.52	2,637,295	1,775,102	3,846,055
79	1,143,834	359,195							
80	1,255,713	776,517							
81	1,150,851	832,294							
82	1,012,661	832,908							
83	710,065	784,806							
84	905,949	1,056,573							
85	735,230	682,657							
86	858,308	556,597							
87	820,643	876,726							
88	1,073,665	1,259,500							
89	654,014	850,105							
91		585,705	91-100	91-100					
93	699,655	473,264	577,501	511,709	544,605	4.84	1,556,014	1,047,317	2,269,187
94	726,324	463,452							
95	335,660	458,285							
96	848,768	550,721							
97	686,993	623,162							
98		884,513							
99	417,934	328,815							
100	327,175	237,459							
101	576,517	520,424	101-110	101-110					
102	608,531	226,687	439,157	493,800	466,479	2.29	1,332,796	897,074	1,943,661
104	224,784	558,991							
105	280,396	571,789					OVERLAY MODULUS @ 55F		850,000
106	287,879	377,627					MODULUS AT 70 F		476,000
107	590,966						SPRING	SUMMER	WINTER
108	723,593	707,281					1,360,000	915,385	1,983,333
110	220,594								
AVERAGE	788,357	768,104							

APPENDIX G

OVERLAY DESIGN OUTPUT FROM THE MECHOD PROGRAM

This appendix presents overlay design output from the MECHOD program for the following projects:

G-1 Rufus - Quinton Project

G-2 Centennial Boulevard Project

G-3 Nelchina Project

G-4 Tudor Road Project

G-1 Rufus - Quinton Project

Filename: RUFUS
Reliability = 50 Standard Dev. = 0.40
Layer Thickness (inches): 6.8 18.0

Seasons	Surface Modulus (ksi)	Calculated Strains AC.	Calculated Strains Subg.	Traffic Repetitions Past	Traffic Repetitions Future	Failure Repetitions Surface	Failure Repetitions Subgrade	Damage Ratio% AC	Damage Ratio% Subg
Spring	872	130	-180	0	4526428	4.15E+06	8.13E+07	109	6
Summer	436	191	-184	0	11275413	2.11E+06	7.36E+07	533	15
Fall	909	115	-143	0	4526428	5.99E+06	2.28E+08	76	2
Winter	1283	98	-154	0	6776089	7.64E+06	1.63E+08	89	4

Total damage = 806.9 % for surface, 27.0 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %

Overlay thickness = 1.0 in.

Spring	872	108	-151	0	4526428	7.63E+06	1.79E+08	59	3
Summer	436	162	-160	0	11275413	3.63E+06	1.38E+08	310	8
Fall	909	96	-122	0	4526428	1.09E+07	4.64E+08	42	1
Winter	1283	80	-127	0	6776089	1.45E+07	3.88E+08	47	2

Total damage = 458.0 % for surface, 13.4 % for subgrade

Overlay thickness = 1.5 in.

Spring	872	99	-139	0	4526428	1.03E+07	2.59E+08	44	2
Summer	436	149	-150	0	11275413	4.79E+06	1.84E+08	236	6
Fall	909	88	-112	0	4526428	1.44E+07	6.81E+08	31	1
Winter	1283	73	-116	0	6776089	1.96E+07	5.82E+08	35	1

Total damage = 345.5 % for surface, 9.7 % for subgrade

Overlay thickness = 2.0 in.

Spring	872	90	-128	0	4526428	1.37E+07	3.74E+08	33	1
Summer	436	138	-140	0	11275413	6.16E+06	2.51E+08	183	5
Fall	909	81	-104	0	4526428	1.90E+07	9.49E+08	24	0
Winter	1283	67	-107	0	6776089	2.62E+07	8.35E+08	26	1

Total damage = 265.8 % for surface, 7.0 % for subgrade

Overlay thickness = 2.5 in.

Spring	872	83	-118	0	4526428	1.80E+07	5.39E+08	25	1
Summer	436	127	-132	0	11275413	8.10E+06	3.26E+08	139	3
Fall	909	75	-97	0	4526428	2.48E+07	1.31E+09	18	0
Winter	1283	62	-98	0	6776089	3.48E+07	1.24E+09	19	1

Total damage = 202.1 % for surface, 5.2 % for subgrade

Overlay thickness = 3.0 in.

Spring	872	77	-110	0	4526428	2.34E+07	7.38E+08	19	1
Summer	436	118	-124	0	11275413	1.03E+07	4.32E+08	109	3
Fall	909	69	-90	0	4526428	3.22E+07	1.82E+09	14	0
Winter	1283	57	-90	0	6776089	4.58E+07	1.79E+09	15	0

Total damage = 157.5 % for surface, 3.9 % for subgrade

Overlay thickness = 3.5 in.

Spring	872	71	-102	0	4526428	3.04E+07	1.04E+09	15	0
Summer	436	110	-116	0	11275413	1.30E+07	5.82E+08	87	2
Fall	909	64	-84	0	4526428	4.14E+07	2.50E+09	11	0
Winter	1283	52	-84	0	6776089	5.97E+07	2.54E+09	11	0

Total damage = 124.0 % for surface, 2.8 % for subgrade

Overlay thickness = 4.0 in.

Spring	872	66	-95	0	4526428	3.92E+07	1.43E+09	12	0
Summer	436	102	-110	0	11275413	1.67E+07	7.38E+08	68	2
Fall	909	59	-78	0	4526428	5.30E+07	3.40E+09	9	0
Winter	1283	48	-78	0	6776089	7.76E+07	3.54E+09	9	0

Total damage = 96.5 % for surface, 2.2 % for subgrade

Recommendation: use 4.0 in. overlay.

G-2 Centennial Boulevard Project

Filename: CENTIN
Reliability = 50 Standard Dev. = 0.45
Layer Thickness (inches): 4.0 16.0

Seasons	Surface Modulus (ksi)	Calculated Strains AC.	Calculated Strains Subg.	Traffic Repetitions Past	Traffic Repetitions Future	Failure Repetitions Surface	Failure Repetitions Subgrade	Damage Ratio% AC	Damage Ratio% Subg
Spring	1247	145	-279	0	1151132	2.13E+06	1.14E+07	54	10
Summer	777	186	-309	0	1533307	1.41E+06	7.22E+06	109	21
Fall	1291	142	-276	0	768956	2.22E+06	1.20E+07	35	6
Winter	1575	127	-263	0	1151132	2.70E+06	1.49E+07	43	8

Total damage = 240.2 % for surface, 45.5 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %

Overlay thickness = 1.0 in.

Spring	1247	121	-236	0	1151132	3.87E+06	2.41E+07	30	5
Summer	777	161	-272	0	1533307	2.26E+06	1.28E+07	68	12
Fall	1291	119	-233	0	768956	3.97E+06	2.56E+07	19	3
Winter	1575	104	-216	0	1151132	5.22E+06	3.59E+07	22	3

Total damage = 139.0 % for surface, 23.0 % for subgrade

Overlay thickness = 1.5 in.

Spring	1247	111	-216	0	1151132	5.14E+06	3.59E+07	22	3
Summer	777	149	-253	0	1533307	2.92E+06	1.77E+07	53	9
Fall	1291	108	-214	0	768956	5.46E+06	3.74E+07	14	2
Winter	1575	94	-196	0	1151132	7.28E+06	5.55E+07	16	2

Total damage = 104.8 % for surface, 16.0 % for subgrade

Overlay thickness = 2.0 in.

Spring	1247	101	-198	0	1151132	7.01E+06	5.30E+07	16	2
Summer	777	137	-236	0	1533307	3.85E+06	2.41E+07	40	6
Fall	1291	99	-196	0	768956	7.32E+06	5.55E+07	11	1
Winter	1575	85	-179	0	1151132	1.00E+07	8.33E+07	11	1

Total damage = 78.3 % for surface, 11.3 % for subgrade

Recommendation: use 2.0 in. overlay.

G-3 Nelchina Project

Filename: NELCHINA
Reliability = 50 Standard Dev. = 0.45
Layer Thickness (inches): 1.5 1.5 28.5

Seasons	Surface Modulus (ksi)	Calculated Strains AC.	Subg.	Traffic Repetitions Past	Future	Failure Repetitions Surface	Subgrade	Damage Ratio% AC	Subg
Spring	1360	243	-235	41653	87648	3.62E+05	2.46E+07	36	1
Summer	915	152	-162	250920	528000	2.38E+06	1.30E+08	33	1
Winter	1983	140	-100	209267	440352	1.61E+06	1.15E+09	40	0

Total damage = 108.8 % for surface, 1.2 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %

Overlay thickness = 1.0 in.

Spring	1360	218	-206	41653	87648	5.18E+05	4.44E+07	25	0
Summer	915	177	-148	250920	528000	1.44E+06	1.95E+08	54	0
Winter	1983	130	-90	209267	440352	2.06E+06	1.86E+09	32	0

Total damage = 110.6 % for surface, 0.7 % for subgrade

Overlay thickness = 1.5 in.

Spring	1360	194	-192	41653	87648	7.60E+05	6.09E+07	17	0
Summer	915	169	-141	250920	528000	1.68E+06	2.43E+08	46	0
Winter	1983	117	-84	209267	440352	2.91E+06	2.44E+09	22	0

Total damage = 85.7 % for surface, 0.6 % for subgrade

Recommendation: use 1.5 in. overlay.

G-4 Tudor Project

Filename: TUDOR
Reliability = 50 Standard Dev. = 0.45
Layer Thickness (inches): 3.2 12.0

Seasons	Surface Modulus (ksi)	Calculated Strains AC.	Subg.	Traffic Repetitions Past	Future	Failure Repetitions Surface	Subgrade	Damage Ratio% AC	Subg
Spring	1500	174	-383	0	154020	1.00E+06	2.76E+06	15	6
Summer	1000	162	-335	0	947676	1.79E+06	5.03E+06	53	19
Winter	2000	99	-162	0	710304	4.99E+06	1.30E+08	14	1

Total damage = 82.6 % for surface, 25.0 % for subgrade

OVERLAY OR RECONSTRUCTION. THE REMAINING LIFE OF SURFACE IS LESS THAN 20 %

Overlay thickness = 1.0 in.

Spring	1500	137	-294	0	154020	2.20E+06	9.02E+06	7	2
Summer	1000	138	-272	0	947676	3.03E+06	1.28E+07	31	7
Winter	2000	80	-127	0	710304	9.97E+06	3.88E+08	7	0

Total damage = 45.4 % for surface, 9.3 % for subgrade

Recommendation: use 1.0 in. overlay.

APPENDIX H

DEFLECTION DATA USED IN ODOT AND TAI PROCEDURES

This appendix presents deflection data used in Oregon Department Of Transportation and The Asphalt Institute overlay design procedures. The data include deflections for the following projects:

H-1 Rufus - Quinton Project

H-2 Centennial Boulevard Project

H-3 Nelchina Project

H-4 Tudor Road Project

H-1 Rufus - Quinton Project

PROJECT: RUFUS - QUINTON (DEFLECTIONS CONVERTED TO 9000 LB LEVEL)

TEST #	STATION	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6	DEF-7
1	15.000	10.07	10.07	9.34	7.33	4.63	1.78	0.79
2	15.051	13.78	13.78	10.78	7.72	5.02	2.51	1.33
3	15.101	9.16	9.16	8.82	6.41	3.98	2.28	1.56
4	15.150	12.21	12.21	9.02	6.53	3.78	1.64	0.75
5	15.200	13.46	13.46	11.52	8.76	4.96	2.46	1.75
6	15.250	15.26	15.26	11.54	8.30	3.70	1.27	0.58
7	15.300	12.71	12.71	10.14	7.13	3.97	1.29	0.80
8	15.351	14.26	14.26	11.53	8.32	4.96	1.33	0.72
9	15.400	11.45	11.45	9.71	6.31	3.23	1.58	0.80
10	15.451	14.61	14.61	12.47	8.47	4.74	2.13	0.91
11	15.500	17.84	17.84	14.70	11.08	5.79	2.38	0.94
12	15.551	15.85	15.85	12.68	9.67	5.11	2.46	1.00
13	15.600	15.93	15.93	12.79	9.33	5.23	2.42	0.66
14	15.651	16.69	16.69	13.84	10.58	6.22	3.18	1.69
15	15.700	10.91	10.91	7.88	5.26	2.45	0.89	0.77
16	15.751	11.88	11.88	9.20	6.41	3.14	1.53	0.99
17	15.802	12.24	12.24	9.99	6.73	3.10	1.77	1.27
18	15.851	9.86	9.86	8.40	6.21	4.02	2.37	1.79
19	15.904	9.59	9.59	8.71	6.17	3.46	1.62	1.17
20	15.958	12.94	12.94	10.24	7.48	3.87	1.80	0.90
21	16.000	12.73	12.73	11.23	8.88	7.33	2.93	1.83
22	16.000	12.06	12.06	10.95	8.44	5.23	2.93	1.62
23	15.950	13.89	13.89	11.19	8.72	5.27	2.75	1.85
24	15.920	10.84	10.84	9.50	7.51	4.71	2.59	1.56
25	15.850	12.76	12.76	10.58	7.99	5.16	2.71	1.84
26	15.800	10.19	10.19	8.52	6.54	3.74	1.65	0.63
27	15.750	7.16	7.16	6.12	4.76	3.47	1.77	1.18
28	15.715	10.50	10.50	8.93	6.48	3.59	1.46	0.24
29	15.650	15.69	15.69	13.78	10.54	6.25	3.05	1.62
30	15.600	13.20	13.20	11.89	9.32	5.88	3.01	1.92
31	15.550	8.54	8.54	6.93	4.75	2.64	1.19	0.45
32	15.500	7.93	7.93	7.01	4.92	2.28	0.65	0.31
33	15.450	14.52	14.52	12.59	9.54	5.51	2.63	1.17
34	15.400	13.09	13.09	10.52	7.93	4.94	2.32	1.09
35	15.350	10.19	10.19	8.27	6.21	3.38	1.50	0.47
36	15.300	9.70	9.70	7.65	5.65	2.70	1.09	0.22
37	15.250	12.28	12.28	10.30	7.92	3.67	1.66	0.94
38	15.200	8.86	8.86	8.25	6.07	3.87	2.05	1.29
39	15.150	8.59	8.59	6.43	4.48	2.59	1.11	0.56
40	15.100	10.03	10.03	8.76	6.46	4.00	2.04	1.40
41	15.100	11.64	11.64	9.82	7.58	4.47	2.23	1.47
42	15.050	11.59	11.59	10.21	7.43	4.42	2.14	1.25
43	15.000	11.70	11.70	9.63	7.41	4.00	1.86	1.18
	ODOT							
	AVERAGE	12.06	12.06	10.05	7.44	4.29	2.00	1.10
	STD	2.46	2.46	1.99	1.60	1.12	0.63	0.47
	80%TILE	14.12	14.12	11.72	8.78	5.23	2.53	1.50
	TAI							
	RRD	16.97	16.97	14.03	10.64	6.53	3.26	2.05
	RRD(T)	16.63	16.63	13.75	10.43	6.40	3.19	2.01

H-2 Centennial Boulevard Project

PROJECT: Centennial BLVD (DEFLECTIONS CONVERTED TO 9000 LB LEVEL)
(EASTBOUND)

TEST #	STATION	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6	DEF-7
1	200	18.27	16.37	12.30	8.70	6.30	2.95	7.24
2	400	21.92	19.65	12.81	7.75	6.00	3.25	6.07
3	600	23.12	20.72	14.17	9.49	6.77	2.52	7.89
4	800	21.40	19.18	13.52	8.71	6.24	2.82	7.73
5	1000	24.14	21.64	14.79	9.30	6.25	2.87	7.34
6	1200	23.23	20.82	13.01	8.24	5.58	2.27	6.15
7	1400	21.91	19.63	12.57	7.79	4.89	1.73	6.40
8	1600	25.96	23.27	14.73	8.90	6.26	2.81	8.11
9	1800	24.90	22.32	14.96	10.14	6.75	2.82	8.68
10	2000	19.61	17.57	12.60	8.86	6.10	2.40	7.42
11	2200	27.41	24.56	16.32	10.23	6.90	2.38	7.87
12	2400	22.91	20.53	13.53	8.44	5.28	2.75	7.46
13	2600	16.42	14.72	8.66	4.83	2.87	1.11	3.38
14	2800	24.73	22.17	12.40	6.45	3.82	1.20	4.37
15	3000	15.07	13.51	8.09	4.69	2.96	1.30	3.28
16	3200	12.33	11.05	6.60	3.52	2.11	0.68	2.44
17	3400	18.06	16.19	10.14	6.19	4.03	1.60	4.17
18	3600	15.90	14.25	8.42	4.25	2.72	1.23	3.30
19	3800	14.70	13.17	8.19	5.09	3.53	2.12	4.11
20	4000	12.79	11.46	7.22	4.33	2.79	1.43	3.41
21	4200	14.25	12.77	8.42	5.12	3.74	2.13	4.76
22	4400	15.10	13.54	8.75	5.54	3.90	2.12	4.49
23	4600	18.86	16.90	12.22	8.44	6.35	3.30	6.43
24	4800	13.79	12.36	8.35	5.37	3.82	2.15	3.11
25	5000	14.47	12.97	9.32	6.22	4.55	2.22	5.32
26	5200	13.84	12.40	8.97	6.09	4.44	2.15	5.43
27	5400	17.98	16.11	11.51	7.68	5.05	1.76	6.71
28	5600	16.35	14.65	10.14	6.62	4.54	2.19	6.32
29	5800	18.62	16.69	12.25	9.00	6.68	3.52	7.46
30	6000	18.26	16.37	12.43	8.95	6.44	3.04	6.27
31	6200	17.72	15.88	10.35	7.21	5.03	2.36	6.41
32	6400	17.81	15.96	11.43	7.60	5.44	2.56	7.21
33	6600	21.40	19.18	14.46	10.79	8.07	4.14	8.15
34	6801	12.14	10.88	9.00	7.08	5.51	2.91	5.40
35	7000	18.18	16.30	11.05	7.12	5.09	2.30	6.68
	ODOT							
	AVERAGE	18.67	16.74	11.25	7.28	5.05	2.32	5.91
	STD	4.12	3.70	2.51	1.88	1.43	0.74	1.71
	80%TILE	22.14	19.84	13.35	8.85	6.26	2.94	7.35
	TAI							
	RRD	26.92	24.13	16.26	11.03	7.92	3.79	9.34
	RRD(T)	26.65	23.88	16.10	10.92	7.84	3.75	9.25

H-3 Nelchina Project

PROJECT: NELCHINA

TEST #	LOAD (LB)	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6
0	9,667	12.76	10.12	7.13	3.90	1.85	0.98
2	9,492	13.58	10.35	7.52	4.17	2.01	1.14
4	9,604	10.94	8.66	6.18	3.50	1.81	1.06
6	9,556	13.98	10.87	7.91	4.61	2.32	1.26
8	9,699	10.91	6.81	3.74	2.01	1.14	0.83
10	9,492	12.72	7.95	4.06	2.09	1.22	0.87
12	9,476	14.84	8.94	4.72	2.32	1.38	0.83
14	9,270	14.57	8.07	4.21	2.17	1.18	0.79
16	9,254	13.43	8.39	4.69	2.28	1.22	0.79
18	9,174	12.13	7.32	3.82	1.93	1.06	0.67
20	9,270	12.24	8.15	4.33	2.24	1.18	0.79
22	9,270	14.25	8.62	4.80	2.28	1.22	0.75
24	9,286	13.78	7.52	4.21	2.13	1.14	0.67
26	9,333	14.17	9.13	5.28	2.80	1.50	0.83
28	9,222	12.40	7.13	3.74	1.89	1.02	0.67
30	9,158	10.67	6.57	3.46	1.57	0.87	0.63
32	9,222	11.73	8.11	5.04	2.68	1.50	0.94
34	9,254	12.68	8.15	4.84	2.52	1.34	0.83
36	9,174	11.06	8.35	4.25	2.36	1.34	0.83
38	9,206	12.28	8.46	5.12	2.80	1.46	0.87
40	9,222	12.52	7.91	4.33	2.24	1.38	0.79
42	9,079	13.82	8.39	4.72	2.36	1.30	0.83
44	9,079	15.55	9.96	5.35	2.72	1.57	1.06
46	9,174	14.33	8.23	4.49	2.44	1.46	0.91
48	9,079	12.87	7.91	4.09	2.13	1.14	0.71
50	9,063	16.46	10.87	6.34	3.43	1.89	1.06
51	9,015	20.35	14.09	8.23	4.41	2.28	1.26
52	9,063	19.45	11.38	6.54	3.43	1.69	0.94
53	9,031	16.02	9.84	5.91	3.31	2.05	1.38
54	9,063	17.91	11.97	7.40	4.25	2.48	1.50
55	8,936	25.28	18.39	11.38	5.83	2.99	1.61
56	9,031	19.17	12.40	7.56	4.09	2.13	1.22
57	9,095	16.10	10.79	6.26	3.46	2.09	1.42
58	9,031	13.31	8.58	4.92	2.80	1.65	1.10
59	8,920	13.31	7.99	4.25	2.24	1.34	0.91
60	9,015	12.36	7.36	4.37	2.20	1.18	0.71
61	8,904	18.39	13.70	8.27	4.02	2.05	1.06
62	8,809	19.92	14.49	8.82	4.80	2.48	1.46
63	8,745	24.57	17.17	10.98	5.79	2.60	1.38
64	8,920	19.21	13.03	7.91	4.21	2.09	1.22
65	8,745	27.68	16.65	10.24	5.35	2.36	0.94
66	8,745	30.79	18.78	10.24	4.72	1.69	0.55
67	8,681	26.77	19.06	10.16	5.24	2.32	0.91
68	8,729	25.04	16.22	9.45	4.72	2.13	1.02
69	8,809	22.52	14.25	8.23	4.61	2.28	1.22
70	8,586	36.42	24.88	13.43	6.85	2.40	0.67
71	8,920	27.24	17.05	10.59	5.91	2.68	1.06
72	8,777	31.54	20.04	11.85	6.46	3.07	1.42
73	8,904	30.59	20.35	12.83	6.69	3.11	1.38
74	8,761	33.19	21.30	12.87	6.54	2.80	1.06
76	8,729	14.61	5.63	27.60	16.93	8.11	4.25
77	8,443	37.76	27.28	13.35	6.50	2.80	1.06
78	8,634	36.14	21.10	11.57	6.14	2.80	1.34
79	8,856	27.83	18.82	10.16	5.35	2.52	1.22
80	8,872	24.92	17.05	10.87	5.87	2.64	1.30
81	8,968	18.07	11.57	6.97	3.94	1.89	1.02
82	9,158	14.69	9.57	5.75	3.03	1.54	0.83
83	8,681	10.75	8.31	5.35	2.99	1.50	0.79
84	8,856	23.31	15.12	7.95	3.58	1.50	0.75
85	8,459	30.12	20.04	13.70	7.87	4.06	2.32
86	8,888	22.40	16.30	10.24	6.38	4.41	3.19
87	8,713	21.42	13.58	7.52	4.06	2.28	1.50
88	8,681	14.49	10.43	6.26	2.99	1.54	0.87
89	9,079	12.13	7.91	4.53	2.40	1.30	0.75
90	9,127	12.48	8.66	3.78	2.24	1.14	0.71
91	9,015	13.58	9.57	5.94	3.43	2.01	1.38

92	9,111	11.26	7.60	4.37	2.24	1.30	0.87
93	9,111	11.97	8.70	5.51	2.95	1.65	1.02
94	9,174	11.30	8.23	5.35	3.11	1.14	0.59
98	8,952	21.85	14.72	8.43	4.41	2.13	1.14
99	8,872	18.39	14.17	8.86	5.00	2.60	1.50
100	9,063	19.53	13.86	8.90	4.69	2.32	1.22
101	9,063	22.76	15.79	9.80	4.96	2.13	1.02
102	8,999	18.82	12.60	8.15	4.92	2.83	1.77
103	8,936	21.14	15.63	10.08	5.08	2.32	1.10
104	8,936	20.59	14.88	8.90	4.21	1.61	0.67
105	8,697	19.69	14.29	9.65	5.59	3.11	2.05
106	8,793	24.45	17.01	10.31	4.84	2.01	0.87
107	8,999	17.09	11.10	6.54	3.54	1.81	1.06
108	9,079	11.42	7.24	4.02	2.13	1.30	0.87
109	8,872	13.94	8.78	4.92	2.56	1.30	0.79
110	8,522	16.85	12.36	7.72	4.49	2.60	1.65
111	8,840	14.06	12.13	10.20	7.56	5.04	3.58
112	8,793	23.31	18.15	12.32	7.44	4.21	2.56
113	8,825	17.48	11.54	7.05	3.90	1.89	1.02
114	8,872	17.05	11.73	7.28	3.94	1.93	1.06
115	8,777	10.59	7.13	4.33	2.83	1.73	1.10
116	8,697	20.83	14.61	9.37	5.12	2.60	1.54
117	8,697	16.77	11.89	7.76	4.61	2.72	1.77
118	8,936	15.28	6.65	4.57	3.74	2.52	1.73
121	8,554	14.84	11.14	7.80	4.13	1.93	1.06
122	8,761	17.99	13.35	8.94	5.35	2.87	1.57
123	8,872	7.09	5.43	3.98	2.36	1.30	0.91
124	8,888	16.10	11.65	7.60	3.82	1.69	0.83
125	8,888	14.41	10.83	7.32	3.74	1.81	0.94
126	8,984	7.36	5.87	4.37	2.76	1.50	0.98
127	8,968	7.44	5.55	3.82	2.17	1.14	0.83
ODOT							
AVERAGE	8,987	17.77	11.92	7.43	4.03	2.06	1.16
STD	255	6.65	4.55	3.41	2.00	0.98	0.58
80%TILE		23.36	15.74	10.30	5.71	2.88	1.65
TAI							
RRD		31.07	21.02	14.25	8.03	4.02	2.32
RRD(T)		40.39	27.32	18.53	10.43	5.23	3.02

H-4 Tudor Road Project

PROJECT: TUDOR ROAD (DEFLECTIONS CONVERTED TO 9000 LB LEVEL)

STATION	DEF-1	DEF-2	DEF-3	DEF-4	DEF-5	DEF-6	DEF-7
1	10.70	8.40	7.46	5.03	3.44	1.92	1.04
2	7.78	5.69	4.73	2.85	1.92	1.08	0.68
3	9.19	7.00	5.75	3.53	2.22	1.17	0.73
4	9.77	8.01	5.92	3.67	2.13	1.37	0.92
5	10.33	8.02	6.79	4.36	2.79	1.29	0.47
6	9.41	6.84	5.61	3.35	2.14	1.13	0.65
7	6.90	5.25	4.79	3.25	2.46	1.38	0.81
8	5.88	4.39	3.93	2.52	1.74	0.97	0.57
9	9.31	7.01	6.05	3.65	2.24	1.14	0.57
10	11.07	8.35	7.04	4.42	2.87	1.56	0.90
11	9.90	7.84	6.42	4.03	2.64	1.38	0.77
12	8.49	6.49	5.62	3.58	2.40	1.30	0.73
13	6.79	5.06	4.44	2.78	1.80	1.02	0.61
14	4.16	3.04	2.84	1.87	1.34	0.78	0.41
15	13.38	9.70	7.96	2.79	1.56	0.81	0.49
16	11.26	7.99	6.74	3.92	2.34	1.09	0.61
17	7.46	5.53	5.15	3.52	2.43	1.38	0.81
18	5.08	3.93	3.20	1.99	1.22	0.62	0.38
19	8.80	6.60	5.20	3.20	1.91	1.02	0.60
20	9.43	6.78	5.86	3.49	2.26	1.15	0.61
21	7.82	5.75	4.68	2.78	1.72	0.91	0.55
22	11.37	10.09	7.60	5.17	3.65	2.14	1.41
23	10.46	9.12	6.92	4.57	3.01	1.72	0.89
24	9.51	7.57	6.40	4.13	2.70	1.47	0.80
25	8.10	7.13	5.29	3.32	2.04	1.06	0.57
26	10.97	8.51	6.92	4.22	2.45	1.28	0.61
27	9.00	7.50	6.17	4.03	2.62	1.35	0.71
28	9.66	7.59	5.41	3.29	1.91	0.94	0.53
29	12.90	8.87	7.08	3.85	2.07	0.98	0.62
30	10.55	7.96	6.40	3.81	2.35	1.30	0.78
31	10.35	7.58	6.62	4.10	2.54	1.43	0.80
32	17.26	12.88	10.38	5.91	3.62	1.79	0.96
33	12.47	9.69	8.06	5.12	3.34	1.98	1.25
34	12.07	10.67	8.45	5.62	3.70	2.15	1.17
35	10.92	8.56	6.54	4.00	2.54	1.45	0.84
36	12.99	10.83	7.84	4.93	3.11	1.84	1.19
37	18.15	12.17	8.67	4.83	2.78	1.45	0.80
38	9.53	7.40	5.11	2.98	1.67	1.10	0.70
39	8.92	6.64	5.10	2.95	1.89	1.14	0.90
40	11.12	8.63	7.11	4.26	2.96	1.98	1.52
41	17.07	13.47	11.85	8.24	5.84	4.00	2.65
42	10.96	9.28	7.22	4.57	2.85	1.64	0.94
43	11.52	9.24	7.67	5.22	3.63	2.55	1.88
44	8.55	7.02	5.17	3.15	1.91	1.15	0.77
45	12.80	10.78	8.61	5.77	3.65	2.34	1.53
46	12.22	9.70	8.22	5.43	3.76	2.32	1.52
47	12.20	9.45	8.16	5.29	3.58	2.21	1.45
48	11.73	10.00	7.99	5.31	3.48	2.13	1.37
49	13.04	10.56	8.43	5.62	4.14	2.75	2.05
50	12.23	8.88	7.98	5.16	3.52	2.29	1.46
51	12.45	10.22	8.86	6.20	4.32	2.85	1.90
52	12.03	9.65	7.87	5.01	3.27	1.85	1.09
53	12.77	10.51	8.64	5.47	3.56	2.02	1.20
54	10.38	7.86	6.12	3.75	2.60	1.76	1.30
55	10.94	8.53	6.69	4.12	2.87	1.96	1.48
56	11.97	8.45	6.62	3.87	2.55	1.59	1.14
57	11.34	9.29	7.55	5.00	3.56	2.33	1.57
58	14.39	11.57	9.97	6.98	5.11	3.45	2.43
59	11.40	8.75	7.03	4.43	2.87	1.77	1.16
60	12.10	9.93	8.43	5.67	3.80	2.13	1.14
61	9.72	7.39	5.85	3.57	2.23	1.32	0.87
62	14.37	10.07	7.19	4.17	2.63	1.60	1.15
63	7.87	5.53	4.29	2.45	1.60	1.01	0.74
64	10.44	8.18	6.00	3.38	1.99	1.14	0.75
65	17.53	13.29	9.91	5.96	3.94	2.65	1.96
66	9.77	7.75	6.33	3.93	2.61	1.66	1.22

67	12.62	10.21	7.87	4.96	3.33	2.09	1.41
68	10.85	9.57	6.27	4.07	2.67	1.89	1.42
69	11.12	8.95	7.96	5.84	4.34	2.91	1.86
70	18.80	15.16	12.68	8.31	5.64	3.47	2.24
71	15.49	12.20	10.29	6.98	4.83	3.30	2.28
72	16.14	12.79	10.86	7.40	5.09	3.49	2.48
73	16.45	13.27	11.88	8.51	6.17	4.41	3.15
74	21.47	18.19	14.69	10.15	6.88	4.69	3.20
75	14.84	10.58	6.93	3.66	2.19	1.53	1.22
76	13.86	10.94	9.27	6.09	4.06	2.42	1.37
77	13.93	10.79	8.88	5.59	3.48	1.99	1.25
78	13.69	10.77	8.86	6.09	4.35	3.08	2.23
79	10.09	7.61	6.21	4.02	2.70	2.05	1.51
80	8.72	7.12	4.51	2.68	1.62	1.16	0.78
81	9.66	6.55	5.35	3.20	2.07	1.41	0.95
82	11.28	8.07	6.00	3.53	2.26	1.44	1.02
83	11.62	7.74	6.35	3.74	2.47	1.52	1.00
84	11.45	8.10	6.26	3.74	2.40	1.56	1.08
85	12.72	9.13	6.80	4.02	2.61	1.65	1.13
86	11.15	8.07	5.85	3.25	2.03	1.43	1.11
87	10.26	7.10	4.87	2.66	1.69	1.06	0.74
88	11.69	8.57	6.32	3.40	2.03	1.15	0.79
89	15.37	11.07	8.05	3.98	2.24	1.20	0.91
90	7.41	5.61	4.60	2.87	1.78	0.92	0.48
91	7.31	5.70	5.65	4.04	3.17	2.01	1.13
92	5.20	4.35	3.37	2.22	1.45	0.85	0.55
93	5.38	4.07	3.67	2.46	1.67	0.96	0.67
94	6.09	5.03	4.26	3.01	2.12	1.39	0.95
95	8.91	7.53	5.41	3.53	2.31	1.33	0.75
96	6.17	5.05	4.51	3.13	2.14	1.37	0.83
97	5.84	4.87	4.02	2.76	1.81	1.13	0.69
98	6.23	5.67	4.34	3.04	1.96	1.18	0.67
99	11.93	8.43	5.84	3.46	2.37	1.71	1.25
100	10.75	7.45	6.27	3.82	2.76	2.02	1.49
101	9.37	6.41	5.08	2.99	2.12	1.46	1.14
102	10.15	6.64	4.64	2.50	1.70	1.20	0.93
103	12.75	9.08	6.88	3.94	2.71	1.86	1.35
104	14.39	8.82	6.09	2.87	1.88	1.37	1.09
105	14.18	9.55	7.06	4.09	2.84	2.05	1.53
106	10.04	7.24	5.55	3.65	2.66	2.03	1.42
107	9.31	7.93	4.26	2.53	1.58	1.19	0.97
108	16.08	11.81	8.70	5.11	3.24	2.12	1.46
109	16.18	13.31	10.97	7.30	4.73	2.74	1.59
110	14.63	10.45	8.93	5.66	4.11	2.98	2.32
ODOT							
AVERAGE	11.11	8.55	6.82	4.27	2.82	1.75	1.15
STD	3.14	2.48	2.06	1.47	1.07	0.77	0.56
80%	13.75	10.63	8.55	5.51	3.72	2.39	1.62
TAI							
RRD	17.40	13.50	10.94	7.22	4.96	3.28	2.27
RRD(T)	22.62	17.55	14.22	9.39	6.45	4.27	2.96

APPENDIX I CALCULATION OF STRUCTURAL NUMBERS USED IN AASHTO PROCEDURE

For original design ($SN_{original}$)

Project Name	AC Thickness (inch)	Layer Coeff.	Base Thickness (inch)	Layer Coeff.	Subbase Thickness (inch)	Layer Coeff.	SN
Rufus-Quinton	6.8	0.42	18.0	0.14	-	-	5.38
Centennial Blvd	4.0	0.42	16.0	0.14	-	-	3.92
Nelchina	1.5	0.42	10.5	0.14	18.0	0.10	3.90
Tudor	3.2	0.42	12.0	0.14	-	-	3.02

For existing pavements after many years of service (SN_{xeff})

Project Name	AC Thickness (inch)	Layer Coeff.	Base Thickness (inch)	Layer Coeff.	Subbase Thickness (inch)	Layer Coeff.	SN
Rufus-Quinton	6.8	0.30	18.0	0.12	-	-	4.20
Centennial Blvd	4.0	0.25	16.0	0.14	-	-	3.24
Nelchina	1.5	0.14	10.5	0.12	18.0	0.04	2.19
Tudor	3.2	0.40	12.0	0.14	-	-	2.96