

Report No. FHWA-RD-77-154

**PREDICTIVE DESIGN PROCEDURES,
VESYS USERS MANUAL**

**An Interim Design Method for Flexible Pavements
Using the VESYS Structural Subsystem**



**January 1978
Final Report**

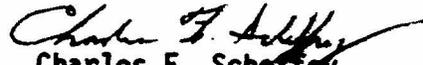
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**FEDERAL HIGHWAY ADMINISTRATION
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Washington, D. C. 20590**

FOREWORD

The VESYS procedures for the analysis and design of flexible pavements represents a major portion of the work conducted under FCP Project 5C, "New Methodology for Flexible Pavement Design." The procedures presented here are a culmination of nearly ten years of concentrated effort to better understand pavement response and performance and incorporate this information into improved design procedures utilizing mechanistic principles and layered theory.

This manual is being distributed to pavement researchers and will be made available to anyone who is interested in learning about the new concepts and approaches which have been used in the structural subsystem. It will also be made available, along with computer programs, to any State department wishing to investigate the use of the system as an analysis tool for checking their current design procedures.


Charles F. Scherff
Director, Office of Research
Federal Highway Administration

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16. Abstract This manual has been written to provide the pavement manager and design engineer with a ready reference of procedures to predict the structural responses and hence the integrity of flexible pavements. A pavement section of known geometry is chosen, and its behavior over time is predicted by sets of mechanistic models which have been computer programmed. The computer program package known as the VESYS System computes pavement response, distress, and serviceability. Results of the analysis must be compared with sets of decision criteria imposed by the user agency. The analysis process is repeated until the computed levels of pavement behavior over a specified lifetime, meet the established design criteria. The manual is developed so that it can be used with a minimal amount of reference to other materials, however, supporting references are provided throughout and these should be consulted for a better understanding of the methods and concepts presented. As new information and test procedures become available and refinements are made to the analyses procedures, updated references will be distributed to replace or be added to the current information.					
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PREFACE

This manual outlines a procedure for the analysis and design of flexible pavements. The analytic techniques upon which this procedure is based have been assembled from sound fundamental principles, evaluations of laboratory data, and field studies.

The concepts used have been formulated in State Highway Planning and Research, National Cooperative Highway Research Program, Administrative Contract, and FHWA staff studies. The overall framework was developed and programmed at the Massachusetts Institute of Technology under FHWA contract (2). A modification of the MIT program (VESYS IIM) is now available for implementation by highway departments and other agencies cooperating with the FHWA in applying the mechanistic predictive procedures to the structural analysis and design of pavement systems.

Work on the manual was initiated by the Pavement Systems Group of the Office of Research and Development for the purpose of organizing, systematizing, and publishing the design procedure. It will assist the pavement designer in analyzing the structural integrity of flexible pavement systems. Work was accomplished under Project 5C, "New Methodology for Flexible Pavement Design," under the direction of William J. Kenis. FHWA staff who contributed to this effort include Dr. T. F. McMahon, Mr. George Tiller, Mr. James Sherwood, Mr. Loren Staunton, and Mr. Brian Brademeyer. Typing of the manual was done by the FHWA Word Processing Center, and Mrs. Fredericka Smith.

The predictive design procedure is adaptable to an overall highway management system. Such a system will be capable of predicting pavement distress and maintenance requirements. The optimum design and maintenance strategy alternative will be identified through an evaluation of total pavement cost.

TABLE OF CONTENTS

PREFACE	ii
CHAPTER 1 INTRODUCTION	1
1.1 OBJECTIVE	1
1.2 SCOPE	1
1.3 RELATED DOCUMENTS	2
1.4 DESIGN CONCEPTS	2
CHAPTER 2 DESIGN PROCEDURE	4
2.1 SELECTION OF INITIAL SECTION	4
2.2 PREPARATION OF COMPUTER INPUT	5
2.3 STRUCTURAL ANALYSIS	14
2.4 ASSESSMENT OF STRUCTURAL ADEQUACY AND DESIGN CRITERIA	15
2.5 DECISION CRITERIA	17
CHAPTER 3 STRUCTURAL SUBSYSTEM	22
3.1 PRIMARY RESPONSE MODEL	22
3.2 GENERAL RESPONSE MODEL	23
3.3 DAMAGE MODEL	24
3.4 PERFORMANCE MODEL	31
CHAPTER 4 OPERATING INSTRUCTIONS	47
4.1 VESYS SOURCE CODE	47
4.2 INPUT DATA	48
4.3 TYPE OF RUNS AVAILABLE	50
4.4 DICTIONARY OF COMMANDS	53
4.5 ERROR MESSAGES	61
CHAPTER 5 MATERIAL CHARACTERIZATION	66
5.1 GENERAL	66
5.2 APPLICABLE DOCUMENTS	67
5.3 PREPARATION OF CYLINDRICAL SPECIMENS FOR DIRECT COMPRESSION TESTING	69
5.4 PREPARATION OF BEAM SPECIMENS FOR FLEXURE TESTING	74
5.5 EQUIPMENT FOR DIRECT COMPRESSION TESTING OF CYLINDRICAL SPECIMENS	75
5.6 EQUIPMENT FOR FLEXURE TESTING OF BEAMS	77
5.7 INCREMENTAL STATIC-DYNAMIC TEST, DIRECT COMPRESSION	77
5.8 FLEXURE FATIGUE TEST ON BEAMS	84
CHAPTER 6 DESIGN EXAMPLE	97
6.1 DESIGN SITUATION	97
6.2 SEARCH FOR ALTERNATIVES	97
6.3 PREPARATION OF COMPUTER INPUT	98
6.4 SUMMARY OF DESIGN EXAMPLE	104
REFERENCES	127

LIST OF FIGURES AND TABLES (continued)

	<u>Page</u>	
Table 6.1	Traffic Rate	106
Table 6.2	Example for the Determination of AMPLITUD and VCAMP	107
Table 6.3	Example for the Determination of AMPLITUD and VCAMP	107
Table 6.4	Example for Determination of Mean and Variance of Load Duration	109
Table 6.5	Mean Duration $d(r,s)$ Seconds	109
Table 6.6	Summary of Findings for Beta	110
Table 6.7	Calculation of Variability of Material Response Properties	110
Table 6.8	Calculation of K_1 and K_2	111
Table 6.9	Calculation of GNU and $ALPHA$	111
Table 6.10	Summary of Design Example	112
Table 6.11	Predictive Design Procedures	113
Figure 6.1	1,000 Second Creep Test	120
Figure 6.2	Unconfined Compressive Master Modular Creep Compliance $D(t)$ at Reference $T = 70^\circ F$	121
Figure 6.3	Flexural Fatigue Test - at $70^\circ F$	122
Figure 6.4	Dynamic Series of Incremental Static-Dynamic Tests	123
Figure 6.5	Permanent Strain Curves for Asphalt Concrete at $70^\circ F$ Using Alternate Procedure I	124
Figure 6.6	VESYS Design Procedures	125
Figure 6.7	Time Temperature Shift Principle	126

CHAPTER 1 INTRODUCTION

1.1 OBJECTIVE

The objective of this manual is to provide the pavement manager and design engineer with a ready reference of procedures to predict the structural responses and hence the integrity of flexible pavements.

1.2 SCOPE

The design procedure presented includes use of some of the most recent developments for the analysis and design of flexible pavements. It has been used to evaluate in-service pavements, possible future loads, new pavements, and material systems. A pavement section of known geometry is chosen, and its behavior over time is predicted by sets of mechanistic models which have been computer programed. The computer program package known as the VESYS System computes pavement response, distress, and serviceability. Results of the analysis must be compared with sets of decision criteria imposed by the user agency. The analysis process is repeated until the computed levels of pavement behavior over a specified lifetime, meet the established design criteria.

The manual is composed of six chapters:

1. INTRODUCTION
2. DESIGN PROCEDURE
3. STRUCTURAL SUBSYSTEM
4. OPERATING INSTRUCTIONS
5. MATERIAL CHARACTERIZATION
6. DESIGN EXAMPLE

APPENDIX A - MATHEMATICAL DEVELOPMENT OF THE VESYS IIM DAMAGE AND SERVICEABILITY MODELS (1) is provided as a separate publication.

Each chapter has been organized to reflect subject matter which is of specific interest at different levels of use. Chapters 1 and 2 are of specific interest to both management and engineering personnel. They provide the basic philosophy associated with the design procedures presented. The overall procedure is outlined and descriptions of its use are presented.

Chapter 3 describes the formulation of the structural subsystem. It is of particular importance to researchers interested in the mathematical models, and will serve as a basis for making modifications. It is anticipated that modifications to this subsystem will be made for purposes of upgrading predictive techniques. Appendix A provides even greater detail of the mathematical development of the models.

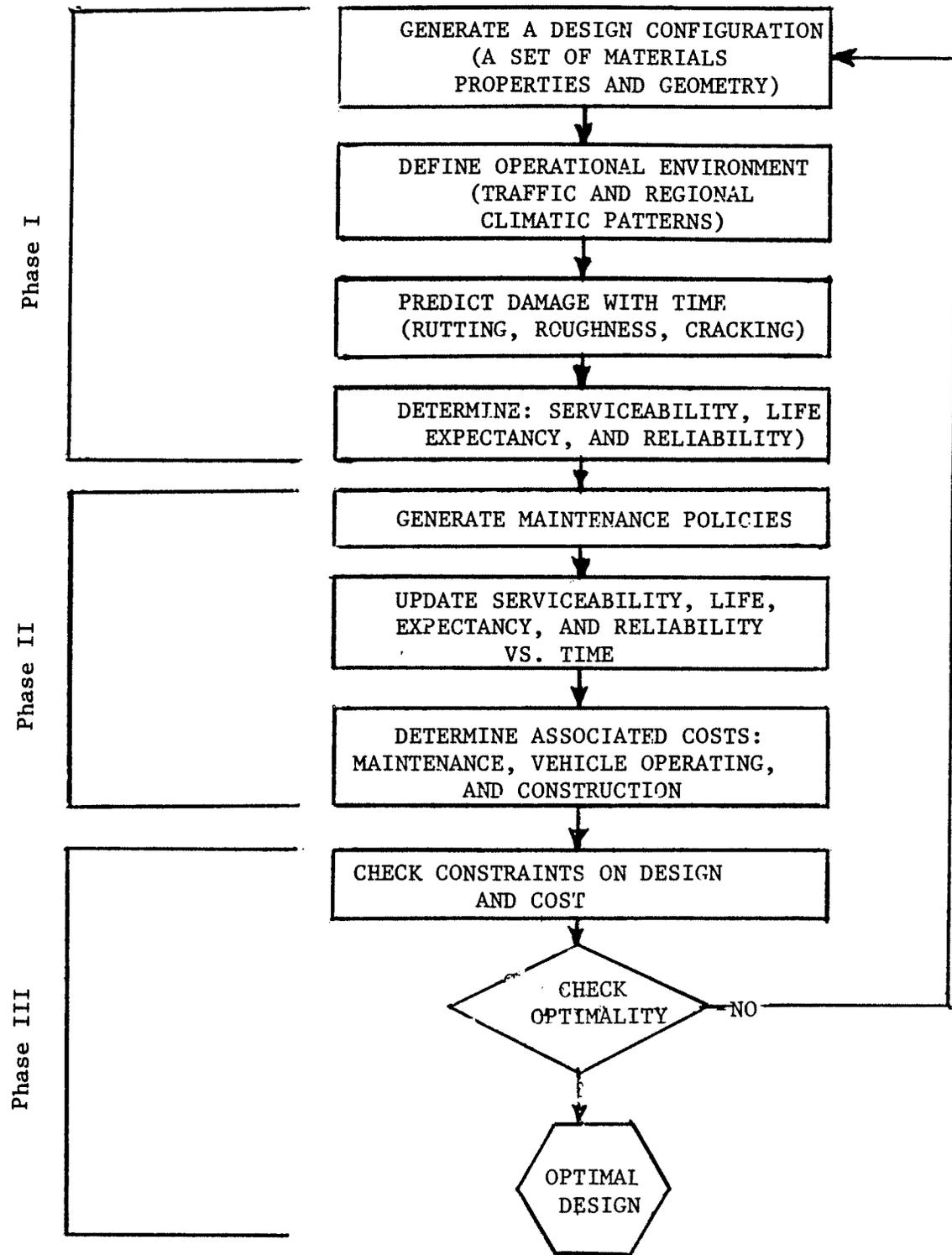


Figure 1.1. Graphical representation of a pavement design process (Ref. 2).

TABLE OF CONTENTS

PREFACE	ii
CHAPTER 1 INTRODUCTION	1
1.1 OBJECTIVE	1
1.2 SCOPE	1
1.3 RELATED DOCUMENTS	2
1.4 DESIGN CONCEPTS	2
CHAPTER 2 DESIGN PROCEDURE	4
2.1 SELECTION OF INITIAL SECTION	4
2.2 PREPARATION OF COMPUTER INPUT	5
2.3 STRUCTURAL ANALYSIS	14
2.4 ASSESSMENT OF STRUCTURAL ADEQUACY AND DESIGN CRITERIA	15
2.5 DECISION CRITERIA	17
CHAPTER 3 STRUCTURAL SUBSYSTEM	22
3.1 PRIMARY RESPONSE MODEL	22
3.2 GENERAL RESPONSE MODEL	23
3.3 DAMAGE MODEL	24
3.4 PERFORMANCE MODEL	31
CHAPTER 4 OPERATING INSTRUCTIONS	47
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5.7 INCREMENTAL STATIC-DYNAMIC TEST, DIRECT COMPRESSION	77
5.8 FLEXURE FATIGUE TEST ON BEAMS	84
CHAPTER 6 DESIGN EXAMPLE	97
6.1 DESIGN SITUATION	97
6.2 SEARCH FOR ALTERNATIVES	97
6.3 PREPARATION OF COMPUTER INPUT	98
6.4 SUMMARY OF DESIGN EXAMPLE	104
REFERENCES	127

LIST OF FIGURES AND TABLES

		<u>Page</u>
Figure 1.1	Graphical Representation of a Pavement Design Process	3
Figure 2.1	Design Process	20
Figure 2.2	TYPE 1 Analysis	21
Figure 3.1	Modular Structure of VESYS	35
Figure 3.2	Primary Response Model TYPE 1 Analysis	36
Figure 3.3	General Response Model	37
Figure 3.4	Rut-Depth Model	38
Figure 3.5	Strain Response to a Single Stress Pulse	39
Figure 3.6.a	Nth Haversine Load Pulse	40
Figure 3.6.b	Response to a Haversine Load Pulse at Nth Repetition	40
Figure 3.7	Roughness Model - Slope Variance	41
Figure 3.8	Roughness Correlation Coefficient	42
Figure 3.9	Fatigue Cracking Model	43
Figure 3.10.a	Probability Density Function	44
Figure 3.10.b	Cumulative Distribution Function	44
Figure 3.11	Performance Model - Reliability	45
Figure 3.12	Distribution of PSI at Time t	46
Table 5.1	Test Types for Determining Materials Properties for Input to VESYS IIM	88
Table 5.2	Limiting Strain Values for Consistent Results	89
Figure 5.1	Triaxial Cell for Testing Cylindrical Specimens	90
Figure 5.2	LVDT Holders	91
Figure 5.3	Repeated Flexure Apparatus	92
Figure 5.4	Stress Strain of Incremental Static Test Series	93
Figure 5.5	Summary Report Sheet	94
Figure 5.6	Fatigue Coefficient as a Function of Temperature	95
Figure 5.7	Fatigue Exponent as a Function of Temperature	96

LIST OF FIGURES AND TABLES (continued)

	<u>Page</u>	
Table 6.1	Traffic Rate	106
Table 6.2	Example for the Determination of AMPLITUD and VCAMP	107
Table 6.3	Example for the Determination of AMPLITUD and VCAMP	107
Table 6.4	Example for Determination of Mean and Variance of Load Duration	109
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Figure 6.3	Flexural Fatigue Test - at $70^\circ F$	122
Figure 6.4	Dynamic Series of Incremental Static-Dynamic Tests	123
Figure 6.5	Permanent Strain Curves for Asphalt Concrete at $70^\circ F$ Using Alternate Procedure I	124
Figure 6.6	VESYS Design Procedures	125
Figure 6.7	Time Temperature Shift Principle	126

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<u>MULTIPLY</u>	<u>BY</u>	<u>TO OBTAIN</u>
inches	2.54	centimeters
feet	0.3048	meters
square inches	6.4516	square centimeters
square feet	0.0929	square meters
miles per hour	1.6093	kilometers per hour
pounds	0.45359237	kilograms
kip	0.45359237	metric tons
pounds per cubic foot	16.018489	kilograms per cubic meter
pounds	4.448222	newtons
kip	4.448222	kilonewtons
pounds per square inch	6.894757	kilopascals
pounds per cubic inch	2.7144712	kilopascals per centimeter
Fahrenheit degrees	*	

*To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

CHAPTER 1 INTRODUCTION

1.1 OBJECTIVE

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Chapter 3 describes the formulation of the structural subsystem. It is of particular importance to researchers interested in the mathematical models, and will serve as a basis for making modifications. It is anticipated that modifications to this subsystem will be made for purposes of upgrading predictive techniques. Appendix A provides even greater detail of the mathematical development of the models.

Chapters 4 and 5 are oriented toward the designer, computer analyst, and laboratory technician. The User's Guide, Chapter 4, has been written so that it can be used independently by the computer analyst. Descriptions of computer input variables are also given and are related to the models introduced in Chapter 3.

Chapter 5 outlines step-by-step procedures for obtaining the necessary material input data. Chapter 6 includes a step-by-step design example problem. Special publications in the form of appendixes will be made available to provide insight into the revised or future mathematical development of the individual models comprising the subsystem. These should be of value in modifying the models, and applying the program to local situations.

1.3 RELATED DOCUMENTS

The manual is developed so that it can be used with a minimal amount of reference to other materials, however, supporting references are provided throughout and these should be consulted for a better understanding of the methods and concepts presented. As new information and test procedures become available, and refinements are made to the analyses procedures, updated references will also be distributed to replace or be added to the current information.

1.4 DESIGN CONCEPTS

A goal of the Federal Highway Administration's (FHWA) pavement research, is a rational design procedure that can be used to establish optimum pavement designs for a variety of materials and local conditions. Figure 1.1 shows the conceptual basis for the VESYS Structural and Management Systems (2). Phase I may be performed with the computer program known as the VESYS Structural Subsystem. VESYS, as currently configured, follows the life cycle through a probabilistic prediction of the impacts of various design strategies. Further developments in the design procedure will incorporate Phases II and III.

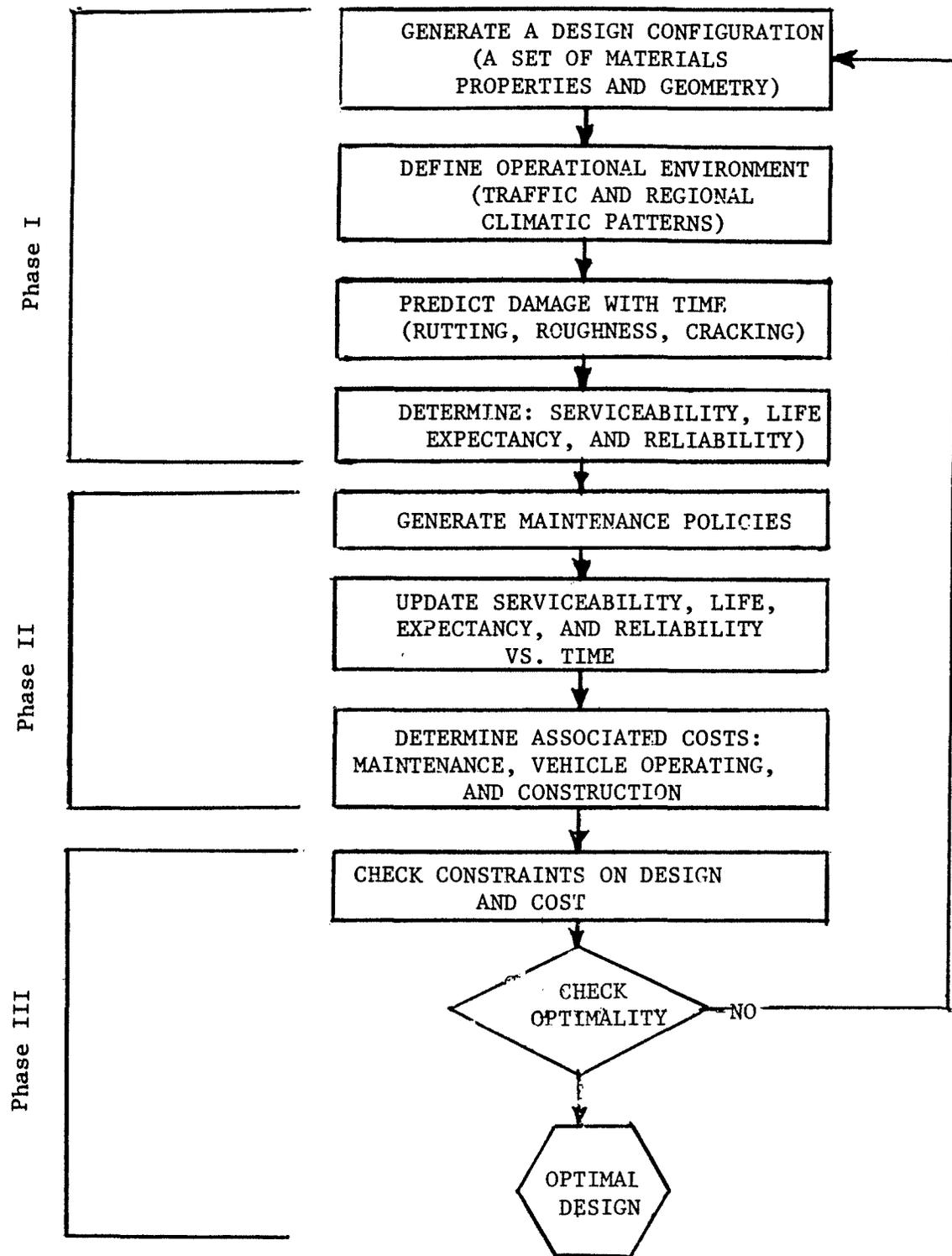


Figure 1.1. Graphical representation of a pavement design process (Ref. 2).

CHAPTER 2 DESIGN PROCEDURE

The design procedure uses advanced mechanistic concepts to predict the behavior and performance of flexible pavements. Strain and deflection responses are computed, then used in conjunction with other criteria to predict pavement distress in terms of cracking, rutting, and roughness. Distress is used to define pavement performance in terms of the life history of the present serviceability index. All of the components of the design procedure have been formulated to take into account the inherent variabilities in traffic estimates, materials properties, environmental conditions, and in the many forms of construction practices used. The predictions are probabilities of their occurrence. The designer may then exercise his judgment in making modifications to an initially chosen pavement section so that it meets specific sets of preselected design criteria.

The design process depicted diagrammatically in Figure 2.1 consists of five phases:

1. SELECTION OF INITIAL SECTION
2. PREPARATION OF COMPUTER INPUT
3. STRUCTURAL ANALYSIS
4. ASSESSMENT OF STRUCTURAL ADEQUACY
5. DECISION

Constraints which have been imposed by others or which occur naturally are also listed. These influence the design, service life, and function of the pavement and therefore constitute the basis for specifying inputs to the design procedure and for establishing criteria which the design must satisfy. It is not intended that this procedure impose specific sets of design criteria at this time; however, recommendations are given or referenced to guide the designer in evaluating the structural adequacy of the selected section.

The structural adequacy of the pavement is given by the mean and variance of distress, and Serviceability Index. The ranges of distress and serviceability predicted reflect the random nature of traffic, materials, and climate.

The final step in the design procedure is the decision. Does the predicted serviceability meet the performance and service requirements set forth in the constraints? If the designer is satisfied with the predictions, the design is complete, if not, a new section is chosen and the processes repeated.

2.1 SELECTION OF INITIAL SECTION

Step 1 - Select the thickness design procedure in use by your agency.

Step 2 - Gather information as you would normally for input to this procedure. For instance, if the AASHO procedure is used, then values for the layer coefficients, soil support, regional factor and 18 kip equivalencies must be determined.

Step 3 - Use the selected procedure in the normal manner to determine an initial thickness design.

2.2 PREPARATION OF COMPUTER INPUT

The descriptions of computer input contained in this article relate specifically to the June 1977 version of the VESYS IIM computer program. Categories of input data are shown diagrammatically in Figure 2.2. Step-by-step instructions are contained in what follows for obtaining the necessary input data for a Type 1 analysis (see Note 2.1). Where data relates to a specific input computer command, it is so designated in order that it can be keyed to the information contained in Chapters 3, 4, and 5.

2.2.1 Traffic Analysis

Future pavements may be subjected to traffic volumes and axle weight distributions which are significantly different from the types of traffic being carried by today's in-service pavements. Predictions of future traffic characteristics must be obtained by experts in planning and management who have the experience and tools which allow the most reliable predictions. The traffic inputs to the analysis phase are based on projections of realistic traffic characteristics which tend to have a significant influence on pavement behavior. It is suggested that expected actual axle load distributions be utilized in lieu of the equivalent 18 kip representations used in the AASHO procedures. It is generally accepted that the AASHO equivalent load concept (developed under accelerated loading conditions and for specific materials and standard pavement types) may not lend itself to adaption to new damage concepts, new materials, extended life predictions and other environments.

Vehicle speed in terms of load duration is also introduced as a significant traffic characteristic. Different load durations influence the amount of pavement response, which in turn influences the accumulation of damage throughout the analysis period. The mean traffic rate for a new road may also vary over the analysis period. For example, it may be known that a marked increase in heavy vehicles will use the road after 10 years because of the opening of several new industrial areas. In order to account for such conditions, the VESYS programs allow for the representation between average daily truck traffic and time.

2.2.1.1 Total Traffic Analysis Period - The total traffic analysis period is the time over which the structural analysis is to be conducted. Normally, for new designs,

a 20-year period is selected. The analysis will compute the distress and performance for the estimated number of axle load repetitions which are expected to be carried by the pavement over this period.

2.2.1.2 Incremental Traffic Analysis Periods - The incremental traffic analysis periods are time periods spaced over the total traffic analysis period. The incremental periods may be of equal or unequal length but may not exceed 25. Predicted damage is printed out at the end of each incremental analysis period. Normally, for a 20-year total analysis period, 20 incremental analysis periods are selected.

Step 1 - Select the number of times computer printout of distress and performance is desired. If a 20-year analysis period is selected, then 20 points in time should provide adequate representation of the predicted changes in pavement behavior. The number of time points must not exceed 25. (This value is introduced by the computer command NTRANDOM.)

Step 2 - Select the time units which will be applicable to the incremental array discussed in Step 3. Time units may be in years, months, days, hours, minutes, or seconds. (This value is introduced by the computer command TUNITS.)

Step 3 - Select the times at which computer printout of distress and performance is desired. The number of times in the array must be identical to the number of times selected in Step 1. The last value in this array terminates the analysis period. The time increments may be of equal or unequal length. For instance, only five points in time may be selected for depicting computer printout over a 20-year analysis period. An equally spaced array would be given in yearly time units as 4, 8, 12, 16, 20. An unequally spaced array may be given as 1, 3, 8, 11, 20. (The array is introduced by the computer command TRANDOM.)

2.2.1.3 Traffic Rate - The traffic rate specifies the average number of heavy truck axles per day which are estimated to be applied to the roadway for each incremental traffic analysis period. The user should see (Note 2.2) if 18 kip equivalencies are used to develop traffic rate and load inputs.

Step 1 - Obtain from Planning, the average daily traffic ADT (i) which is expected to use all lanes for each ith incremental analysis period selected in Step 3 of Article 2.2.1.2.

Step 2 - Estimate the percent of heavy trucks, B(i), in the traffic stream. When such data are lacking, estimates may be made from information given in Table III-1 of the Asphalt Institute's (AI) Thickness Design Procedure, MS-1 (3). (See Note 2.3).

Step 3 - Determine the percent of heavy trucks, $C(i)$, in the design lane for each time increment (see Note 2.4). These may be estimated from Table III-2 of the A.I. procedure mentioned above.

Step 4 - Estimate the array of average daily truck traffic, $ADTT(i)$, for each incremental analysis period, expected on the design lane:

$$ADTT(i) = \frac{B(i)}{100} \times \frac{C(i)}{100} \times ADT(i) \quad (2.1)$$

Step 5 - Estimate the average daily truck axles applied to the design lane in each incremental traffic analysis period:

$$LAMBDA (i) = ADTT (i) \times AVG \text{ AXLES/TRUCK} \quad (2.2)$$

2.2.1.4 Tire-Pavement Contact - The tire-pavement contact is the radius "r" in inches of a circular area "a" which is equivalent to the loaded area being simulated. An average estimate of "r" equal to 6.4 inches is reasonable for current day dual-tired truck traffic ("r" is represented by the computer command RADIUS).

2.2.1.5 Mean and Variance of Duration of Axle Loadings - The mean duration of repeated axle loadings is an estimate of the pulse time over which a moving vehicle's weight has a significant influence on the response of critical points in the pavement system. The mean duration, $d(s)$, of loading may be estimated by the time taken for the tire contact area to transverse X times its diameter. It may, therefore, be expressed as a function of vehicle speed and the radius of the loaded area:

$$d(r,s) = \frac{r X}{8.8s} \quad (2.3)$$

where: d = duration of loading in seconds
 r = radius of loaded area "a" in inches
 for dual-tire contact
 s = truck speed in mph
 X = number of diameters

Table (6.5) gives some values of duration for given values of vehicle speed, radius, and X. For values of $X = 6$ and $r = 6$ inches, equation (2.3) reduces to:

$$d(s) = \frac{4}{s} \quad (2.4)$$

The variance of load duration is then estimated as:

$$\sigma_d^2 = 19 \frac{\sigma_s^2}{s^4} \quad (2.5)$$

σ_s^2 = variance of truck traffic speed in mph²

s = mean of truck traffic speed in mph

(The mean and variance are introduced by the computer commands DURATION and VCDUR, respectively.)

2.2.2 System Geometry

To model a three-layer system, use the thickness in inches of the top and base layers determined in Step 3 of Article 2.1. To model a two-layer system, the material properties for a pair of adjacent layers should be identical. A homogeneous half space is modeled by inputting the same material properties for all three layers. (The layer thicknesses are represented by the computer commands THICK 1 and THICK 2). A future VESYS structural subsystem will allow the user to predict the performance of N-layer pavements.

2.2.3 Environment

The major environmental influences on pavement response are temperature and moisture. The computer program accumulates damage based upon expected traffic during each temperature period (see Article 2.2.1.3). The current VESYS IIM program handles temperature changes (in the top pavement layer), through a time-temperature shift of pavement response. Presently, moisture content is considered through the response and permanent deformation properties of the layer materials. The next version of the VESYS program will incorporate these variables on a seasonal basis.

Step 1 - Select the number of equal seasonal temperature intervals into which the yearly pavement temperature history is divided. A maximum of 25 intervals is permitted. Thus, 25 temperature intervals correspond to a temperature change every 14.6 days. Likewise, 12 temperature periods represent the temperature over 30.4 days, or the monthly values.

(This value is introduced by the computer command NTEMPS.)

Step 2 - Select the vector of mean pavement temperatures expected to occur in the middle of the asphalt concrete pavement layer for each interval selected in Step 1. (This vector is introduced by the computer command TEMPS.) There are several procedures available for estimating pavement temperatures (4) (5). Mean monthly temperatures may, however, be used initially until the user becomes familiar with these procedures and can reliably select those most suitable to his locality.

2.2.4 Traffic Load Characteristics

The user should see (Note 2.2) if 18 kip equivalencies are used to generate traffic rate and load characteristics. An estimate of the distribution of axle weights may be obtained from an analysis of the W-4 tables for single and tandem axles. The column headed "Total all Trucks and Combinations - Probable Number" is used in conjunction with a set of statistical formulations to compute the mean and variance of the axle weight distribution for single and tandem axles in excess of 8,000 and 12,000 pounds, respectively. The damaging effect of tandem axles, however, can be quite different than that due to single axles, depending upon vehicle speed, geometry, and stiffness of the pavement.

A method for obtaining the mean and variance of the single-axle weight distribution, adjusted to account for the effects of tandem axles, is given by use of the single-load adjustment factor F. Provision for the use of the adjustment factor F is based upon layer theory where theoretical stress or strain response in the pavement system produced by a tandem configuration is related to a similar response produced by an equivalent single-axle load. (F is the ratio of tandem to equivalent single-axle load.) Since the factor changes for different distress mechanisms, no attempt has been made to compute these values in the computer program. An engineering estimate based on results of the WASHO and AASHO Road Tests indicates values of F at 1.5 and 1.77, respectively. A value chosen close to 1.0 is very conservative for design purposes and will result in damage accumulations which will be greater than if a larger value of F were selected. A value of F equal to 1.5 is recommended for use in the following equations.

Step 1 - Calculate the mean and variance of the axle weight distributions for single and tandem axles in excess of 8,000 and 12,000 pounds, respectively, as follows:

$$X = \frac{\sum(f_s X_s) + \sum(f_t X_t)}{\sum f_s + F \sum f_t} \quad (2.6)$$

$$\sigma_x^2 = \frac{\sum(f_s X_s^2) + \sum(f_t X_t^2)/F}{\sum f_s + F \sum f_t} \cdot X^2 \quad (2.7)$$

where F = a factor to convert the weight of a tandem axle to an equivalent single axle load (1.5 recommended).

\bar{X} = the mean of the distribution of single and adjusted tandem axle loads.

f_s, f_t = the frequency of occurrence of the number of axles in each load group.

X_s, X_t = midpoint of each single- and tandem-load group.

σ^2_X = variance of the mean of the single and adjusted tandem axle load distributions.

Step 2 - Compute the mean and variance of the intensity of repeated loadings:

$$\bar{A} = \frac{X}{2a} (1000) \quad (2.8)$$

$$\sigma^2_A = \frac{\sigma^2_X}{4a^2} (1,000,000) \quad (2.9)$$

where \bar{A} = mean intensity of repeated loadings in psi
 a = the equivalent contact area between the dual tires and pavement surface in square inches

σ^2_A = variance of the intensity of repeated wheel loadings in psi².

(\bar{A} and σ^2_A are introduced by the computer commands AMPLITUD and VCAMP, respectively. (See Note 2.5.)

2.2.5 Material Properties

Advantages of the VESYS design system are its ability to utilize specific properties of materials, and to acknowledge the existence of the variability of these properties in pavement systems.

Two categories of mechanical properties are required for the structural analysis, primary response properties, and distress properties. The primary response properties express the stress-strain relationships of the layer materials to the given loads. These properties are in the form of elastic or

viscoelastic characteristics which may exhibit nonlinear behavior because of previous load histories, plastic effects, and stress dependencies. The distress properties are those properties of the layer materials, used to convert response into damage. They are determined from special laboratory tests simulating the stress and environmental conditions anticipated in the structure being analyzed.

The material properties used in the VESYS program are given in Table 5.1 along with certain test conditions necessary for their determination. Two laboratory test procedures entitled (a) Incremental Static-Dynamic, and (b) Flexural Fatigue are described in Chapter 5.

It is well known that there is considerable variation in the material properties existing in the in situ pavement. These variations exist because of variations in the materials during mixing and during laydown, compaction techniques, temperatures, moistures, and construction practices. These variations in the material properties have a significant effect on the behavior of the pavement throughout its service life. The structural analysis phase of the VESYS programs was developed to take these variabilities into account.

Program inputs, therefore, must be defined in terms of statistical estimates of the means and variances of the material properties expected to occur in the field.

2.2.5.1 Primary Response Properties

The pavement primary response properties are the creep compliance functions for both rate-independent and rate-dependent layer materials.

The elastic compliance defines materials essentially elastic (rate-independent) such as cement-treated materials, open-graded granular materials, and fine-grained materials below optimum moisture content. For these materials, the creep compliance function is essentially a horizontal straight line when plotted against time; its value, the elastic compliance, has an inverse equivalent to the Resilient, Dynamic, Elastic, or Magnitude of Complex Modulus.

The creep compliance function for time-dependent (rate-dependent) materials defines the level of plastic flow induced in a material when it is subjected to static loading. Such materials as asphalt concrete at high temperatures and fine-grained materials above optimum moisture contents exhibit this behavior and are usually termed viscoelastic.

Input to the VESYS program for primary response requires only use of the 1,000-second creep test defined in Chapter 5.

When asphalt concrete samples are tested, a sufficient number of tests at different temperatures are run to establish the master creep compliance curves and hence the time-temperature shift parameters.

For fine-grained soils or granular base type materials, creep compliance curves should be determined for specimens at different moisture contents and densities.

Care should be taken in testing materials to assure that test results reflect the effects of stress state, temperature, moisture content, and conditions corresponding to those of the in situ pavement.

Step 1 - Conduct the "Incremental Static-Dynamic" test series for each layer material in accordance with Article 5.7.

Step 2 - Use the array of times reported in Article 5.7.1(12a). (The number of times and the array of times are incorporated by the computer commands NTSTATIC and TSTATIC, respectively.)

Step 3 - Use the array of creep compliances, corresponding to the array of times, as reported in Articles 5.7.1(12b), 5.7.2(17), and 5.7.3(4), for each layer material. (The arrays of creep compliances for the top, middle, and bottom layers are incorporated by the computer commands LAYER 1, LAYER 2, and LAYER 3, respectively.)

Step 4 - Use the coefficients of variation of each layer material as reported in Article 5.7. (These coefficients are incorporated by the computer commands VARCOEF 1, VARCOEF 2, and VARCOEF 3.)

Step 5 - Input the value of BETA selected in Article 6.3.5.

Step 6 - Input the value of the reference temperature, T_0 , at which the creep compliances are input. (The value of T_0 is incorporated by the computer command REFTEMP.) T_0 REFTEMP may be omitted when 70°F master creep curves are input.

2.2.5.2 Distress Properties -

Fatigue - The asphalt fatigue characteristics ($K_1(T)$ and $K_2(T)$) are used in the Miner's Law formulation for cracking damage given by equations (3.16) and (3.17) of Chapter 3. The development of the fatigue law is explained more fully in Appendix A. In the VESYS system, fatigue damage is computed using properties which are related to the surface layer temperature over the analysis period. The analysis also

provides for the variations of K1 and K2 due to other causes such as variation in air voids and asphalt content. K1 and K2 are input as arrays and each element represents the value to be used at the corresponding temperature from the TEMPS array. Exactly NTEMPS values must be provided. Information is provided on the changes of these properties with temperature in reference (6), from which Figures 5.6 and 5.7 were generated. Given the values of K1 and K2 at 70°F these plots may be used to estimate the values to use for the temperatures of interest.

Step 1 - Determine, from laboratory fatigue tests, the mean and variances of the parameters K1 and K2 in Miner's fatigue formulation in accordance with Article 5.8. (The values of K1 and K2 are incorporated by the computer commands STRNCOEF and STRNEXP, respectively; the coefficients of variation of K1 and K2 are introduced by the computer commands COEFK1 and COEFK2, respectively; and the correlation coefficient for STRNCOEF and STRNEXP is identified by the computer command K1K2CORL.)

Permanent Deformation - The permanent deformation characteristics μ_i and α_i are determined from laboratory tests on each layer material ($i = 1, 2, 3$) defined by equations (6 and 7) of Chapter 5. The development of this equation is explained more fully in Appendix A and its use in the system's permanent deformation law is discussed in Chapter 3 and developed in detail in Appendix A.

Step 1 - Determine from the laboratory Incremental Static-Dynamic Test the parameters μ_i and α_i in accordance with Article 5.7. (The values of μ_i and α_i are incorporated by the computer commands GNU and ALPHA, respectively.)

2.2.6 System Properties

The pavement system properties B and C are used in the computation of pavement roughness as defined by equation (3.12) of Chapter 3.

Step 1 - Use a value of B = 1. (B is introduced by the computer command CORLCOEF.)

Step 2 - Select a value of C greater than zero. A recommended value of C = .058 will provide estimates of pavement roughness for normal ranges of loads, material variability, and construction quality control. (C is introduced by the computer command CORLEXP.)

Other values may be used as greater experience is gained in the use of VESYS (see Note 2.6).

2.2.7 System Performance Bounds

Step 1 - Select the mean and standard deviation of the initial serviceability index. Normally a mean value between 4.5 and 5 is selected depending upon the quality of construction. Values of standard deviation between .2 and .3 are assumed reasonable. The initial PSI and standard deviation are incorporated by the computer commands QUALITYO and STDEVO respectively.

Step 2 - Determine the unacceptable level of serviceability index (PSIFAIL) requiring overlay. A value of 2.5 can be used if other levels have not been established. Select the TOLERANCE or minimum acceptable reliability that the PSI is above the failure level.

2.3 STRUCTURAL ANALYSIS

The analysis phase uses the VESYS structural subsystem. The development of the models is described in Chapter 3 and Appendix A. A computer analyst's guide is presented in Chapter 4. The output of the VESYS computer program, for a Type 1 analysis, consists of the following information:

Primary Response - The mean and coefficient of variation, with time, of the vertical deflection of the pavement's surface and radial strain at the bottom of the top layer, due to a uniformly distributed, stationary circular unit load. The variation of primary response is due only to the randomness in the layer creep compliances. The coefficients $G(i)$ and exponents $\delta(i)$ of the least-squares approximation to the system response are also given.

General Response - The mean and variance of the radial strain and vertical deflection response, due to a moving load at each input temperature. It is a function of the mean and variance of primary response, load duration, and tire contact pressure.

Distress - Defined by the mean and variance of three damage indicators: rut depth, roughness, and cracking.

1. The mean and variance of RUT DEPTH (in inches) over the analysis period. Rut depth is the accumulation of permanent deformation with the increase in the number of wheel load repetitions. Each increment of permanent deformation is a function of the general moving load deflection response, the number of previous repetitions, and the system permanent deformation properties.
2. The mean and variance of SLOPE VARIANCE (in millionth radians) over the analysis period. Slope variance is a

function of the magnitude and variability of rut depth, the variation in the primary deflection response and system roughness properties.

3. The mean and variance of the (dimensionless) cracking DAMAGE INDEX over the analysis period. It is a measure of the dissipated fatigue life of the pavement. When the damage index has attained a value of 1, all of the fatigue life will have been used and a crack will be initiated at the underside of the AC layer. The time required for crack propagation to the surface is not included in this model. The damage index is a function of the number of load repetitions, the mean and variance of the general radial strain response at a given temperature, and the mean and variance of the pavement's fatigue properties.
4. The INTENSITY OF CRACKED AREA (in square feet per 1,000 square feet) over the analysis period. This quantity represents the probability of the existence of crack initiation.

Performance - Defined by the serviceability index, reliability and expected lifetime of the pavement over time. The state of pavement serviceability is predicted using the probabilistic values of slope variance, rut depth, and area cracked from the damage models. These amounts of distress are combined utilizing the probabilistic AASHO equation for the present serviceability index. This index is assumed to have a normal distribution defined by its mean and variance. The reliability is the probability that the pavement serviceability is above some specified minimum (PSIFAIL). The time when the reliability falls below a given value (TOLERNCE) is the expected lifetime of the pavement.

2.4 ASSESSMENT OF STRUCTURAL ADEQUACY AND DESIGN CRITERIA

The user should develop sets of design and performance criteria compatible with the outputs of the VESYS structural analysis. Limits should be established for those variables upon which the decision making process is based. The designer must use these criteria to determine whether or not the initial pavement selected is structurally adequate. If it does not meet the criteria, a new design must be selected and evaluated. Suggested steps necessary in establishing criteria are as follows; however, other procedures may be employed:

DAMAGE INDEX - Used primarily to compare alternate designs. An observable crack at the surface indicates that the damage index, at that point in the pavement, had previously reached the value 1 (there is no remaining fatigue life). At present, there is no set criteria for fatigue damage index, however, the most adequate design is the one in which the damage index is the lowest over the lifetime.

Limiting the mean damage index to 0.75 (75 percent of the fatigue life is used) over the lifetime of the pavement may be somewhat conservative for all pavements; however, it is a good starting point for comparing alternate designs for high-type pavements.

In order to establish realistic criteria, comparisons between VESYS predictions and measured cracking damage on in-service pavements must be made. These comparisons will allow the user to apply calibrations to the VESYS model so that the DAMAGE INDEX can be used to express cracking damage in a meaningful manner. These calibrations must consider (a) the fatigue criteria used, (b) the level of service intended for a given roadway, and (c) the time for crack propagation to the pavement's surface.

INTENSITY OF CRACKED AREA - The VESYS model expresses cracking damage at the underside of the top layer through the damage index and through the intensity of cracked area defined as square feet of cracking per 1,000 square feet of wheel path surface area. The wheel path surface area is defined as a 2-foot band centered about one wheel path. Cracking is presently considered as class 1 cracks (class 2 cracks are exhibited by cracks which have progressed to the stage where they have connected together to form a grid-type pattern and should be designated so in the crack survey). A value of 1,000 indicates a 100 percent probability that the damage index has exceeded 1 at all points along the wheel path, and therefore the pavement wheel path should exhibit considerable area cracking.

To relate the predictions of intensity of cracked area (ICA) to the occurrence of fatigue cracking in the field use the following physical relationship:

$$ICA = \frac{N}{BL} \times 1,000$$

where: N = number of square feet, in one or both wheel paths, containing class 1 cracking.

B = band width of wheel paths, usually taken as 2 feet per wheel path.

L = length of pavement section in feet.

Note that the pavement area outside the wheel paths is not considered in the analysis.

WHEEL PATH RUTTING - A measure of the mean depth of rut in both wheel paths where the rut is the depression

under the center of at least a 4-foot straight edge. The tolerable levels can be estimated from past pavement performance within each local environment.

ROUGHNESS - A measure of the variance of slope measurements taken along the wheel path in terms of slope variance. Tolerable levels can be estimated from past performances within each local environment.

UNACCEPTABLE PRESENT SERVICEABILITY INDEX - The present serviceability Index is a measure of the ability of a pavement to serve traffic. It is determined subjectively or objectively in accordance with AASHO Road Test findings. The unacceptable serviceability index must be established by the user agency for specific classes of roadway. Normally a lower limit between 1.5 and 3.0 is used depending upon the level of service required.

EXPECTED LIFETIME - A measure of length of time required for the serviceability index to reach the unacceptable level. The expected lifetime is a function of the serviceability index history and of the limits prescribed for the unacceptable levels. If an expected lifetime of 20 years is desired, the analysis period should be at least 20 years.

RELIABILITY - A measure of the probability that the serviceability index of the pavement is greater than the unacceptable level. Normally a 50 percent probability level would be an adequate value for use in the design of most pavements, however, as the user becomes more familiar with this variable, he can select other tolerances appropriate for a specific type of construction.

The designer must make changes to the input variables of the VESYS programs when the selected design does not meet the criteria. Changes in material properties or in layer thickness affect the VESYS output. Either course may be followed in modifying the design. However, once suitable materials properties are established, replicate runs of the analysis using various thickness should be performed to better optimize the design.

2.5 DECISION CRITERIA

The foregoing structural analysis using VESYS allows the designer to evaluate each alternative design for its performance capabilities. However, it must be realized that this is only one step in the design procedures which will eventually be forthcoming from current research efforts. The ultimate goal in pavement design is a complete pavement management system which will aid the designer in selecting the optimum design

for current and predicted loading and environmental conditions. In the meantime, the designer or administrator should invoke certain other criteria when making his decision to accept a given design. These criteria can best be described by saying that they are related to the function of the pavement and generally include the following: (7)

Safety - A minimum skid number must be maintained and variations in lateral and longitudinal profile made commensurate with the function of the road.

Maintainability - The maintenance required will be a function of the design selected and the serviceability required.

Reliability - The level of reliability selected for the design must be a function of the impact of failures and, consequently, maintenance on the performance of the pavements traffic carrying function.

Riding Quality - A function of the limiting serviceability levels chosen for the design.

Funding - Allocation of funds has a direct relationship with the function a pavement is to serve. Often funding is the major criteria for the design decision.

NOTE 2.1 - A Type 1 analysis is used for the prediction of pavement response, distress, and performance. Other types of analysis may be used for other purposes. For instance, curve fitting, or the computation of stress, strain, and deflection at any point in the pavement may be achieved. In addition, the damage and performance models can be used independently when the proper input data are provided. (For an explanation of TYPES, see Chapter 4, Section 4.3.)

NOTE 2.2 - The input LAMBDA may be taken as the expected number of daily 18 kip equivalent axle loads in the design lane, at various times in the pavement life. For this situation, the input AMPLITUD, which represents load intensity, would be 9,000 pounds divided by the tire-pavement contact area, and the input VCAMP would be zero. For example, the following inputs model an 18 kip axle load:

RADIUS = 6.4
AMPLITUD = 70.0
VCAMP = 0.0

NOTE 2.3 - In accordance with the Asphalt Institute definition, heavy trucks are at least two-axle six-tire vehicles. Pickup and light panel trucks are excluded.

NOTE 2.4 - The design lane is the lane on which the greatest number of heavy truck axle loads is expected. Normally, this will be the outer lane of a multilane highway.

NOTE 2.5 - For a Type 1 analysis (damage-performance), a value of 1 psi is input for the computer command LOADING. This is because the general response model can account for amplitude in the modification of static response to simulate the behavior of the pavement under a moving load. Since the primary response model is linear with load, the values of stress, strain, and deflection for any other static loading amplitudes are simply multiples of that value.

NOTE 2.6 - One method for obtaining C involves approximating the slope variance equation (3.12) as follows:

$$SV = (K) (VAR [RT])$$

where K is a regression coefficient (6) and equal to $2/C^2$ when B = 1. Using field data for slope variance and variance of rut depth, values of K can be obtained for different types of roadway.

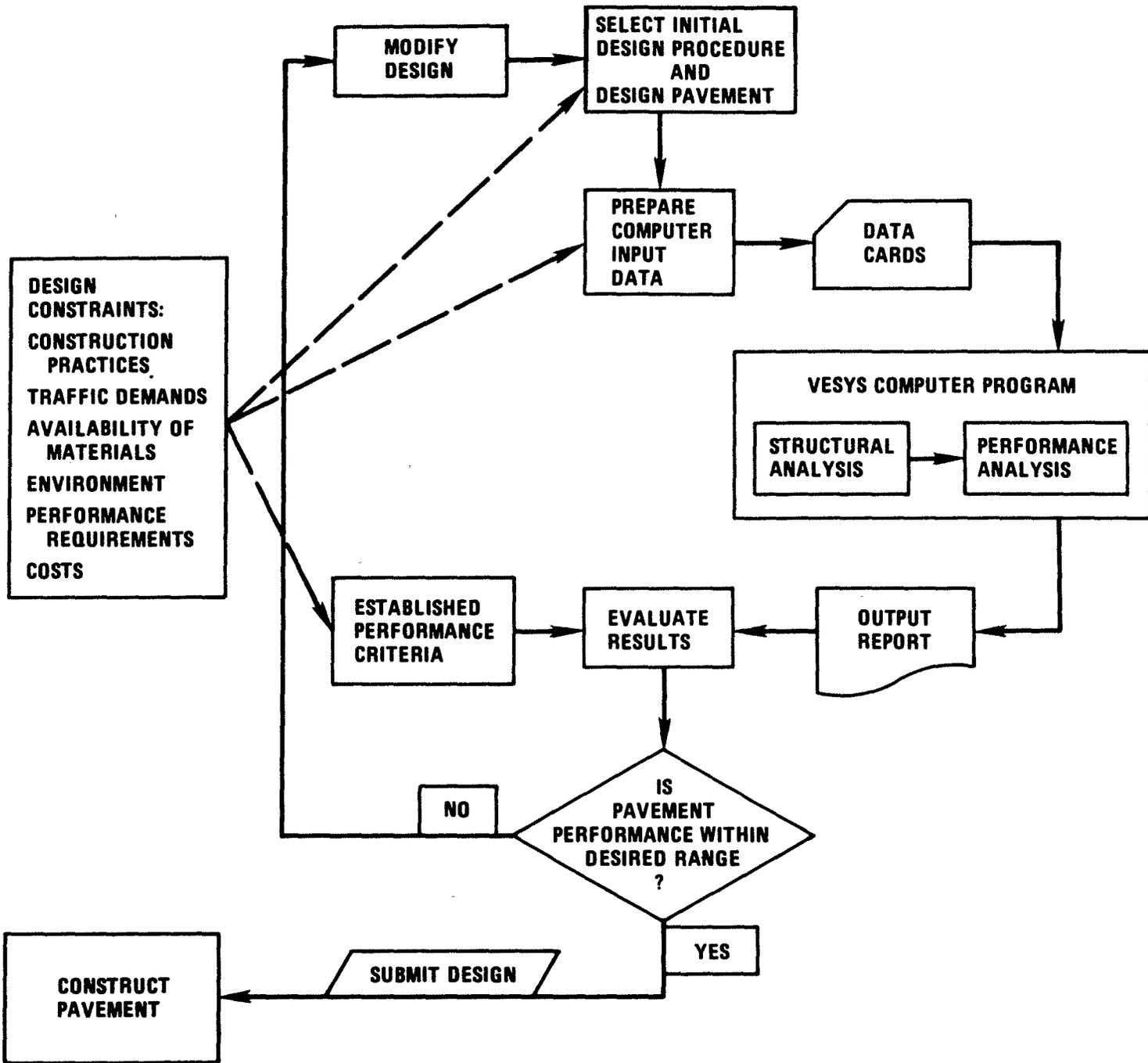


FIGURE 2.1 DESIGN PROCESS

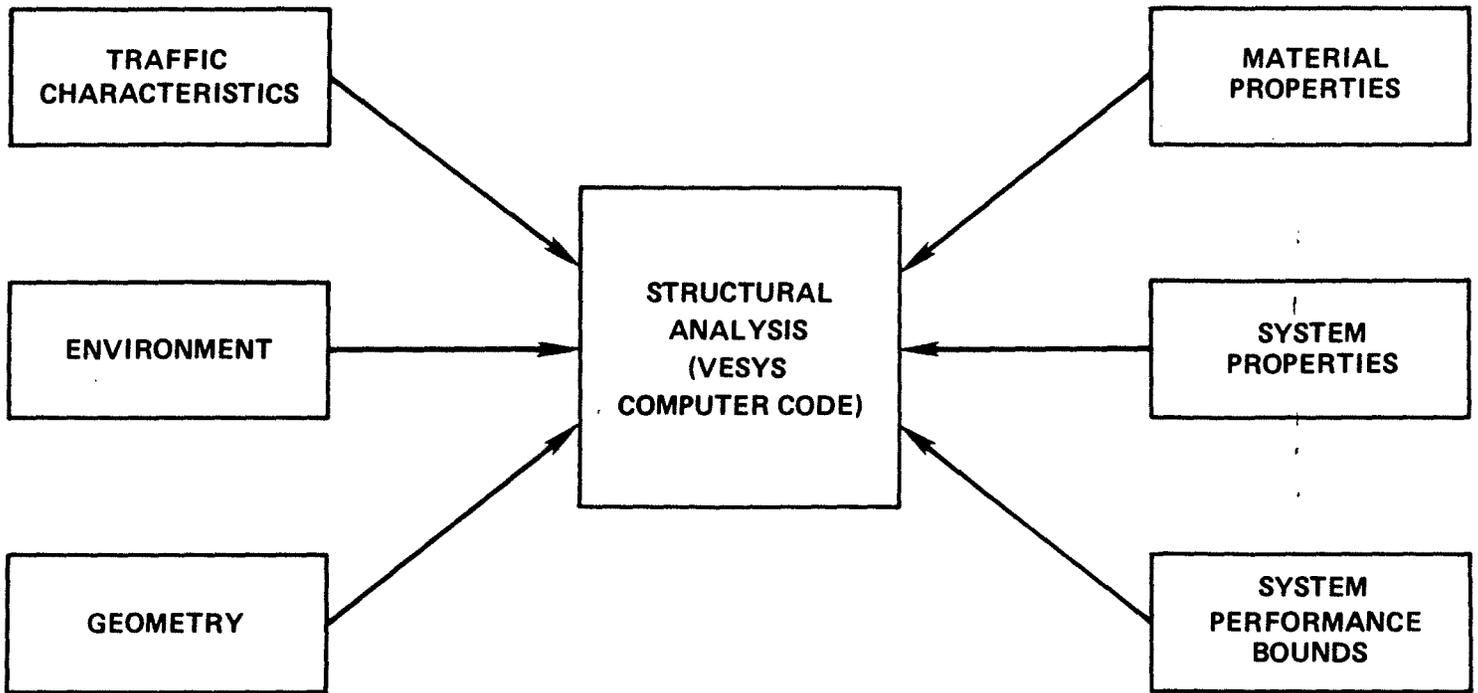


FIGURE 2.2 - TYPE I ANALYSIS - CATEGORIES OF COMPUTER INPUT

CHAPTER 3
STRUCTURAL SUBSYSTEM
(VESYS IIM)

The objective of the VESYS Structural Subsystem is the prediction of the occurrence of specific types of distress as a function of the materials' properties, traffic, and environment. This chapter provides insight into the formulation of the four sets of models comprising the structural subsystem: primary response, general response, damage, and performance. The VESYS subsystem has been developed so that the various models can be modified or replaced by the user as the need arises. This requires a knowledge of the relevant data for input to the computer program and an understanding of the interrelations between the models. These interactions and the flow of information are shown in Figure 3.1.

The working hypothesis for the VESYS model assumes that all responses of the pavement can be stated in terms of: the loading conditions, the geometry of the pavement structure, the physical properties of the layer materials, and the effect of the environment on these properties. The material property of compliance can be characterized as linear elastic and/or linear viscoelastic for input to the primary response model. The influence of load amplitude and duration is considered in the computation of the general response due to a haversine load. The damage laws are formulated from observations of the behavior of the distress properties of materials and from the primary and general response of the pavement system. The serviceability of the pavement is hypothesized to be represented by the AASHTO definition of Serviceability Index.

3.1 PRIMARY RESPONSE MODEL

Primary response ψ_j (j denotes any one of the seven responses listed in paragraph 3) is defined as the time dependent state of stress, strain, or deformation existing in the pavement due to a stationary load applied to the pavement's surface. The Primary Response Model represents the pavement system by a three-layer semi-infinite continuum such that the upper two layers are finite in thickness while the third layer is infinite in extent. All layers are infinite in horizontal extent. Each layer may be described as elastic or viscoelastic, and the materials in each layer are assumed to be isotropic and locally homogeneous. The model constitutes a closed form probabilistic solution to the three-layer linear viscoelastic boundary value problem. It is valid for single stationary circular loading at the pavement's surface. It assumes complete shear at the interfaces and that the material layers are incompressible.

The viscoelastic model which is used in the VESYS IIM program to compute stress and strain in the pavement structure is identical to an elastic layer theory model except that the material properties may be characterized as time-dependent (viscoelastic). The geometric representations, boundary

conditions, and loading functions are the same in the two models. These similarities allow the use of the "elastic-viscoelastic correspondence" principle to relate the elastic solution to the viscoelastic one (2). The closed form probabilistic solutions to the static load response of elastic and viscoelastic three-layer systems along with the necessary conversions relating the two solutions are presented by Bradmeyer (10). Figure 3.2 shows the basic makeup of the primary response model. Stochastic inputs are the mean creep compliances for each layer material and the coefficient of variation about the mean. The geometric properties are the thicknesses of the layers. The stationary load condition includes the magnitude of the applied stress and the radius of the circular area of load-pavement contact. Both the geometric and stationary load conditions are deterministic input values. The computer then performs certain mathematical computations involving least squares curve fitting, partial derivatives of the material properties, and the evaluation of the Bessel terms, all of which are used in the probabilistic layer theory block. The statistical distributions in terms of mean values and coefficients of variation of the seven stress-strain components listed below are computed upon command:

1. vertical stress
2. shear stress
3. radial stress
4. vertical displacement
5. radial displacement
6. circumferential strain
7. radial strain

If any one layer which is used in the analysis has time-dependent properties, then the system response will also be represented as a function of time. For a Type 1 computer analysis (described in Chapter 4), the mean and coefficient of variation of the radial strain at the bottom of the asphalt layer and of the vertical displacement at the roadway surface are passed automatically over to the general response model. The coefficient of variation of the vertical deflection is also passed to the roughness model. Note that this is also the standard deviation for a mean of one.

3.2 GENERAL RESPONSE MODEL

General response R_{ij} (j denotes any one the seven responses listed in paragraph 3) is defined as the state of stress, strain, or deformation in the pavement (during the q th temperature season) due to a moving load applied on the pavement's surface. The moving load is modeled by a haversine function with a given load amplitude and duration. The primary response (due to a stationary unit load) is combined with the time derivative of the haversine loading function to compute the general "peak" response occurring at the midpoint of the haversine loading. The solution method is presented in Appendix A. The expected value and variance of general response are calculated

assuming that amplitude, duration, and primary response are uncorrelated, random variables. The general vertical deflection "peak" response of the surface is automatically passed to the rutting model, and the general radial strain at the bottom of the asphalt is used to predict fatigue damage. A schematic of the general response model is shown in Figure 3.3.

3.3 DAMAGE MODEL

The damage model currently consists of three separate models to predict the accumulation of pavement cracking, rutting, and roughness.

Static and general load responses are passed to the appropriate damage model to be operated on for prediction of distress.

Other inputs are described in more detail in Chapters 2 and 4 and in the remainder of this section.

3.3.1¹ Rut Depth Model

The rut depth model is shown diagrammatically in Figure 3.4. It combines viscoelastic layer theory with a laboratory-based permanent deformation accumulative damage law. The law uses the results of repeated load laboratory tests to estimate the permanent deformation properties of the layer materials (see Note 3.1). Computer output from the model is the expected value and variance of rut depth. These values are computed for each incremental analysis period where the axle loading rate and temperature are constant. Load amplitude, vehicle speed, and material properties are assumed as random variables over the analysis period. The expected value and variance of rut depth are printed out at any time desired.

Before proceeding with the development of the rutting model, it will be interesting to look at a typical response curve of a highway paving material subjected to a single load pulse as shown in Figure 3.5. Research has shown (8) (9) that this response consists of both recoverable and irrecoverable components. The recoverable part may be elastic or viscoelastic in nature, while the permanent part may be plastic or viscous. In general, all material behavior may be described by a combination of these four mechanical models. The total strain response may be represented as follows:

$$\epsilon(t) = (\epsilon_E + \epsilon_{VE})_{\text{Recoverable}} + (\epsilon_V + \epsilon_{PL})_{\text{Permanent}} \quad (3.1)$$

where ϵ_E = elastic strain--recoverable, time-independent, can be idealized by elastic spring.

$\epsilon_{VE}(t)$ = viscoelastic strain--recoverable after time, time-dependent, can be idealized by elastic spring and viscous dashpot in parallel.

$\epsilon_V(t)$ = viscous strain--nonrecoverable, time-dependent, can be idealized by viscous dashpot with leak.

ϵ_{PL} = plastic strain--nonrecoverable, time-independent, can be idealized by solid block on table.

In Figure 3.6b, a typical flexible pavement deflection response curve due to a haversine load pulse of amplitude A and duration d (Figure 3.6a) is shown at load repetition n, where the flexible pavement has been subjected to a previous loading history of $n_i - 1$ load repetitions. As n increases, the permanent deformation $R_p(n)$ at each individual load pulse response becomes smaller. It is represented mathematically for each incremental temperature period as:

$$R_p(n) = R_4(d/2) \cdot f(n) \quad (3.2)$$

where $R_p(n)$ = the permanent deformation at load repetition n.

$R_4(d/2)$ = general deflection response of pavement surface as a function of load duration and temperature.

$f(n)$ = a monotonically decreasing function of the number of previously applied loads.

Previous research has shown that $f(n)$ is reasonably represented as:

$$f(n) = \mu_{sys} (n)^{-\alpha_{sys}} \quad (3.3)$$

where μ_{sys} = a system rutting characteristic representing the fractional part of the general response that becomes permanent.

α_{sys} = a system rutting characteristic representing the rate of change of permanent deformation.

The system rutting characteristics are computed in the VESYS IIM computer program using the following:

- (a) the individual layer permanent deformation characteristics, μ_K and α_K ; $K = 1, 2, 3,$
- (b) unload compliances of each layer material at different load repetitions, based on the deformation properties and load compliance
- (c) stationary unload deformation responses at different load repetitions computed using unload compliances
- (d) stationary load deformation response, computed using load compliances.

Integration of equation (3.2) over n yields the accumulated rut depth RT :

$$RT = R_4 (d/2) F(n) \quad (3.4)$$

where $F(n) = \mu_R n^{\alpha_R}$
 $\alpha_R = 1 - \alpha_{sys}$
 $\mu_R = \mu_{sys} / \alpha_R$

Assuming the functions $F(n)$ and R_4 , during the q th temperature season, are uncorrelated random variables, the expected value and variance of rut depth are obtained by taking approximate moments:

$$E[RT] = E[R_4 (d/2) E[F(n)]] \quad (3.5)$$

$$\text{Var}[RT] = E[R_k(d/2)]^2 \text{Var}[F(n)] + E[F(n)]^2 \text{Var}[R_k(d/2)] \quad (3.6)$$

3.3.2 Roughness Model

The accumulated deformation at any time along the longitudinal profile of the roadway wheel path is assumed to differ because of the randomness of loads, materials, and construction practices. Model development (1) (2) (10) demonstrates the basic relationship that the variance of the slope of the surface deformation of a body is equal to the negative second derivative of the spatial auto correlation function $A(x)$ evaluated at $x = 0$:

$$\text{Var}[S] = \left. \frac{-\partial^2 A(x)}{\partial x^2} \right|_{x=0} \quad (3.7)$$

where S = slope of surface deformation.

Var = variance operator.

$A(x)$ = spatial auto correlation function as a function of the space variable x (distance along the roadway wheel path).

The spatial auto correlation function, $A(x)$, of the pavement's surface deformation along the wheel path can be expressed as:

$$A(x) = E[RT(x_1) \cdot RT(x_2)] \quad (3.8)$$

where E = expectation operator

$RT(x_j)$ = surface deformation (rut depth) at the location x_j .

The variance of surface deflections, for a deterministic load, is assumed to be totally attributed to the variation in material properties. This is defined by the variance in the system's primary deflection response. The random variable η is assumed to have a mean of 1. It is shown (1) (2) (10) that equation (3.8) reduces to:

$$A(x) = (\rho_{\eta_1 \eta_2} \sigma_{\eta_1} \sigma_{\eta_2} + 1) (RT)^2 \quad (3.9)$$

where $\rho_{\eta_1 \eta_2}$ = the correlation coefficient for primary surface deflection response.
 RT = mean rut depth

The correlation coefficient is defined by the model:

$$\rho_{\eta_1 \eta_2} = 1 - B(1 - e^{-X^2/C^2}) \quad (3.10)$$

where B, C = pavement roughness properties due to material variability.

Substituting and solving equation (3.7) yields:

$$\text{Var}[S] = (2B/C^2) (\sigma_{\eta}^2) (RT)^2 \quad (3.11)$$

Taking approximate moments yields the computer relationships for the mean and variance of slope variance:

$$E[SV] = (2B/C^2) \sigma_{\eta}^2 (\text{Var}[RT] + (E[RT])^2) \quad (3.12)$$

$$\text{Var}[SV] = (4B/C^2)\sigma_{\eta}^2 E[RT] {}^2\text{Var}[RT] \quad (3.13)$$

3.3.3 Fatigue Cracking Model

A phenomenological model, a schematic of which is given in Figure 3.9, is used for the prediction of the extent of cracking based on a probabilistic Miner's hypothesis. The criterion for cracking is based on fatigue resulting from the tensile strain at the bottom of the asphalt concrete layer. It is given as follows:

$$C_q(t) = n_q / N_q \quad (3.14)$$

where $C_q(t)$ = increment to the crack index resulting from a repetition of loads in the qth incremental analysis period (time interval)

n_q = the number of axle loads applied to the pavement in the qth incremental analysis period

N_q = the number of loads to failure under temperature and strain conditions of the qth time interval

The number of loads for crack initiation in the qth temperature season is given by the following relationship:

$$N_q = K_{1q} (1/R_{7q})^{K_{2q}} \quad (3.15)$$

where R_{7q} = the general radial strain response

K_{1q} and K_{2q} = material fatigue properties

Test procedures for determination of K1 and K2 (mean, coefficient of variation, correlation coefficient) are given in Section 5.8.

The stochastic solutions to equation (3.14) are obtained assuming that n_q and N_q are independent (uncorrelated), random variables:

$$E[C(t)] = \sum_{q=1}^Q E[n_q] E[1/N_q] \quad (3.16)$$

Likewise, the variance is obtained:

$$\text{Var}[C(t)] = \sum_{q=1}^Q (E[1/N_q] \sigma^2_{n_q} + E[n_q] \sigma^2_{1/N_q}) \quad (3.17)$$

The variance of load number is found from the average rate of traffic loads occurring in a Poisson distribution. The expected value and variance of loads to failure are found using second order Taylor series expansion approximations assuming that only K1 and K2 are correlated and that strain response is uncorrelated with K1 and K2. Detailed solutions are found in reference (1).

The expected cracking damage $E[C]$ is expressed as a dimensionless index. A crack is initiated at the bottom of the AC layer when the value of $E[C]$ equals one. In order to express cracking in a more meaningful manner, it is assumed that C takes on a normal distribution with mean $E[C]$ and variance $\text{VAR}[C]$.

The probability density function $f(c)$ expressing these quantities is shown in Figure 3.10a. It can be expressed mathematically as:

$$f(c) = (2\pi \text{Var}[C])^{-1/2} \exp\left(-\frac{(C-E[C])^2}{2 \text{Var}[C]}\right) \quad (3.18)$$

The cumulative distributive function shown in Figure 3.10b is defined as:

$$F(C_0) = \int_{-\infty}^{C_0} f(c)dc \quad (3.19)$$

where $f(c)$ = probability density function.

$F(C_0)$ = cumulative distribution function of C at the point C_0 (area under the curve $f(c)$ between $C = -\infty$ and $C = C_0$ as shown in Figure 3.10b).

This area represents the probability of C being less than C_0 denoted by:

$$\Pr[C < C_0] = F(C_0) \quad (3.20)$$

The probability of C being greater than C_0 is denoted by:

$$\Pr[C \geq C_0] = [1 - F(C_0)] \quad (3.21)$$

$F(1)$ is the probability that the damage index (C) is less than one (i.e., the pavement does not exhibit cracking distress). The expected area cracked in square feet per 1,000 square feet is given as:

$$\text{Area Cracked} = 1,000 [1 - F(1)] \quad (3.22)$$

3.4 PERFORMANCE MODEL

3.4.1 Serviceability Index

The performance of a pavement in a given environment is considered as its ability to provide an acceptable level of

serviceability, with a specified degree of reliability at an assumed level of maintenance. The impairment or loss in the ability to provide the necessary services in a given locale may then be considered as the failure of the pavement. When reviewed in this context, "Failure" becomes a loss in performance; it is the extent to which the pavement has failed to render itself serviceable, and it results from an accumulation of damage over a given time period. (Figure 3.11 depicts the overall performance model.)

In this model, the AASHO definition of present serviceability index is expressed as a function of the objective distress components of cracking, roughness, and rutting. The model uses the following general expression:

$$PSI = PSI_I + b(\log(1+SV)) + c \sqrt{\tilde{C} + d(RT)^2} \quad (3.23)$$

where: PSI_I = initial serviceability index
 $b = -1.91$ $c = -0.01$ $d = -1.38$
 SV = Slope Variance (millionth radians)
 \tilde{C} = Area Cracked (sq. ft./1,000 sq. ft.)
 RT = Rut Depth (in)

The expected value and variance of the present serviceability index are calculated by assuming that the initial index and the damage components are uncorrelated random variables.

3.4.2 Pavement Reliability

The reliability of a pavement system at any time t , is given by the probability that the serviceability index PSI is above some unacceptable level PSI_f which has been established beforehand:

$$\text{Reliability} = \Pr \{PSI \geq PSI_f\} = 1 - F(PSI_f) \quad (3.24)$$

where PSI = present serviceability index at time t .
 PSI_f = limiting or failure level of present serviceability index.

$F(\text{PSI}_f)$ = cumulative distribution function
of PSI evaluated at PSI_f .

The distribution of PSI's is obtained assuming a Gaussian distribution. It is computed using a standard computer subroutine (Figure 3.12).

3.4.3 Marginal (State) Probabilities

The marginal probability of serviceability index is the probability of the serviceability index being in a given interval $i-1$ to i

$$M_i(\text{PSI}) = F(\text{PSI})_i - F(\text{PSI})_{i-1} \quad (3.25)$$

where $M_i(\text{PSI})$ = the probability that the PSI of the pavement will be in a certain specified state.

$F(\text{PSI})_i$ = represents the cumulative distribution function of PSI evaluated at PSI_i . It is the probability that PSI will be less than the specified value.

3.4.4 Expected Life of the Pavement

In VESYS, the "reliability" of a pavement at any point in time is the probability that the PSI exceeds the minimum acceptable level. The time for the reliability to fall below a predefined minimum value ("Tolerance") is taken as the expected life.

NOTE 3.1 - A simple procedure is presented in Chapter 5 for the determination of the layer material permanent deformation properties.

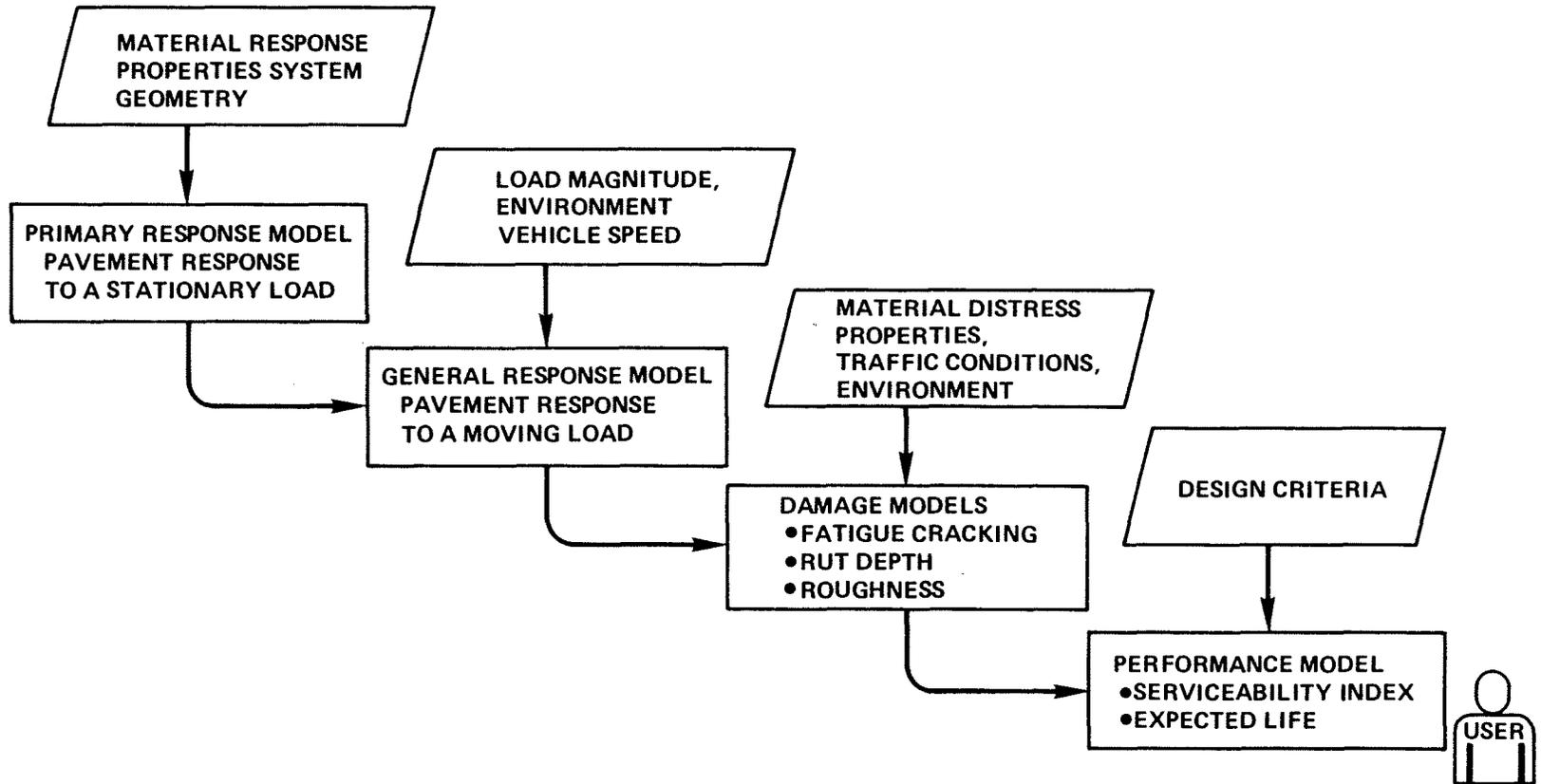


FIGURE 3.1 MODULAR STRUCTURE OF VESYS

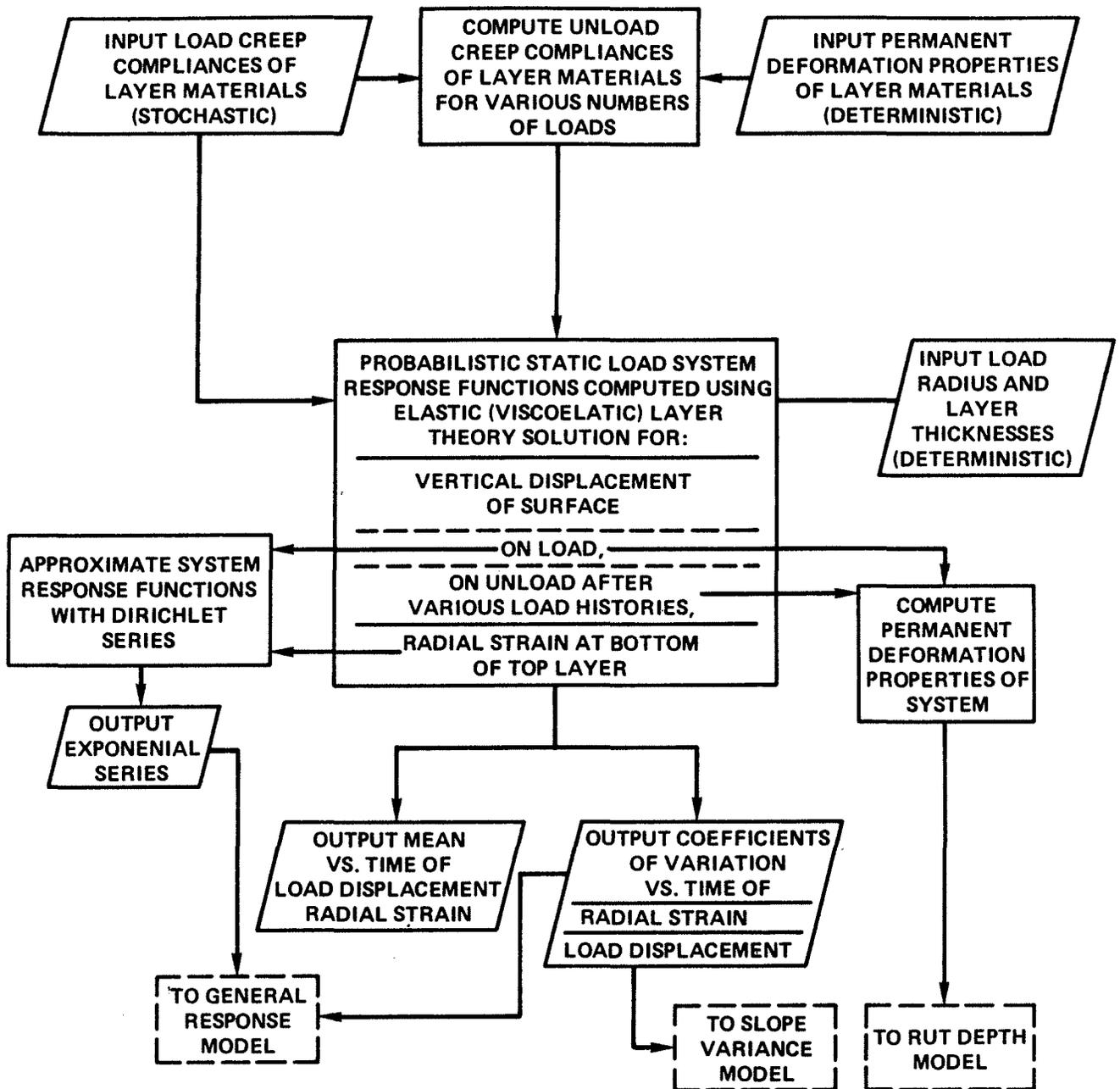


FIGURE 3.2 PRIMARY RESPONSE MODEL
TYPE 1 ANALYSIS

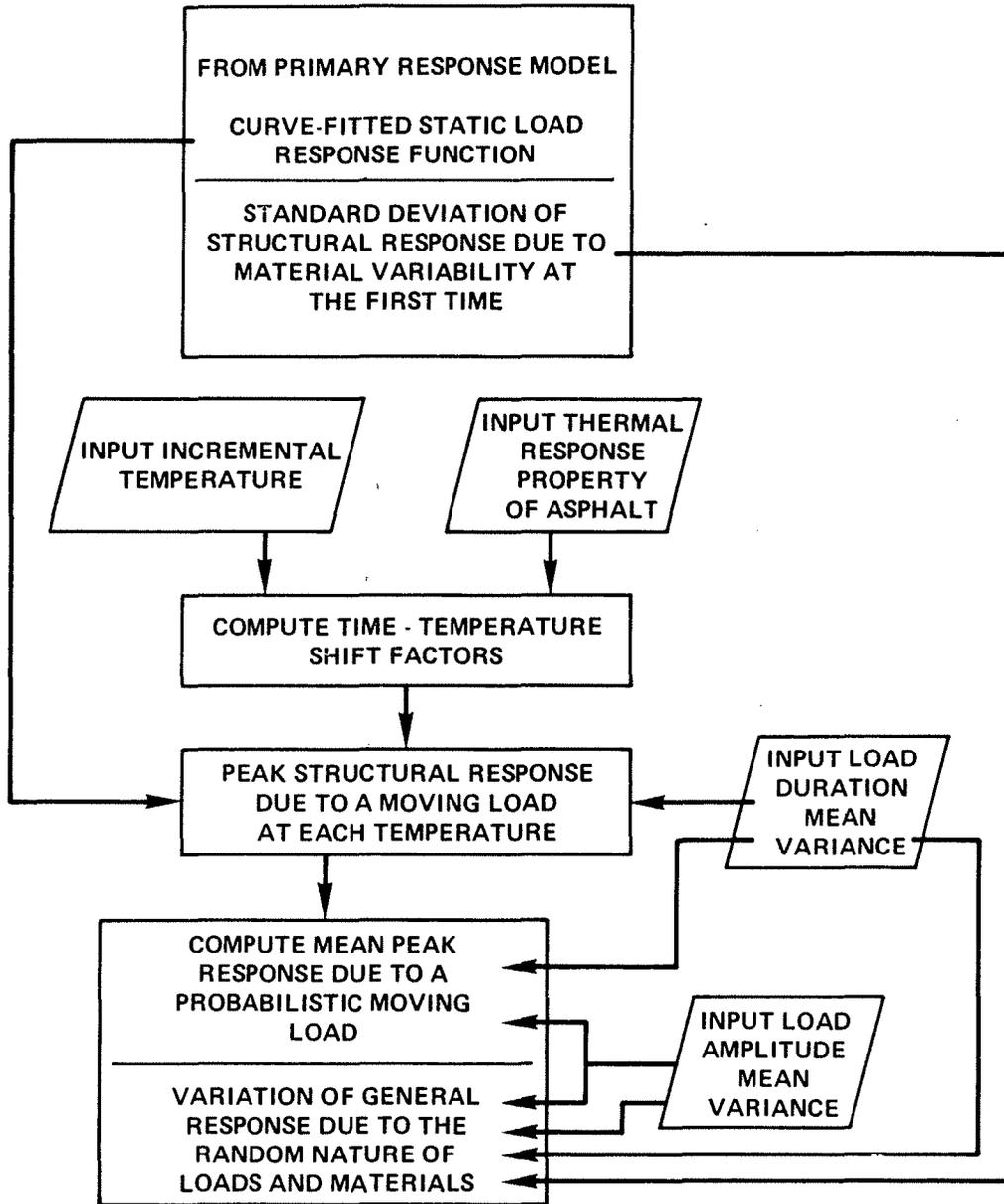


FIGURE 3.3 GENERAL RESPONSE MODEL

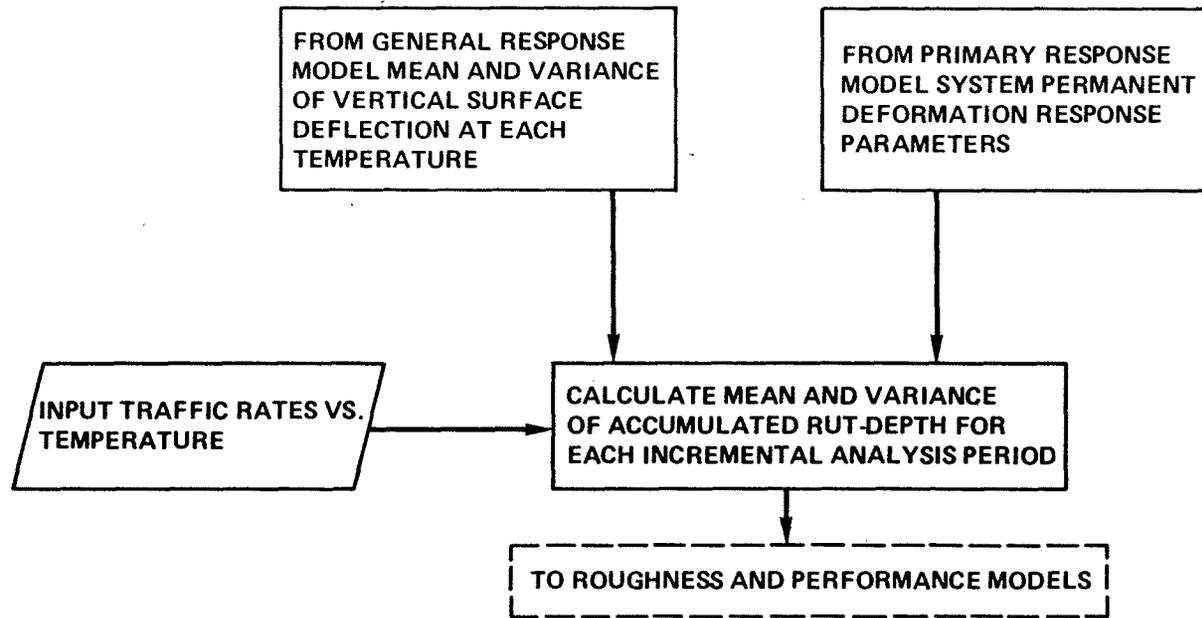


Figure 3.4 RUT-DEPTH MODEL

- ϵ_E = elastic strain
- ϵ_{VE} = viscoelastic strain
- ϵ_V = viscous strain
- ϵ_{PL} = plastic strain

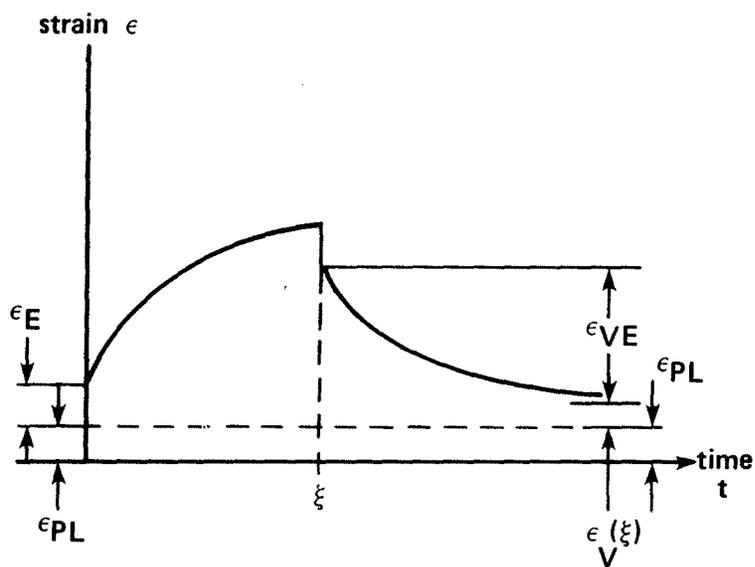


FIGURE 3.5 STRAIN RESPONSE TO A SINGLE STRESS PULSE

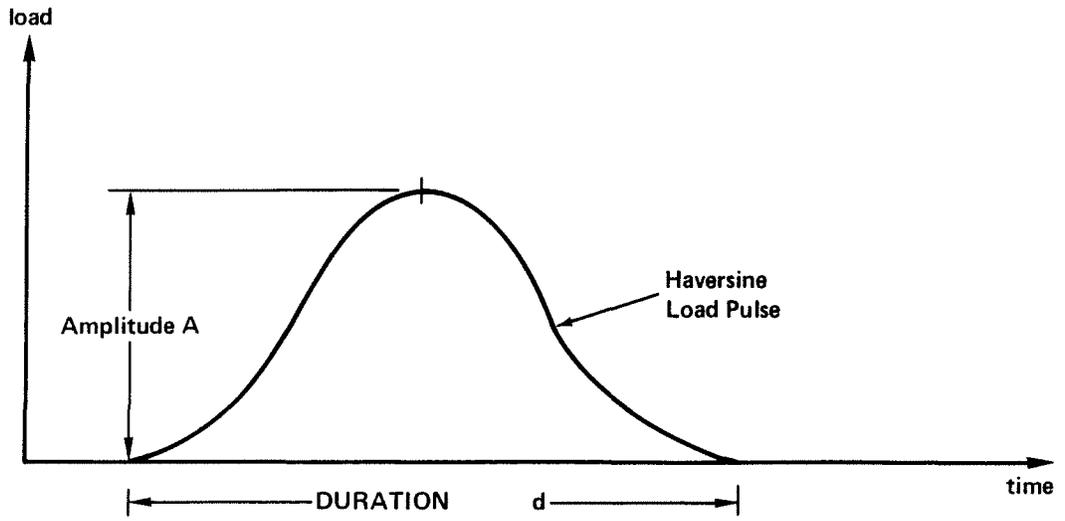


FIGURE 3.6a - nth HAVERSINE LOAD PULSE

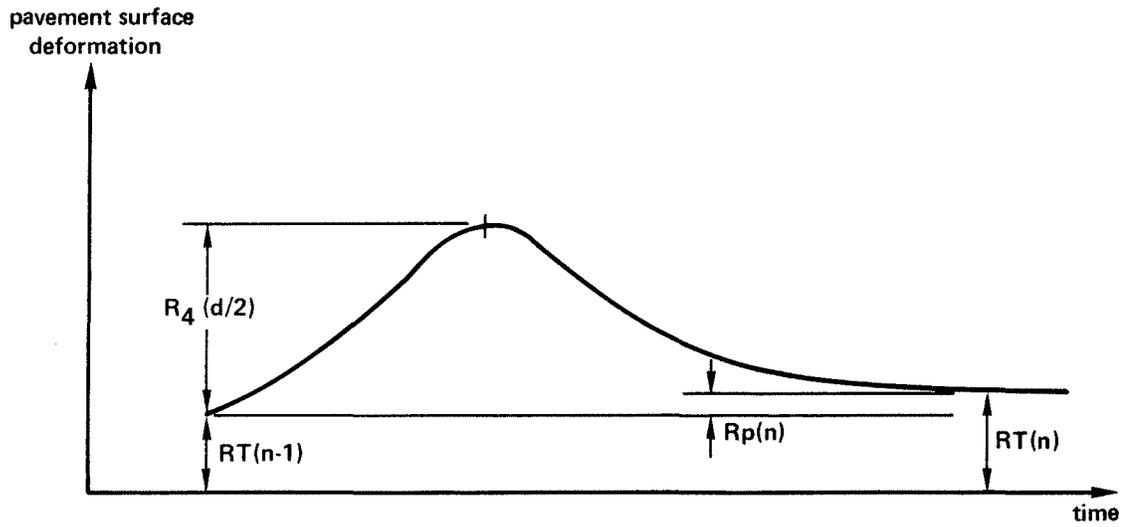


FIGURE 3.6b - RESPONSE TO HAVERSINE LOAD PULSE AT nth REPETITION

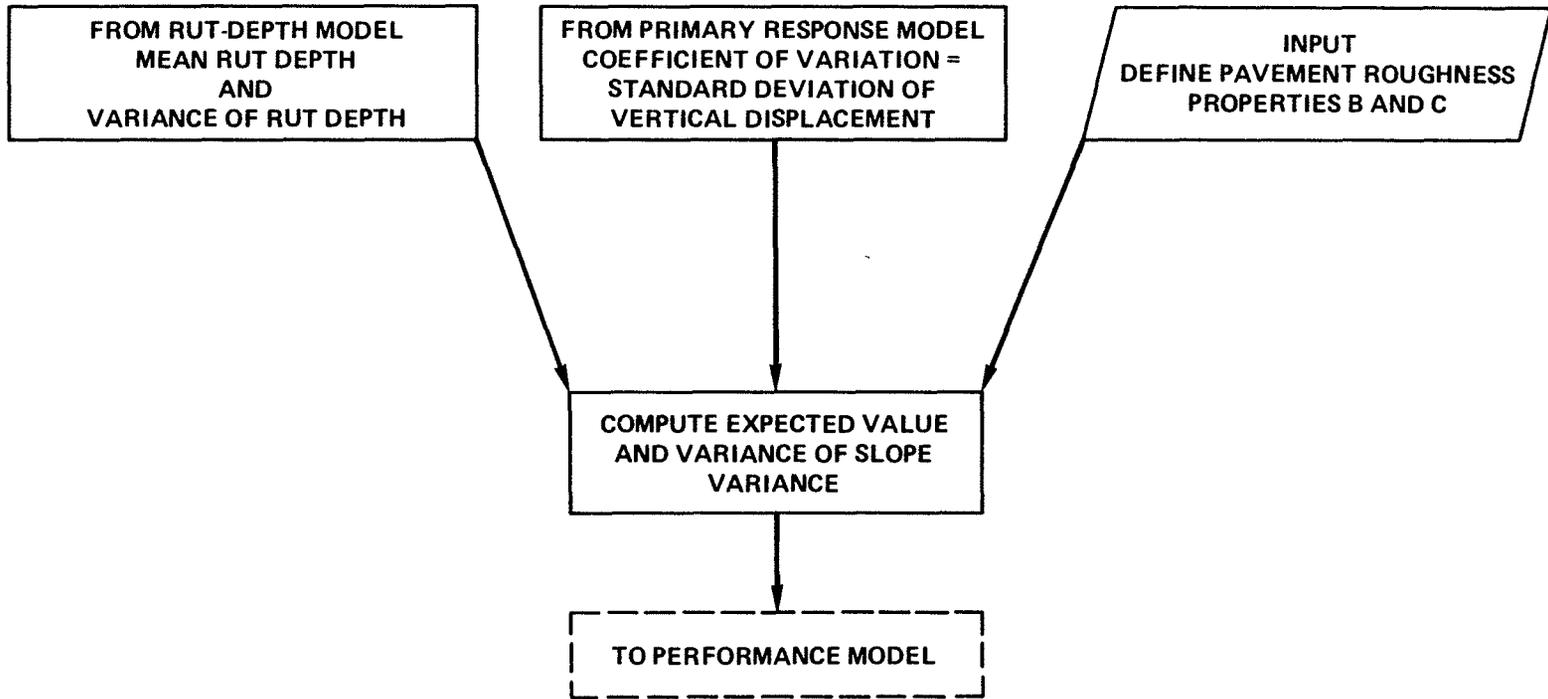


FIGURE 3.7 ROUGHNESS MODEL - SLOPE VARIANCE

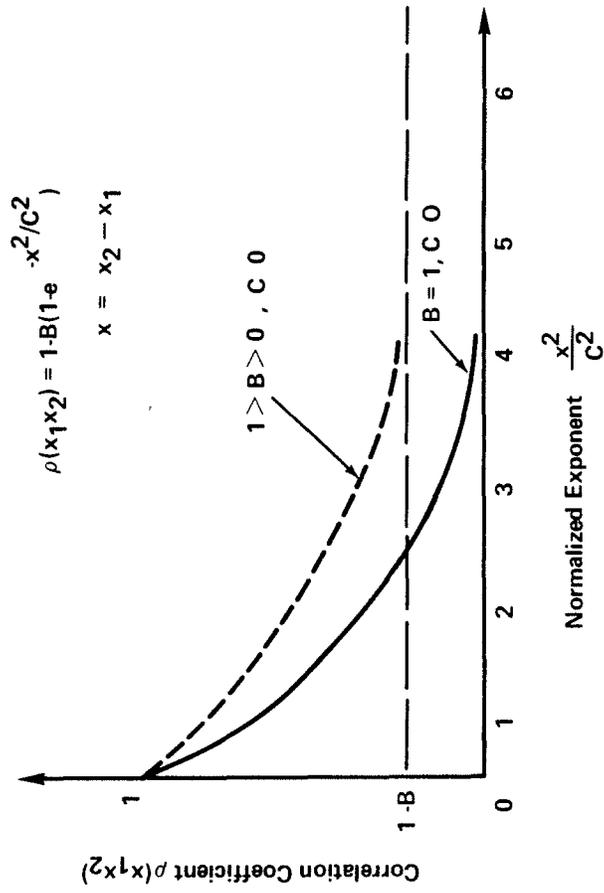


FIGURE 3.8 ROUGHNESS CORRELATION COEFFICIENT

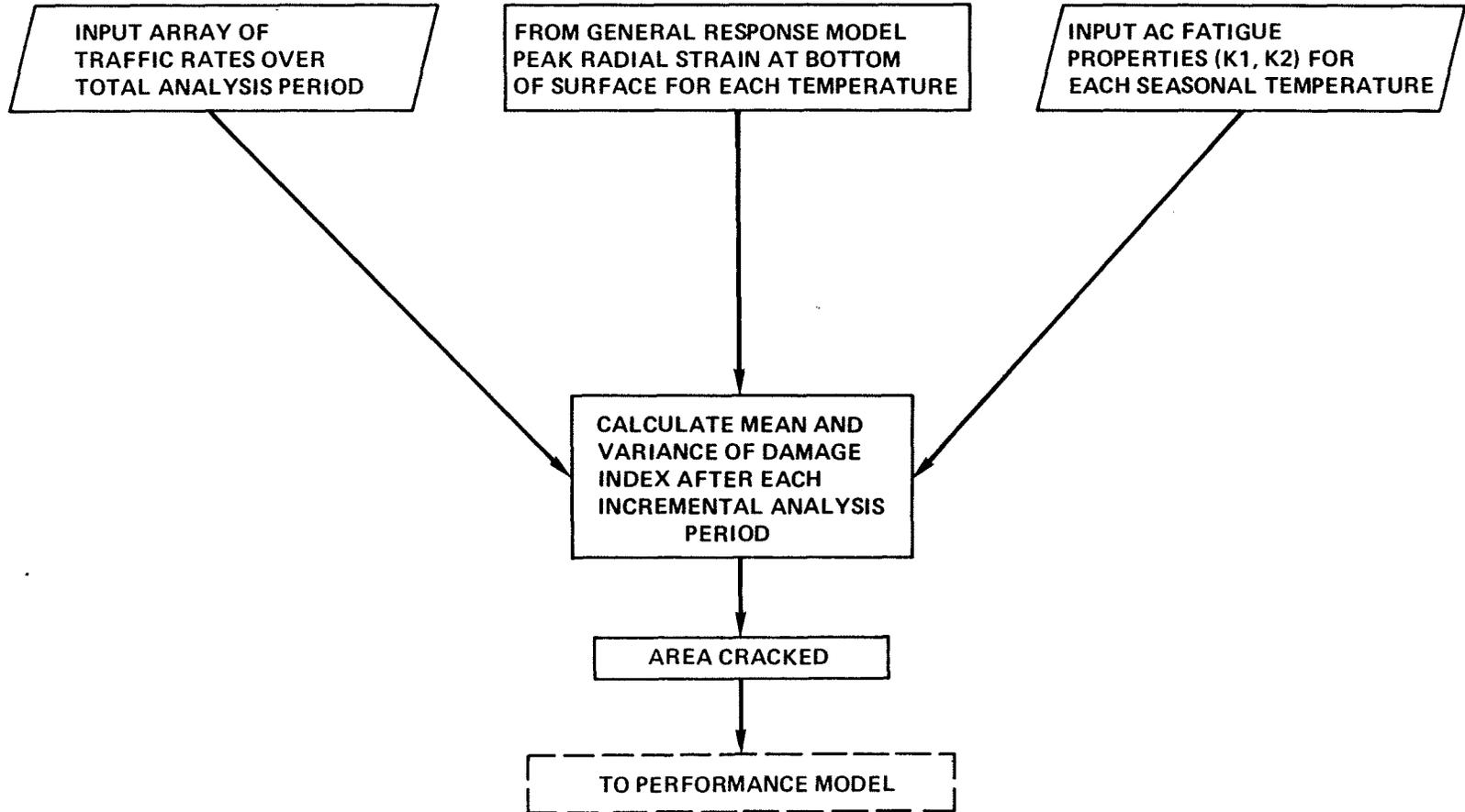


FIGURE 3.9 FATIGUE CRACKING MODEL

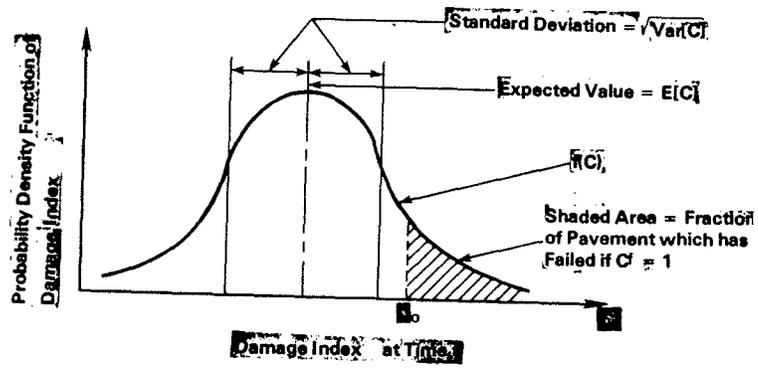


FIGURE 3.10a PROBABILITY DENSITY FUNCTION

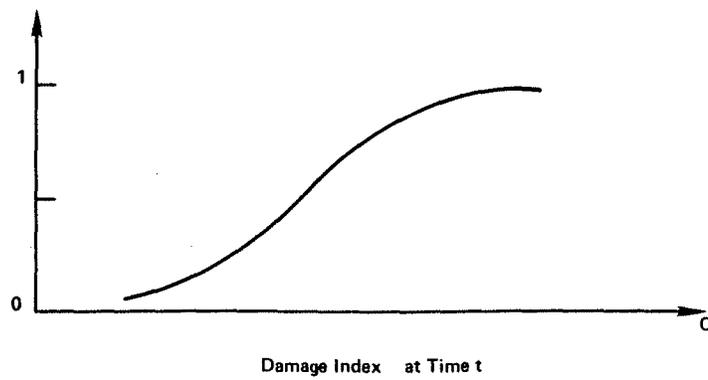


FIGURE 3.10b CUMULATIVE DISTRIBUTION FUNCTION

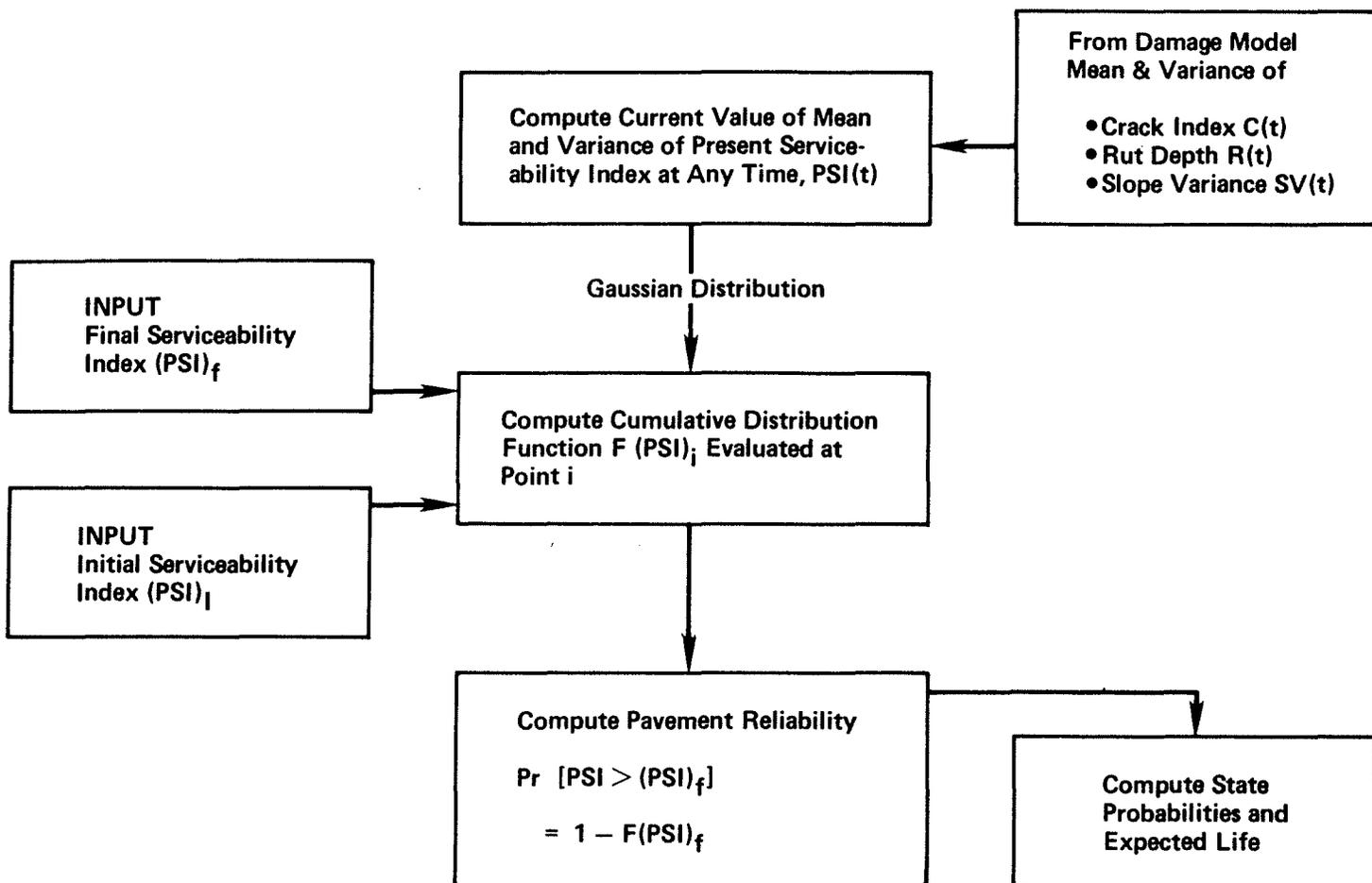


FIGURE 3.11 PERFORMANCE MODEL - RELIABILITY

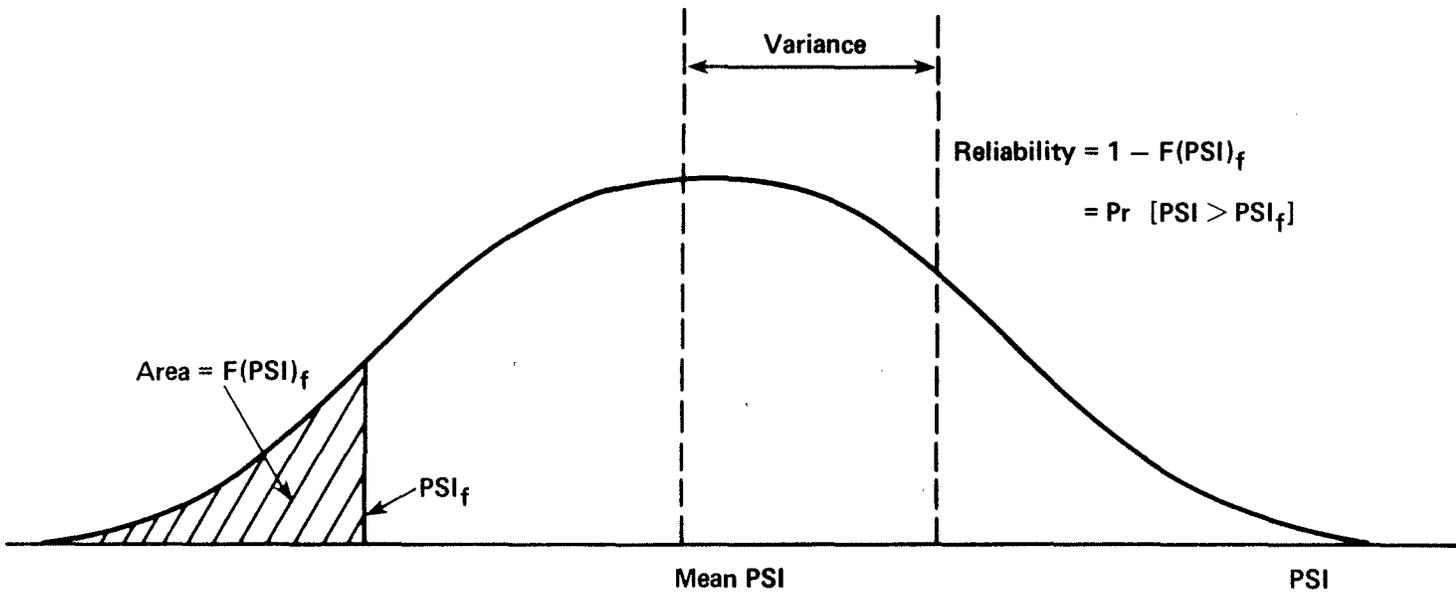


FIGURE 3.12 DISTRIBUTION OF PSI AT TIME t

CHAPTER 4
OPERATING INSTRUCTIONS FOR VESYS

The purpose of this chapter is to give the users of VESYS the information needed to install and operate the program on their own computer. Anyone wishing to use the program should first familiarize himself with the basic information contained in the other chapters of this manual, especially Chapter 3: Structural Subsystem.

Features of the computer code include:

Simplicity--The user punches certain commands on the input cards, followed by the appropriate data. VESYS scans the input deck using these commands to identify each piece of datum. It can, thus, check for missing information and automatically substitute default values where needed. The program also performs extensive error checking and prints messages to help locate the source of any errors it finds.

Flexibility--By specifying the appropriate commands and input data, the user can select the range and level of analysis he desires. This flexibility allows the execution of the entire program as a unit, or of any of the main modules independently.

Modularity--The arrangement of the various analytical portions of VESYS into well-defined modules makes any future modification a fairly simple task. The modular framework can be kept intact while components are modified, replaced, or added. This technique was used during the development of the program when a deterministic primary response model was replaced by the current probabilistic solution.

4.1 VESYS SOURCE CODE

Developed on: IBM 360/65 under OS

FHWA System: IBM 360/65 under OS

Compiler: IBM FORTRAN G Level 21

Typical Statistics:

<u>Step</u>	<u>CPU Seconds</u>	<u>Core (Bytes)</u>
COMPILE	66.34	124 K
LINK EDIT	4.67	46 K
Go (Execute)	59.22	144 K

Machine-Dependent Considerations:

1. Word size - 32 bits
2. Core is not set automatically in FHWA computer and cannot be cleared except by a program. All uninitialized locations contain garbage at beginning of run.

Input/Output Files:

1. Input is via logical unit 5 (card reader).
2. Output is via logical unit 6 (line printer).

4.2 INPUT DATA

4.2.1 Commands

Input data values for VESYS are read from cards. Each input variable is associated with a "command" word, which is punched before the value of the variable on a data card. The program reads the command first, and then uses it as a key-word for matching the subsequent data value to the proper variable. This allows flexibility in the order the data are input.

After the value of a variable is read, it is checked against a predefined "reasonable" range of values. If the value of any variable lies outside this range, an error message is printed and the program is terminated.

Because many of the input variables have predefined "default" values stored within the program, it is not necessary to input a value for every variable. VESYS automatically assumes the default value for any of these variables which are not input.

VESYS is designed to cycle back to its own starting point so that multiple sets of data may be run with one execution of the program. The data for each separate problem are terminated in the input deck by an ENDOFRUN command. This command signals the program to begin executing with the data that have been read thus far. When the problem is complete, VESYS begins reading data for the next "run" with the first card after the previously read ENDOFRUN command. The last ENDOFRUN command in a data deck is followed immediately by an ENDOFJOB command, which causes the program to cease processing.

When a "job" is submitted with multiple "runs," the first run uses the default values, supplanted where indicated by the input data. Each subsequent run begins with the data values left over from the previous run and supplants new input data. It may be useful to think of each run of a job as having the values used in the previous run by default. Any variables to be changed can be explicitly input. Others will remain the same. This feature allows the user to see the effect of changing a few variables without having to reread all of the data deck.

The input commands recognized by VESYS are of three basic types:

1. LOGICAL - No data value is needed. The presence or absence of the command indicates which way a decision is to be made in the program.
2. SCALAR - One data value is read in the field immediately following the command. Absence of the command causes the default value, if any, to be assumed. Absence of a data value following the command will cause "zero" to be assumed, since blanks are read as zeroes.
3. ARRAY (or "Vector") - An array of several data values are read on the card(s) following this command. (No defaults exist for array values.) No other commands or values can be on the same card as an ARRAY COMMAND. The number of data values stored in the array is either determined by an associated SCALAR COMMAND (Ex. - NTEMPS determines how many TEMPS are read) or is a fixed number (Ex. - there are always three values after ALPHA).

4.2.2 Formats

There are only two input formats; one for reading commands and the values associated with scalar commands, and another for reading the array values following an array command.

All commands, and the values with scalar commands, are read with FORMAT (4(A8,E12.4)), that is,

```

/1      9      21      29      41      49      61      69      80:
/:COMMAND VALUE COMMAND VALUE COMMAND VALUE COMMAND VALUE:

```

After an array command, the subsequent card(s) contain the array values in this format: FORMAT (6E12.4), that is,

```

/1      13      25      37      49      61      72:
/:VALUE      VALUE      VALUE      VALUE      VALUE      VALUE:

```

4.2.3 General Instructions and Suggestions for Command Use

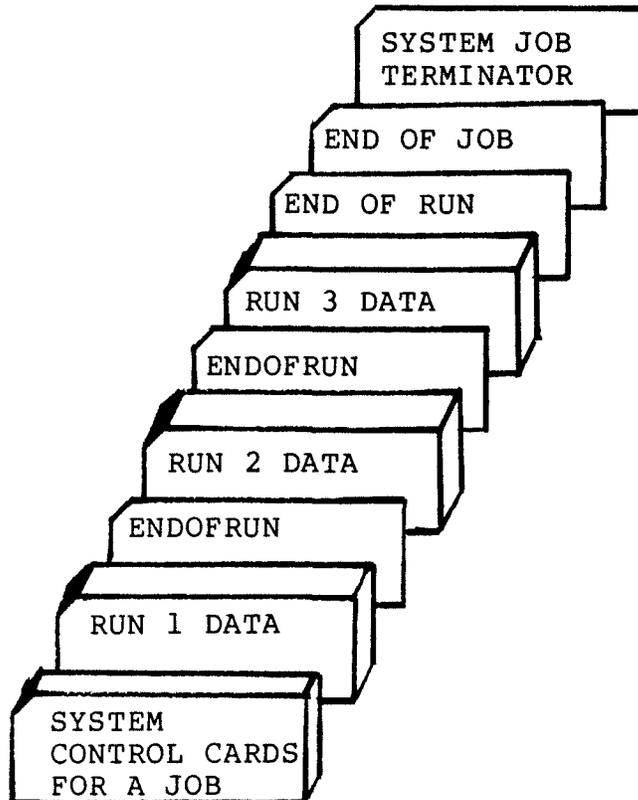
1. All commands must begin in the first column of the command field. All commands consist of eight characters, including trailing blanks. All eight characters, including blanks, must be correct for a command to be recognized.
2. All data values must have a decimal point punched in the field. This includes integers.
3. Blank command fields are ignored. Blanks in data fields are read as zeros.

4. When an array (or vector) command is read, the data value field is ignored. Data values for the array are read from subsequent cards.

5. Each array command must appear on a card by itself. No other commands may appear on this card.

6. There are no default values for arrays.

4.2.4 Deck Structure



EXAMPLE OF A VESYS "JOB" WITH THREE "RUNS."

4.3 TYPES OF RUNS AVAILABLE

There are four types of runs available to the user of VESYS. The particular analysis desired is selected by specifying the appropriate value for the TYPE command:

Value of TYPE

Analysis Performed

1.0	Primary Response and Damage/ Performance
2.0	Primary Response Only
3.0	Damage/Performance Only
4.0	Curve-fitting Only

4.3.1 Type 1 Analysis:

This calls for a full run which produces predictions of pavement response and expected lifetime on the basis of system geometry, materials' characteristics, and environment. The primary response model passes primary response information to the damage model. Serviceability predictions are then made, based on the primary response information and the various environmental parameters. The following variables will ordinarily be supplied by the user for a Type 1 run:

TITLE			
TYPE	1.0		
ITYPES	1001000.0	Control variables	
INDEX			
THICK1			
THICK2			
LOADING		System geometry	
RADIUS			
NTSTATIC			
TSTATIC			
LAYER1		Creep compliance	} Materials' properties
LAYER2			
LAYER3			
VARCOEF1			
VARCOEF2			
VARCOEF3			
STRNCOEF			
STRNEXP			
COEFK1			
COEFK2		Fatigue, rutting, and roughness variables	
K1K2CORL			
GNU			
ALPHA			
CORLOEF			
CORLEXP			
TOLERNCE			
QUALITY			
STDEV		Serviceability bounds	
PSIFAIL			

NTRANDOM
TUNITS
TRANDOM
LAMBDA
AMPLITUD
VCAMP
DURATION
VCDUR

Traffic variables

} System
environment

NTEMPS
TEMPS
REFTEMP
BETA

Temperature variables

ENDOFRUN signals end of inputs, begins execution of run.

The primary response information is computed in the primary response model and passed to the damage model.

Subsequent Type 3 runs (damage/performance only) may use the values which are generated for these variables. The advantage of this is that it permits analysis of the same pavement under several different traffic, temperature and serviceability conditions without recomputing the primary response information. A considerable amount of computer time can be saved in this way because the static load analysis requires a significant computational effort.

4.3.2 Type 2 Analysis:

This calls for primary response calculations only. It produces values for stresses, strains and deflections in a three-layered linear viscoelastic system. The kinds of response which are calculated are selected by ITYPES. The points at which response is given are specified in cylindrical coordinates. The depth is given by ZPOINT and the radial distances from the center of the load are given in RPOINTS. Although a single run only calculates response at a single depth, subsequent runs can be made in which the value of ZPOINTS is altered and the other inputs are left unchanged. The values calculated in a Type 2 run cannot be passed to a subsequent Type 3 run.

4.3.3 Type 3 Analysis:

It is recommended that Type 3 runs be made only after the primary response variables have been calculated in a Type 1 run. For a user to input all the required information requires a good understanding of the program. Primary response values can be passed directly from a Type 1 run to subsequent Type 3 runs of the same job. This is explained above for the Type 1 analysis.

4.3.4 Type 4 Analysis:

This runs the curve-fitting routines on a set of data. The coefficients and DELTAS for a Dirichlet series which approximates the input curve are printed out. The approximation used is based on a least-squares fit. This type of analysis may be used in order to find the user input DELTA values which result in accurate curve fits for the creep compliance data from layer materials. Although VESYS will compute values for DELTAS when they are not specifically input, a better set of curve fits may be obtained by a carefully chosen set of DELTAS.

As soon as a rigorous technique is developed for selecting DELTA values, the procedure will be built into VESYS. A suggested procedure for selecting DELTAS may be found in Article 6.

4.4 DICTIONARY OF COMMANDS

ALPHA (Array - no default) Internal array ALPH(I).

Array of permanent deformation materials property parameters for the three layers (see also GNU). These are read in the order: top, middle, bottom. [See Articles 2.2.5.2 and 5.7.1 STEP 13]

AMPLITUD (Default is 80.0) Internal variable is AMP.

The mean intensity of repeated loadings in psi. Only the heavier traffic is considered in determining the mean load intensity; light vehicles should be ignored.

In a Type 1 analysis, the input value of AMPLITUD will be multiplied by the value of LOADING for which the primary response was computed. Hence, the value 1.0 should be used for LOADING, or the value of AMPLITUD should be divided by LOADING before being input. [See Article 2.2.4]

BETA (Default is .113) Internal variable is BETA.

This parameter describes the variation in the time-temperature shift factor as a function of temperature.

The value of BETA is applied only to the top layer. The base layer is assumed to be temperature-independent. [See Article 2.2.5.1]

COEFK1 (Default is 0.0) Internal variable is CK1.

Coefficient of variation for STRNCOEF. [See Article 2.2.5.2]

COEFK2 (Default is 0.0) Internal variable is CK2.

Coefficient of variation for STRNEXP. [See Article 2.2.5.2]

CORLCOEF (Default is 0.0) Internal variable is B.

The coefficient B in the system's spatial auto-correlation function. [See Article 2.2.6 STEP 1]

CORLEXP (Default is 1.0) Internal variable is C.

Part of the exponent in the system's spatial auto-correlation function. CORLEXP corresponds to C in equation (3.12). [See Article 2.2.6 STEP 2]

DURATION (Default .05) Internal variable DUR.

The mean duration of repeated loadings in the random load analysis. [See Article 2.2.1.5]

ENDOFJOB (Option selector) No internal variable.

Specifies that no more data remain to be run and execution of VESYS IIM may now be terminated. Note that any data which are input after the last ENDOFRUN will never be used because that command is needed to cause processing to begin.

ENDOFRUN (Option selector) No internal variable.

Specifies that all data needed for the current run have been read and execution may begin. Any variable which has not been specifically set will retain the value it had in the preceding run. If this is the first run of a job, an undefined variable will take on its default value, if any. For exceptions to these rules, see the Command Chart, Suggestions for Command Use, and relevant commentaries. A job consists of one or more "runs" followed by an ENDOFJOB command. It is important to remember that the ENDOFJOB must be immediately preceded by an ENDOFRUN.

GNU (Array - no default) Internal variable GGU(I).

Array of permanent deformation materials property parameters for the three layers (see also ALPHA). [See Article 2.2.5.2]

INDEX (Default 1.0) Internal variable INDEX.

This specifies a reference number for the current run. After each run, the value of INDEX is automatically increased

by one. The incrementing can be overridden at any time by inputting a new value for INDEX. If the command is not used, the runs within a job will be numbered sequentially from one.

ITYPES (Default 1001000.0) Internal name ITYPES.

This specifies the kinds of information which are to be calculated in a Type 2 analysis. An option is selected by putting a non-zero digit in the appropriate decimal place:

1.0 = vertical stress
1X.0 = shear stress
1XX.0 = radial stress
1XXX.0 = vertical deformation
1XXXX.0 = radial deformation
1XXXXX.0 = circumferential strain
1XXXXXX.0 = radial strain

Any combination of these analyses may be specified. For example, a value of 1000001.0 will cause radial strain and vertical stress to be calculated at the points of interest.

In a Type 1 analysis, the value of ITYPES is ignored. For this type of run, only radial strain directly beneath the center of the load at the first interface and the vertical deformation at the surface will be calculated. These are the response measures which are needed in the Damage Model.

K1K2CORL (Default 0.0) Internal variable CK12.

Correlation coefficient for STRNCOEF and STRNEXP (frequently called K1 and K2 in the literature). These two parameters can be expected to be negatively correlated; they interact to a fairly great extent. [See Article 2.2.5.2]

LABDATA (Array - no default) Internal array DATA(I).

The array of data which is to be curve-fitted to a Dirichlet series in a Type 4 run. The array TCURVE represents the time at which the corresponding points in LABDATA are taken.

There must be exactly NTCURVE elements in this array (maximum is 50), and the number of points must be input before the LABDATA array.

LAMBDA (Array - no default) Internal variable ADT(I).

The array of average daily traffic in the Damage Model. Each element of this array represents the traffic rate at the corresponding point in the TRANDOM array.

There must be NTRANDOM points in this array (maximum is 25). NTRANDOM must be read in before LAMBDA.

Only the heavier traffic should be counted in the traffic rate; light vehicles should be ignored. [See Article 2.2.4]

LAYER1	(Arrays - no default)	Internal variables.
LAYER2		DLAYER(I,1)
LAYER3		DLAYER(I,2)
		DLAYER(I,3)

Master creep compliance curves for the three layers (top, middle, bottom). Each point in these curves is the value of creep compliance for the load duration given by the corresponding point in the TSTATIC array. There must be exactly NTSTATIC elements in these arrays (maximum 25), and NTSTATIC must be input before any of these arrays.

For purposes of curve-fitting, it is advisable to limit these arrays to one or two points for each order of magnitude of time represented. Difficulties also arise when less than three points are input in these arrays. [See Article 2.2.5.1]

LOADING (Default 1.0) Internal variable QQ.

In a Type 2 analysis, this represents the intensity of applied loading in psi.

In a Type 1 analysis, the value input here will multiply the repeated load variable AMPLITUD. AMPLITUD is treated as a random variable with mean and variance adjusted to reflect the expected distribution of wheel loads. This is simplified by setting LOADING to one, causing the system response curves to be calculated in terms of a unit load intensity, so that the values of RADIUS, VCAMP, and AMPLITUD can be set to model the repeated load conditions directly. [See Article 2.2.4]

NRPOINTS (Default 1.0) Internal variable NUMRS.

The number of points in the RPOINTS array. This must be input before the array, and a maximum of 50 points is permitted.

NTCURVE (Default 1.0) Internal variable NTCURV.

The number of points in the TCURVE and LABDATA arrays. A maximum of 50 is permitted. This variable must be input before the arrays in question. These inputs are only used in a Type 4 analysis.

NTEMPS (Default 1.0) Internal variable NTEMP.

The number of points in the TEMPS array. This must be input before the array, and a maximum of 24 TEMPS is permitted. [See Article 2.2.3]

NTRANDOM (Default 1.0) Internal variable NTIME.

The number of points in the TRANDOM and LAMBDA arrays. This value must be input before either array, and a maximum of 25 points is permitted. [See Article 2.2.1.2]

NTSTATIC (Default 1.0) Internal variable NT.

The number of points in the TSTATIC, LAYER1, LAYER2, and LAYER3 arrays. This value must be input before any of these arrays, and a maximum of 25 points is permitted. Difficulties arise if fewer than three points are specified (see commentary on TSTATIC). [See Article 2.2.5.1]

PSIFAIL (Default 2.5) Internal variable PSIMIN.

The minimum acceptable serviceability, defined as $(PSI)_F$. The expected lifetime of the pavement is the time required for the reliability to fall below the value specified by TOLERANCE. The reliability is the probability that PSI is greater than $(PSI)_F$. [See Article 2.2.7 STEP 2]

QUALITYO (Default 5.0) Internal variable EMO.

The mean serviceability index at time zero. Serviceability is assumed to have a Gaussian distribution. The standard deviation for this distribution at time zero is given by the input variable STDEVO.

Note that this command is spelled with a numeric zero, not an alphabetic "oh." [See Article 2.2.7 STEP 1]

RADIUS (Default 6.0) Internal variable AAA.

The radius of the applied loading in inches (the load is assumed to be circular).

This value may be used to compute an estimate of DURATION and VCDUR (see relevant commentaries). [See Article 2.2.1.4]

REFTEMP (Default 70.0) Internal variable TREF.

The reference temperature at which the master creep compliance curves in LAYER1, LAYER2, and LAYER3 are given. This variable is expressed in degrees Fahrenheit. [See Article 2.2.5.1 STEP 6]

RPOINTS (Array - no default) Internal variable (RR(I)).

The array of radial distances from the center of the load at which primary response information is desired in a Type 2 analysis. This input is ignored in a Type 1 run.

The variable NRPOINTS specifies the number of elements in this array. It must be input before RPOINTS. The maximum number is 50.

STDEVO (Default 0.0) Internal variable SIGO.

The standard deviation of the initial serviceability index in the performance model. The mean of this initial serviceability index is given by QUALITYO.

Note that this command must be spelled with a numeric zero, not an alphabetic "oh." [See Article 2.2.7 STEP 1]

STRNCOEF (Default 1.0) Internal variable K1(I).

The value of the coefficient K1 in the Miner's law formulation for damage (see equation 3.17).

The value of K1 varies with temperature. Thus, it is input as an array, and each element represents the value to be used at the corresponding temperature in the TEMPS array. Exactly NTEMPS values must be provided. [See Article 2.2.5.2]

STRNEXP (Default 0.0) Internal variable K2(I).

The value of the exponent K2 in the Miner's law formulation for damage (See equation 3.15).

The value of K2 varies with temperature. Thus, it is input as an array, and each element represents the value to be used at the corresponding temperature in the TEMPS array. Exactly NTEMPS values must be provided. [See Article 2.2.5.2].

TCURVE (Array - no default) Internal array TCURV(I).

The array of times used in a Type 4 (curve-fitting) run. They are the times (in seconds) at which the LABDATA are taken.

NTCURVE specifies the number of elements of this array, it must be input previously. A maximum of 50 points is permitted.

TEMPS (Array - no default) Internal variable TEMP(I).

Array of temperatures in degrees Farenheit to be used in the Damage Model. These are taken to represent a yearly cycle, each year being broken down into NTEMPS equal segments. Each value of TEMP represents the average temperature for the corresponding time interval. For a given time in the TRANDOM array, the corresponding temperature can be found by extending this yearly cycle a sufficient number of repetitions.

The variable NTEMPS specifies the number of points in the array and it must be input before TEMPS. The maximum number allowed is 24. [See Article 2.2.3 STEP 1]

THICK1 (Default 4.0) Internal variable H1.
THICK2 (Default 6.0) Internal variable H2.

The thicknesses of the surface and base layers, respectively, in inches. A three-layer system is assumed in VESYS; the subgrade is considered semi-infinite.

Avoid setting THICK1 or THICK2 to zero. [See Article 2.2.2]

TITLE (Array - no default) Internal array ITITLE(I).

This keyword specifies that the next card contains a heading which is to be printed on the output at the beginning of each run until replaced by a new TITLE. If no TITLE is specified, 80 blanks are used.

TOLERNCE (Default 50.0) Internal variable TLR.

Minimum acceptable reliability of the pavement, expressed as a percent. Reliability is the probability that serviceability has not reached PSIFAIL at or before some given time. [See Article 2.2.7 STEP 2]

TSTATIC (Array - no default) Internal variable T(I).

Array of times at which creep compliance data (LAYER1, LAYER2, LAYER3) were taken. These times are in seconds. Primary response information is printed for each time in the array.

The variable NTSTATIC specifies the number of elements in this array. It must be input before the TSTATIC and LAYER arrays, and a maximum of 25 points is allowed. Avoid curve-fitting difficulties by using at least three points. [See Article 2.2.5.1 STEP 2]

TRANDOM (Array - no default) Internal variable TIME(I).

Array of times at which a printout of the values computed in the Damage Model is desired. The variable NTRANDOM must

precede the input of this array, and there must be exactly NTRANDOM time values given. A maximum of 25 times is allowed. The units of time given in this array are determined by the value of TUNITS (see relevant commentary).

For each time in the TRANDOM array, there must be a corresponding value for average daily traffic in the LAMBDA array. [See Article 2.2.1.2 STEP 3]

TUNITS (Default 5.0) Internal variable LTIME.

Specifies the units of time which were used in the TRANDOM array. An integer from one to six is input according to the following code:

- 1.0 = seconds
- 2.0 = minutes
- 3.0 = hours
- 4.0 = days
- 5.0 = months
- 6.0 = years

[See Article 2.2.1.2 STEP 2]

TYPE (Default 1.0) Internal variable MTYPE.

This is the basic control variable for the program. It specifies which type of analysis is to be performed, determining which subcomponents will be executed. The following codes are used:

- 1.0 = Primary Response Analysis and Damage/Performance Analysis,
- 2.0 = Primary Response Analysis only,
- 3.0 = Damage/Performance Analysis only,
- 4.0 = Curve-Fitting only.

[See 4.3, TYPES OF RUNS AVAILABLE]

UNLOAD (Option selector) Internal variable UNLOAD.

This command specifies that the vertical displacement response factors for unloading are to be computed. (System GNU and ALPHA.) UNLOAD is automatically selected for a Type 1 analysis.

VARCOEF1 (Default 0.1) Internal variable DVAR(1).
VARCOEF2 DVAR(2).
VARCOEF3 DVAR(3).

Coefficients of variation for the creep compliance curves given by LAYER1, LAYER2, and LAYER3, respectively.

These values are important in the determination of coefficients of variation for system response curves, which in turn affect the damage indicators. The default values of .1 represent a fairly low variance in materials properties. [See Article 2.2.5.1 STEP 4]

VCAMP (Default 400.0) Internal variable VAMP.

The variance of the repeated loading intensity distribution. Only the heavier traffic is considered in determining the variance of axle weight; light vehicles should be ignored.

The value of load intensity will be multiplied by the value of LOADING which was used in computing primary response curves (see AMPLITUD and LOADING). If a value other than 1.0 was used for LOADING, then the value calculated for VCAMP must be divided by the square of LOADING. [See Article 2.2.4]

VCDUR (Default 0.0) Internal variable VDUR.

The variance of the duration of the repeated loadings (see DURATION). [See Article 2.2.1.5]

ZPOINT (Default 4.0) Internal variable ZZ.

The depth at which stress, strain, or displacement information is desired in a Type 2 analysis. This value is ignored in a Type 1 analysis.

A number of radial points may be examined in a single run, but they will all be at the depth given by ZPOINT. If different depths are of interest in a Type 2 analysis of a given system, successive runs may be made changing only the value of ZPOINT.

4.5 ERROR MESSAGES

MAIN PROGRAM

**** ERROR *** PRECEDING DATA IS OUT OF RANGE
(-) JOB ABANDONED.

Routine: MAIN

Meaning: The value of a variable as read on a data card lies outside the "reasonable" range for this particular variable as specified in the DOWN and UPPER arrays.

Additional

Information: The stored range of this variable is given in the parentheses in the message. The line above the message gives the command name and the value specified on the data card.

Action Taken: Execution Terminated.

THE ABOVE DATA INPUT IS NOT RECOGNIZED. DATA CHECK CONTINUES,
BUT JOB WILL BE ABANDONED.
PLEASE CHECK ABOVE DATA CARD FOR TYPING ERRORS OR LEFT
JUSTIFICATION.

Routine: MAIN

Meaning: One of the "commands" punched on a data card
matches none of the entries in the dictionary
of acceptable commands.

Additional

Information: The line printed above this message gives
the command and its value as read from the
data card.

Action Taken: Continue checking data, then terminate
execution.

SUBROUTINE CURVIT

**** ERROR *** ALL TIMES ARE ZERO

Routine: CURVIT

Meaning: All of the times corresponding to the set of
laboratory data to be curve-fitted are stored
as zero.

Additional

Information: Subroutine identification printed in
message below.

Action Taken: Execution Terminated.

**** ERROR *** TIME () IS NEGATIVE

Routine: CURVIT

Meaning: One of the times corresponding to the set
of laboratory data to be curve-fitted is
stored as negative.

Additional

Information: Index for the time in error is printed in
the parentheses of the message. Sub-
routine identification printed in message
below.

Action Taken: Execution Terminated.

**** ERROR *** TIME SPAN GREATER THAN 20 ORDERS OF MAGNITUDE

Routine: CURVIT

Meaning: The difference between the first time and
the last time specified for laboratory
creep data exceeds 20 orders of magnitude.

Additional

Information: Subroutine identification printed in
message below.

Action Taken: Execution Terminated.

THIS ERROR DETECTED IN SUBROUTINE CURVIT.
PLEASE CHECK DATA. JOB ABANDONED.

Routine: CURVIT
Meaning: Subroutine identification for the three errors above.
Additional Information: None.
Action Taken: See errors above.

SUBROUTINE STATIC

**** ERROR *** TIME () IS NEGATIVE

Routine: STATIC
Meaning: One of the times corresponding to the sets of laboratory data from the layer materials (to be curve-fitted) is stored as negative.
Additional Information: Index of the time in error is printed in the parentheses of the message. Subroutine identification printed in message below.
Action Taken: Execution Terminated.

**** ERROR *** DLAYER (, 1) IS NEGATIVE
**** ERROR *** DLAYER (, 2) IS NEGATIVE
**** ERROR *** DLAYER (, 3) IS NEGATIVE

Routine: STATIC
Meaning: One of these three messages is printed when any value in the laboratory data from layer material 1, 2, or 3, respectively, is stored as negative.
Additional Information: Index for the data point in error is printed as the first value in parentheses. Subroutine identification printed in message below.
Action Taken: Execution Terminated.

**** ERROR *** ALL TIMES ARE ZERO

Routine: STATIC
Meaning: All of the times corresponding to the sets of laboratory data from layer materials are stored as negative.
Additional Information: Subroutine identification printed in message below.
Action Taken: Execution Terminated.

**** ERROR *** TIME SPAN GREATER THAN 20 ORDERS OF MAGNITUDE

Routine: STATIC
Meaning: The difference between the first time and the last time specified for laboratory creep data exceeds 20 orders of magnitude.

Additional
Information: Subroutine identification printed in message below.

Action Taken: Execution Terminated.

THIS ERROR DETECTED IN SUBROUTINE STATIC. PLEASE CHECK DATA.
JOB ABANDONED.

Routine: STATIC
Meaning: Subroutine identification for the six errors described above.

Additional
Information: None.

Action Taken: See errors above.

SUBROUTINE RANDOM

**** ERROR *** DELTA () IS NEGATIVE

Routine: RANDOM
Meaning: One of the deltas (exponents) in the Dirichlet series representation of the pavement system response curve is stored as negative.

Additional
Information: Index for the delta in error is printed in the parentheses. Subroutine identification printed in message below.

Action Taken: Execution Terminated.

THIS ERROR DETECTED IN SUBROUTINE RANDOM. PLEASE CHECK DATA.
JOB ABANDONED.

Routine: RANDOM
Meaning: Subroutine identification for the error described above.

Additional
Information: None.

Action Taken: See error above.

SUBROUTINE ROUGH

\$\$\$\$ *** \$\$\$ C1.LT.1.E-10 - CYCLE =

Routine: ROUGH
Meaning: The value of C1, a temporary storage variable, has been calculated and stored too small for subsequent calculations to be stable.

Additional

Information: Index for the time increment in the
temperature cycle at which the error
occurs is printed after the equals sign.

Action Taken: Execution Terminated.

CHAPTER 5 MATERIAL CHARACTERIZATION

5.1 GENERAL

Two categories of mechanical properties are required for the structural analysis, primary response properties and distress properties. The primary response properties define the response of the layer materials to the given loads and environments. These properties are in the form of elastic or viscoelastic characteristics which may exhibit non-linear behavior because of previous load histories, plastic effects and stress dependencies. The distress properties are those properties defining the capability of the material to withstand the imposed loads. They are presented in terms of relationships determined from special laboratory tests simulating the stress and environmental conditions anticipated in the structure being analyzed.

The material properties used in the VESYS program are given in Table 5.1 along with the test conditions necessary for their determination. Two laboratory test procedures entitled:

- (a) Incremental Static-Dynamic, and
- (b) Flexural Fatigue

are described in this Chapter (see Note 5.1). The Flexural Fatigue Test is conducted on beam specimens for determination of the fatigue properties. Other procedures as outlined in Table 5.1 may be used where local conditions dictate specific fatigue conditions. The Incremental Static-Dynamic Test is described for use on 4-inch diameter by 8-inch tall specimens for determination of both the primary response properties (creep or elastic compliance) and the permanent deformation properties using the results from the incremental static tests. Details of the test equipment and specimen preparation are also given. A short description of the characteristics of the categories of input properties is given below:

A. Modular Creep Compliance

The primary response properties require determination of the creep compliance function for rate-dependent materials and elastic compliance (see Note 5.2) for rate-independent materials. The rate-dependent properties are obtained by conducting creep tests. Input to the VESYS program for primary response requires only use of the 1,000-second creep test from the "incremental static test series." Values of the creep compliance, as described by equation (5.1), are plotted versus time on log-log paper:

$$D(t) = \frac{\epsilon_{zz}(t)}{\sigma_{zz} - 2\mu(t)\sigma_{rr}} \quad (5.1)$$

where $D(t)$ = modular creep compliance function

σ_{zz} = axial load in a tension or compression test
with or without confinement pressure,
 σ_{rr} = confinement pressure,
 ϵ_{zz} = axial strain
 $\mu(t)$ = Poisson's ratio

Care should be taken in testing materials to assure that test results reflect the effects of stress state, temperature, moisture content and conditions corresponding to those of the in situ pavement. When asphalt concrete samples are tested, a sufficient number of tests at different temperatures are run to establish the master creep compliance curves and hence the time-temperature shift parameters.

For fine-grained soils or granular base type materials, creep compliance curves should be determined for specimens at different moisture contents and densities.

B. Permanent Deformation Properties

The permanent deformation properties μ_i and α_i for each layer $i = 1, 2, 3$ are described by equation (28) of Appendix A. These properties are obtained by conducting the Incremental Static-Dynamic Test on 4-inch diameter by 8-inch tall cylindrical specimens. Since these properties are dependent on in situ stress conditions and local environments, they should be determined on specimens subjected to realistic in situ stress states and at the average moisture content and temperatures expected in the field. The properties are computed from the dynamic series results for all materials or from the simplified incremental static series results for bituminous and fine-grained soils; i.e., materials which exhibit predominant amounts of viscous flow.

C. Fatigue Characteristics

The fatigue properties are represented by the parameters K_1 and K_2 described by Equation 3.17 of Chapter 3. These properties are obtained by conducting repeated flexure tests on beam specimens at bituminous mixes at various temperatures and mix-void contents.

5.2 APPLICABLE DOCUMENTS

ASTM C 617 Capping Cylindrical Concrete Specimens

- ASTM D 1559, AASHTO T 245 Standard Method of Test for Resistance to Plastic Flow of Bituminous Mixture, Using Marshall Apparatus
- ASTM D 1560, AASHTO T 246 Cohesion of Bituminous Mixtures by Means of the Hveem Apparatus
- ASTM D 1561, AASHTO T 247 Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
- ASTM D 1663 Standard Specification for Hot-Mixed, Hot-Laid Asphalt Paving Mixtures
- ASTM D 1/ Standard Method for Preparation of Bituminous Mixture Cylindrical Specimens
- ASTM D 1/ Standard Method for Test for Dynamic Modulus of Asphalt Mixtures
- ASTM D 3202 Standard Recommended Practice for Preparation of Bituminous Mixture Beam Specimen by Means of the California Kneading Compactor
- ASTM D 1557, AASHTO T 180 Method D Standard Methods of Test for Moisture-Density Relations of Soils Using 10-Pound (4.5 kg) Rammer and 18-Inch (457 mm) Drop
- AASHTO T 212 Determination of Tri-axial Classification of Base Materials, Soils, and Soil Mixtures (1971 specifications)
- ASTM D 2940 Standard Specifications for Graded Aggregate Material for Bases or Subbases for Highways or Airports
- ASTM D 698, AASHTO T 99 Standard Methods of Test for Moisture-Density Relations of Soils Using 5.5-Pound (2.5 kg) Rammer and 12-Inch (304.8 mm) Drop.
- ASTM D 1632 Standard Method of Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory
- ASTM D 559, AASHTO T 135 Standard Methods for Wetting-and Drying Tests of Compacted Soil-Cement Mixtures.

ASTM D 560, AASHTO T 136 Standard Method for Freezing-and Thawing Tests of Compacted Soil-Cement Mixtures.

ASTM D 558, AASHTO T 135 Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures.

5.3 PREPARATION OF CYLINDRICAL SPECIMENS FOR DIRECT COMPRESSION TESTING

5.3.1 Laboratory-Molded Bituminous Mixtures

1. Design the mix for binder content, density and voids in accordance with current practice.

2. Prepare the mixture in accordance with ASTM Method D 1560.

3. Prepare specimens in accordance with ASTM D 1561 with the following exceptions:

The height-to-diameter ratio should be 2 to 1 with a minimum diameter of 4 inches. The diameter should be at least four times the maximum nominal size of aggregate particles.

4. Use at least two of the three methods below to produce two different specimen air void contents to bracket the range in air void contents expected in the field (two specimens at each air void content).

a. Low compactive effort - 60 tamping blows with 175 psi compactor foot pressure with mold locked in place and shims in place; 250 psi static load, double plunger method, applied at a rate of .05 inches per minute.

b. Intermediate compactive effort - 60 tamping blows with 250 psi compactor foot pressure; 1,000 psi static load, double plunger method.

c. High compactive effort - 60 tamping blows with 250 psi compactor foot pressure followed by 100 tamping blows with 500 psi compactor foot pressure; 1,000 psi static load, double plunger method, applied at a rate of .05 inches per minute.

The mix at a temperature of 230°F is fed continuously and uniformly into the mold as the first 60 tamping blows are applied. The static load compaction immediately follows the kneading compaction except for 4c in which case the 100 blows at 500 psi follow immediately after the 60 blows and prior to the application of the static load.

The high compactive effort produces specimen densities approximately the same or slightly higher than obtained from Marshall Method (75-blow) or Standard California Kneading Compaction. The intermediate compaction level results in densities slightly lower than those obtained from the 50-blow Marshall Method. These compaction procedures are applicable to dense-graded asphalt concrete mixtures.

5.3.2 Fine-Grained Soils

1. Moisture-Density Relationship.

a. Establish the moisture-density relationship for the soil according to ASTM D 698 (AASHTO T-99) procedures and prepare a graph showing dry density and water content.

b. Determine the specific gravity of the soil according to ASTM D 854.

c. Use the data obtained in Steps a and b to determine dry density at 100 and 80 percent of saturation at various densities. Place this information on the graph drawn in Step a, that is, draw 100 and 80 percent saturation lines.

$$Y_d = \frac{GY_w}{1 + (wG/S)} \quad (5.2)$$

where Y_d = unit weight of dry soil, pounds per cubic foot
(kilograms per cubic meter)

Y_w = unit weight of water, pounds per cubic foot
(kilograms per cubic meter)

G = specific gravity of soil

w = water content of soil, percent

S = degree of saturation, percent

2. Prepare the soil for compaction following the procedure outlined in reference (11), page 155, paragraph III.

3. Compaction of Test Specimens.

a. Selection of moisture contents.

Three different moisture-density specimens, for expected field conditions, should be prepared and at least one of the specimens should be at the optimum moisture and maximum dry

density. An upper and lower moisture limit should then be established. In some instances the optimum moisture may be the lower limit. The actual moistures to be used can only be determined from a knowledge of past estimates of subgrade moisture variabilities and drainage control measures anticipated for the new construction.

b. Selection of compaction method.

Laboratory compaction processes should be selected in accordance with the expected field compaction conditions. Compaction processes which cause shearing deformation in a clay soil of degree of saturation greater than 80 percent tend to result in a dispersed (or parallel) clay structure. Clays with a dispersed structure exhibit greater deformation than would the same soil with a flocculated structure when both are tested under identical conditions. Some general criteria that can be used to guide selection of the appropriate compaction conditions for clay soils are:

(1) If the field compaction conditions will be at a water content corresponding to less than 80 percent of the saturation water content and the in-service water content is expected to remain less than the 80 percent saturation value, then any of the standard impact, gyratory, kneading, or static procedures may be used to simulate the in-service condition.

(2) If the field compaction will be at a water content corresponding to greater than 80 percent of the saturation water content and the in-service water content is expected to remain greater than the 80 percent saturation value, then the compaction process must be of the shearing type; that is, one of impact, gyratory, or kneading to simulate the dispersed structure in service.

(3) If the field compaction conditions will be at a water content corresponding to less than 80 percent of the saturation water content and the in-service conditions are expected to be at a degree of saturation greater than 80 percent, then static compaction should be used to simulate the fluctuated structure in service.

For the above conditions use the following procedures for compacting 4-inch diameter x 8-inch tall specimens:

Impact - Ref (11), page 156, para. IV, or ASTM D 698

Kneading - Ref (11), page 156, para. IV, or ASTM D 2844

Static - Ref (11), page 156, para. V.

5.3.3 Untreated Granular Materials

1. Applicable Materials.

The procedures outlined refer to quality-controlled graded aggregates that, when hauled to and properly spread and compacted on a prepared grade to appropriate density standards, may be expected to provide adequate stability and load support for use as highway or airport bases or subbases. Those materials should meet the requirements of the ASTM standard specifications D 2940-74 "Graded Aggregate Material for Bases or Subbases for Highways or Airports." Top size aggregate in these specifications is 100 percent passing the 2-inch sieve. The processing of other bases such as "Iowa Macadam" or "Ballast" with top sizes up to 4 inches is not included in this manual at this time.

2. Moisture-Density.

a. Establish the moisture-density relationship for the aggregate gradation expected to occur in the field according to ASTM D 1557 Method D (plus 3/4 inch removed) and prepare a graph showing dry density and water content.

- b. Report:
- (a) maximum dry density in pounds per cubic foot
 - (b) optimum moisture percent.

3. Preparation of Aggregate for Compaction (12).

a. Obtain representative aggregate from separated sizes of the given material to obtain the gradation specified in 2a.

b. Determine a sufficient aggregate weight so that after compaction a specimen of 4 or 6 inches in diameter by 8 or 12 inches high, respectively, can be obtained. Specimen diameter should not be less than two times the maximum nominal size of an aggregate particle.

c. Add the desired amount of water to the course aggregate portion (plus No. 4) to obtain specimens at the optimum moisture content obtained in 2a.

d. After mixing for 1 minute, add the fine portion, blend until a uniform mixture is obtained and allow to stand for 5-10 minutes.

4. Compaction.

a. Three levels of compaction or density are desirable; however, at least Low and High density specimens should be

prepared (two specimens at each density level). The High and Low densities should approximate the upper and lower limits of densities which are expected in the field during pavement service life.

b. For open-graded mixtures, use a split mold lined with a thin latex membrane.

c. Prepare High density specimens using the mechanical compaction effort described in AASHTO Method T212. Apply supplemental vibratory compaction for 30 seconds with an electromagnetic hammer to finish the surface while the material is still in the mold.

d. Prepare Low density specimens using the mechanical compaction effort described in ASTM D 698 (six lifts for 12-inch high specimens).

e. One specimen of each density level should be tested at two or three moisture levels:

1. Moisture level 1 (optimum).
2. Moisture level 2 (partially saturated).
3. Moisture level 3 (fully saturated).

The engineer should decide which levels of moisture will predominate in in-service conditions:

(1) For Moisture level 1, the specimens obtained in Step 4 are stored at room temperature.

(2) For Moisture level 2 (partially saturated condition), store specimens in a concrete moist curing room with the bottom porous stone immersed in water.

(3) For Moisture level 3 (fully saturated), specimen must be subjected to free water during the test (12).

5.3.4 Cement Treated Soils

1. Applicable Materials.

The procedures outlined refer to any combination of the soil separates: crushed stone, gravel, sand, silt, clay, cinders, slag, etc. The soil should not have more than 45 percent material retained on the No. 4 sieve or any material particle greater than 2 inches in diameter.

2. Mix Design.

a. Select cement contents by weight in accordance with reference (13), page 17.

b. For the mean cement content found above, calculate the batch weights of soil and cement needed for at least four moisture density test trials, in accordance with reference (13), page 17.

c. Establish the moisture-density relationship for the soil cement mix in accordance with ASTM Designation D 558 or AASHTO Designation T 134.

d. Select maximum density and optimum moisture content for the mean cement content mix.

e. Determine the minimum amount of cement required to harden the mix properly by conducting wet-dry - freeze-thaw tests on specimens molded at different cement contents in accordance with reference (13), page 22.

f. Test for wet-dry and freeze-thaw in accordance with ASTM Designation D 559 and D 560 or AASHTO Designations T 135 and T 136.

3. Preparation of Test Specimens.

a. In accordance with the above procedures and from past experience, estimate the mean cement content (but not less than f), the moisture content and density which are expected to occur in the field throughout the pavement's tolerable service life.

b. Estimate the variation of density and moisture which is expected to occur in the field throughout the pavement's service life.

c. For the cement content determined in a, mold at least one specimen for each level of moisture-density (the mean value and the upper and lower limits of moisture density expected in the field). Use ASTM D 1632 for making soil-cement compression specimens of 4 inches diameter and preferably 8 inches high.

d. Store specimens at room temperature in 100 percent humidity for at least 28 days (do not soak in water).

5.4 PREPARATION OF BEAM SPECIMENS FOR FLEXURE TESTING

5.4.1 Bituminous Mixtures

Beam specimens 15 inches long with 3 1/2-inch depths and 3 1/4-inch widths are prepared according to the ASTM D

3202 Standard Recommended Practice for Preparation of Bituminous Mixture Beam Specimens by Means of the California Kneading Compactor. If there is undue movement of the mixture under the compactor foot during beam compaction, temperature, foot pressure, and number of tamping blows should be reduced. Similar modifications to compaction procedures should be made if specimens with less density are desired. A Diamond blade masonry saw is used to cut 3 inches or slightly less deep, 3 inches or slightly less wide test specimens from the 15-inch long beams. Specimens with suitable dimensions may also be cut from pavement samples. The widths and depths of the specimens are measured to the nearest 0.01 inch at the center, and at 2 inches on both sides of the center. Mean values are determined and used for subsequent calculations.

5.5 EQUIPMENT FOR DIRECT COMPRESSION TESTING OF CYLINDRICAL SPECIMENS

5.5.1 Test Machine

1. An electrohydraulic testing machine capable of applying up to 3,000 pounds and producing either haversine or ramp hold wave forms. The machine should have the capability of attaining the ramp peak load through frequency control in .03 second or the haversine load for at least a .1-second duration of loading. The machine should have the capability of applying any number of load repetitions (frequency control between 1 and 50 cps minimum), however, with additional controls for eliminating intermediate pulses to provide rest periods (time of no load) between pulses.

2. An old consolidation device capable of applying up to 300 pounds and which has been modified with a quick release lever arm may be equally suitable for determination of the primary response property (creep test) of all materials and the permanent deformation properties (incremental creep test) of those materials exhibiting predominant amounts of viscous flow such as asphalt-bound materials and fine-grained materials with moisture contents at optimum and above.

5.5.2 Temperature Control System

The temperature control system should be capable of maintaining the sample at the required test temperature range of 32°F (0°C) to 120°F (50°C) \pm 1°F (.5°C). An insulated test chamber should be constructed around the test setup for asphalt concrete specimens. It is not necessary to test asphalt concrete in the triaxial cell.

5.5.3 Triaxial Test Cell

A triaxial cell suitable for use in testing cylindrical specimens is shown in Figure 5.1. This equipment is similar

to most standard cells except that it is somewhat larger, to facilitate the internally mounted load and deformation measuring equipment, and has additional outlets for the electrical leads from the measuring devices. (Triaxial cells with suitable externally mounted load and deformation measuring equipment also may be used.) For the type of equipment shown, air is used as the cell fluid.

5.5.4 Measurement System

The measurement system consists of a three-channel recorder, load and deformation measuring devices, and suitable signal amplification and excitation equipment. The measurement system shall have the capability of measuring and recording loads up to 3,000 pounds (13.3 kN). This system should also be capable of measuring and recording deformations from 300 to 5,000 micro units of strain and have adequate sensitivity control to produce full-scale recorder output over this range. At the highest sensitivity setting, the system should be able to display 4 micro strain units or less per millimeter on the recorder chart (with minimal noise).

5.5.5 Deformation and Load Measurement Equipment

The deformation measuring equipment consists of Linear Variable Differential Transformers (LVDTs)** attached to the specimen by a pair of clamps. Two LVDTs are used for the measurement of axial deformation. The clamps and LVDTs are shown in position on specimen in Figure 5.1. Details of the clamps are shown in Figure 5.2. Monitor both the load and axial deformation using both LVDTs during all tests.

Preferably, load is measured by placing a load cell between the sample and the loading piston as shown in Figure 5.1.

Use of the internal measuring equipment (sample mounted LVDTs) described above offers several advantages over use of external measuring equipment:

(a) The effect of equipment deformation during testing is not included in the results.

(b) The effect of end cap restraint on soil response is virtually eliminated.

(c) Any effect of piston friction is eliminated by measuring loads at the caps of the samples.

**Type 100-M-H or Type 100 DCD 292 Linear Variable Differential Transformers manufactured by Schevitz Engineering, U.S. Route 130 & Union Avenue, Pennsauken, N.J., have been found suitable for this purpose.

In addition to the measuring devices, it is necessary that suitable signal excitation, conditioning, and recording equipment be available. It is required that simultaneous recording of load and deformation be made and desired that these two items be displayed contiguously.

5.6 EQUIPMENT FOR FLEXURE TESTING OF BEAMS

The repeated flexure apparatus is shown in Figure 5.3. It accommodates beam specimens 15 inches long with widths and depths not exceeding 3 inches. A 3,000-pound capacity electrohydraulic testing machine manufactured by Materials Testing Systems (MTS) capable of applying repeated tension-compression loads in the form of haversine waves for 0.1 second duration with 0.4-second rest periods has been used with success. Any suitable dynamic testing machine or pneumatic pressure system with similar loading capabilities is also acceptable. The two-point loading configuration, theoretically applies a constant bending moment over the center 4 inches of a 15-inch long beam specimen.

A sufficient load, approximately 10 percent of the load deflecting the beam upward, is applied in the opposite direction, forcing the beam to return to its original horizontal position and holding it at that position during the rest period. Adjustable stop nuts installed on the flexure apparatus loading rod prevent the beam from bending below the initial horizontal position during the rest period.

The dynamic deflection of the beam at mid-span is measured with a linear variable differential transformer (LVDT). An LVDT that has been found suitable is Schaevitz type 100 M-H. The LVDT core is attached to a nut bonded with epoxy cement to the center of the specimen. Outputs of the LVDT, and the electric-hydraulic testing machine's load cell through which loads are applied and controlled, are fed to any suitable recorder. The repeated flexure apparatus is enclosed in a controlled temperature cabinet capable of controlling temperatures with $\pm 1/2$ °F. A Missimer's model 100 x 500 CO plug in temperature conditioner has been found to provide suitable temperature control.

5.7 INCREMENTAL STATIC-DYNAMIC TEST, DIRECT COMPRESSION

5.7.1 Bituminous Mixtures

1. Place test specimens in the controlled temperature cabinet and bring it to the specified test temperature at 70°F (21°C). Center the specimen under the loading apparatus in the controlled temperature cabinets.

2. Extend the lower LVDT clamp and slide it carefully down over the specimen to approximately the lower quarter

point of the specimen. Repeat for the upper clamp, placing it at the upper quarter point. Ensure that both clamps lie in horizontal planes and that the holes in the clamps are properly aligned. Place the precalibrated LVDTs into position in the clamps. Connect the LVDTs to the recording unit and balance the recording bridges. This will require recorder adjustments and adjustment of the LVDT stems. When a recording bridge balance has been obtained, determine to the nearest 0.01 inch (0.25 mm), the vertical spacing between the LVDT clamps and record this value. Put the hardened steel disc on top of the specimen and center under the load cell. Adjust and balance the electronic measuring system as necessary.

3. For conditioning, apply tow ramp loads and hold each peak load for 10 minutes duration, with minimal unload time between the two loads, at the test load to be used in Step 4. A third conditioning load is then applied for 10 minutes followed by a 10-minute unload period; re-zero LVDTs.

4. Incremental Static Loading

a. Apply one ramp load of 20 psi to the specimen as quickly as possible and hold loading for 0.1 second. Release the load and measure total permanent deformation after 2 minutes of unload. See Figure 5.4 for a description of the loading function. If the deformation under load starts to exceed 2,500 micro units of strain, immediately reduce the maximum stress level by 5 psi. If the deformation starts to exceed 2,500 micro strain, then reduce the stress level by another 5 psi. Wait 30 minutes and repeat Step 4a at this level.

b. Apply a second ramp load to the specimen at the same stress level used above and hold for 1 second. Release the load and measure the total permanent deformation after 2 minutes of unload.

c. Apply a third ramp load to the specimen at the level used in 4a and hold for 10 seconds. Release the load and measure the total permanent deformation after 2 minutes of unload or when rebound becomes negligible.

d. Apply a fourth ramp load to the specimen at the level used in 4a above and hold for 100 seconds. Release the load and measure the total permanent deformation remaining after 4 minutes of unload or when rebound becomes negligible.

5. Apply a fifth ramp load to the specimen at the level used in 4a above and hold for 1,000 seconds. Measure the magnitude of the creep deformation during loading after

.03, 0.1, 0.3, 1.0, 3.0, 10.0, 30.0, 100.0 and 1,000.0 seconds. Release the load and measure the total permanent deformation after 8 minutes of unload or when rebound becomes negligible.

6. Re-zero LVDTs.

7. Apply repeated haversine loading to the specimen at 70°F (21°C) such that each load application has a magnitude equal to the stress level used in 4a above and each load application has a load duration of a 0.1 second. A 0.9-second rest period follows each load application. Apply a minimum of 100,000 load applications and measure the accumulated deformation at 1, 10, 100, 200, 1,000, 10,000 and 100,000 repetitions (see Note 5.3). Read the peak-to-peak strain (ϵ) at the 200th cycle.

8. Release the load after 100,000 repetitions, record the rebound after 15 minutes and remove the specimen.

9. Using new specimens (at least two per temperature level), repeat Steps 1 through 8 for 40°F and 100°F temperatures. Note that the 100°F level loads may have to be decreased in accordance with Table 5.2 (see Note 5.4).

10. Repeat Steps 1 through 9 for at least two additional void contents to establish (one above and below) the values at the upper and lower tolerance levels. This step may be omitted provided the variation of the material property with void content, as it exists in the field, is known (see example in Chapter 6).

11. Calculate Creep Compliance.

a. Use the 1,000-second response curve (Step 5 above) to obtain this value. Consider the specimen deformation to be zero at the beginning of the 1,000-second load application.

b. For each specimen tested and for each LVDT, calculate the axial deformation, $\delta(t)$ in inches at the times specified in Step 5.

c. Average the two LVDT deformations for each specimen at each time given in Step 5.

d. Calculate axial strain at the times in Step 5:

$$\epsilon(t) = \frac{\delta(t)}{G} \quad (5.3)$$

where $\epsilon(t)$ = axial strain
G = gage length between LVDTs usually 4 inches

e. Calculate Creep Compliance $D(t)$ at the times in Step 5:

$$D(t) = \frac{\epsilon(t)}{\sigma_0} \quad (5.4)$$

where $\sigma_0 = \frac{\text{Applied Load in Pounds}}{\text{Cross Sectional Area of Specimen}}$

f. Construct an average curve (very smooth) of $D(t)$ versus time on log-log paper of the high, mean and low compliance for each void content and temperature level. Extrapolate the curves backward to obtain values of $D(t)$ at .001, .003 and .01 seconds.

g. Compute the coefficient of variation of $D(t)$, due to the different void contents, for a given temperature series at the times .1, 10 and 100 seconds:

$$V_{D_i} = \frac{1}{3} \sum \frac{D_i}{\bar{D}_i} \quad i = 1, 2, 3 \quad (5.5)$$

where V_{D_i} = coefficient of variation at time i

D_i = standard deviation at time i

\bar{D}_i = mean at time i

12. Report Creep Compliance.

a. Report the time at which $D(t)$ was calculated in g above: TSTATIC .001, .003, .02, .1, .3, 1, 3, 10, 30, 100, 1,000 (see Figure 5.5, page 93).

b. Report the mean values of $D(t)$, i.e., $\bar{D}(t)$ at 70°F, for each TSTATIC: (see Figure 5.5, page 93).

LAYER1

(Here it is assumed that the top layer, i.e., layer 1, is composed of asphaltic materials)

c. Report the coefficient of variation of $D(t)$ at 70°F for the spread in void contents:

VARCOEF1

(See the example in Chapter 6.)

13. Calculate Permanent Deformation Properties

Alternate Procedure I

a. Calculate the permanent deformation properties of layer 1 using the results of the Dynamic Series of the Incremental Static-Dynamic Test.

b. Calculate the accumulated strain at 1, 10, 100, 1,000, 10,000 and 100,000 repetitions.

c. Plot the accumulated strain versus number of repetitions on log-log paper.

d. Construct a best-fit straight line through the points plotted and intersecting the vertical axis at one repetition. The value of ϵ_p at this intersection is denoted by I and the slope S (record using Figure 5.5 Dynamic).

e. Measure the strain amplitude at the 200th load repetition. This is denoted as e.

f. Calculate the permanent deformation properties of layer 1 material:

$$\mu_1 = \frac{IS}{e} \quad (5.6)$$

$$\alpha_1 = 1 - S \quad (5.7)$$

g. Report these properties for layer 1 as:

$$\begin{array}{l} \text{ALPHA } \underline{X}, \underline{\quad}, \underline{\quad} \\ \text{GNU } \underline{\underline{X}}, \underline{\underline{\quad}}, \underline{\underline{\quad}} \end{array}$$

where X denotes the determined value for layer 1.

Alternate Simplified Procedure II

a. Calculate the permanent deformation properties of layer 1 using the results of the Incremental Static Test series.

b. Calculate the total permanent strain at the end of each rest period as shown in Figure 5.4.

$$\epsilon_{a_n} = \sum_{i=1}^n \epsilon_{P_i} \quad (5.8)$$

c. Plot the total permanent strain ϵ_a versus the incremental time of loading ($t_{n+1} - t_n$) as shown in Figure 5.3 on log-log paper.

d. Construct a best-fit straight line through the points plotted and intersecting the vertical axis at one repetition. The value of ϵ^a at this intersection is denoted by I and the slope by S.

e. Calculate the permanent deformation properties of layer 1 material as in Procedure I, Step f.

f. Report these properties for layer 1 as in Procedure I, Step g.

5.7.2 Fine-Grained Materials

1. Place the triaxial cell base assembly on the platform of the loading machine.

2. Carefully place the specimen on the sample base. (Porous stones are not necessary for the testing of clay soils.)

3. Place the sample cap on the specimen.

4. Stretch a membrane tightly over the interior surface of the membrane stretcher. Slip the stretched membrane carefully over the specimen. Roll the membrane off the stretcher onto the sample base and cap. Remove the stretcher. Place O-ring seals around the base and cap.

5. Connect the vacuum/saturation line to the vacuum source through a bubble chamber (a vacuum of 5 to 10 psi is generally adequate). If bubbles are present, check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. This is essential for use of the clamp-mounted LVDTs. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with a rubber latex or by use of a second membrane.

6. When leakage has been eliminated, disconnect the vacuum supply. Leave vacuum/saturation inlet open to the atmosphere.

7. Connect LVDT's in accordance with Article 5.7.1, Step 2.

8. Place the triaxial chamber into position. Set the load cell in place on the sample cap.

9. Place the cover plate on the chamber. Insert the loading piston, obtaining a firm connection with the load cell.

10. Tighten the tie rods firmly.

11. Slide the assembled apparatus into position under the axial loading device. Bring the device to a position where it nearly contacts the loading position.

The confining pressure and deviator stress used should approximate the expected in-place state of stresses. A confining pressure of 3 psi and deviator stress of 6 psi are reasonable values for most testing.

12. Connect the chamber pressure supply line and apply the confining pressure (equal to the chamber pressure).

13. Rebalance the recording bridges for the LVDTs and balance the load cell recording bridge.

14. Follow Steps 3 through 7 of Article 5.7.1 except that a deviator load of 6 psi and a chamber pressure of 3 psi are used, ignore temperature requirements.

15. Remove specimen and determine water content.

16. Repeat Steps 1 through 15 for specimens at two other moisture contents expected in the field.

17. Calculations and report values are similar to Steps 11 through 13 of Article 5.7.1.

5.7.3 Untreated Granular Materials

Conduct tests in an identical manner as outlined in Article 5.7.2 for fine-grained material except that:

1. Porous stones are used, for open-graded mixtures, on top and bottom of the specimen. For the partially saturated tests, place the bottom porous stone in a depth of water the height of the stone and allow free drainage to take place from both top and bottom of the porous stones.

2. Apply 10 psi confining pressure (see Note 5.5).

3. Use a deviator stress of 20 psi (see Note 5.5).

4. Report granular material properties for layer 2 appropriately as:

LAYER2 ___ ___ ___ ___ ___
VARCOEF2 ___
ALPHA ___ X ___
GNU ___ X ___

5.7.4 Soil Cement Materials

Conduct tests in an identical manner as outlined in Article 5.7.2 for fine-grained material except that:

1. Apply 10 psi confining pressure (see Note 5.5).
2. Use a deviator stress of 20 psi (see Note 5.5).

5.8 FLEXURE FATIGUE TEST ON BEAMS

Laboratory procedures for determination of the fatigue life of an asphalt paving mixture containing aggregate with maximum sizes up to 1 1/2 inches are described in the following sections. The fatigue life of a simply supported beam specimen subjected to two symmetrical concentrated loads applied at the one-third points is determined from controlled stress mode flexural fatigue tests.

1. Repeated flexure apparatus loading clamps are adjusted to the same deviation as the reaction clamps. The specimen is clamped in the fixture using a jig to position the centers of the two loading clamps 2 inches from beam center. Double layers of Teflon sheets are placed between the specimen and the loading points to reduce friction and longitudinal restraint caused by the clamps.

2. After the beam has reached desired test temperature, repeated loads are applied. Duration of a load application is 0.1 second with 0.4-second rest periods between loads. The applied load should be that which produces an extreme fiber stress level suitable for flexural fatigue tests. For fatigue tests on typical bituminous concrete paving mixtures, the following ranges of extreme fiber stress levels are suggested:

55°F - 150 to 450 psi
70°F - 75 to 300 psi
85°F - 35 to 200 psi

3. The beam center point deflection and applied dynamic load are measured immediately after 200 load applications for calculation of extreme fiber strain. The test is continued at the constant stress level until the specimen fractures. The apparatus and procedures described have been found suitable for flexural fatigue tests at temperatures ranging from 400°F to 100°F and for extreme fiber stress levels up to 450 psi. Extreme fiber stress levels for flexural fatigue tests at any temperature should not exceed that which causes specimen fracture before at least 1,000 loads are applied. A set of 8 to 12 fatigue tests should be run for each temperature

to adequately describe the relationship between extreme fiber strain and the number of load applications to fracture. The extreme fiber stress should be varied such that the resulting number of load applications to fracture ranges from 1,000 to 1,000,000.

4. Evaluate initial strain amplitude for each specimen:

$$e = \frac{12 td}{3(l^2 - 4a^2)} \quad (5.9)$$

where,

- e = extreme fiber strain at 200 repetitions
- a = 1/2 (reaction span length -4), inches
- t = specimen depth, inches
- d = dynamic deflection of beam center, inches at 200 repetitions
- l = reaction span length, inches

Record the number of repetitions to failure N_f for each specimen tested.

5. Plot values of e versus number of repetitions to failure N_f on log-log paper.

6. Construct a straight line representing a mean through the points plotted. The absolute value of the slope of the straight line is S. The highest value of strain on this line is denoted by I, and the corresponding lowest number of repetitions to failure is N_0 .

7. Calculate the mean values of fatigue properties:

$$\bar{K}_2 = \frac{1}{S} \quad (5.10)$$

$$\bar{K}_1 = N_0(I)^{1/S} \quad (5.11)$$

8. Report:

$$\text{STRNEXP} = \bar{K}_2$$

$$\text{STRNCOEF} = \bar{K}_1$$

9. If all of the points on a plot of e versus N_f lie on the mean line, report the probabilistic fatigue parameters as follows:

$$\text{COEFK1} = 0$$

$$\text{COEFK2} = 0$$

$$\text{K1K2CORL} = -1$$

If the points exhibit scatter about the mean, draw a number of lines through the points and calculate a set of fatigue properties ($K1_i$ and $K2_i$) for each of the (n) lines. Report:

$$\text{COEFK1} = S_{K1}/\bar{K1}$$

$$\text{COEFK2} = S_{K2}/\bar{K2}$$

$$\text{K1K2CORL} = \frac{1}{n} \sum_{i=1}^n \frac{K1_i - \bar{K1}}{S_{K1}} \frac{K2_i - \bar{K2}}{S_{K2}}$$

$$\text{where: } S_{K1}^2 = \frac{1}{n} \sum_{i=1}^n K1_i^2 - n\bar{K1}^2$$

$$S_{K2}^2 = \frac{1}{n} \sum_{i=1}^n K2_i^2 - n\bar{K2}^2$$

(See NOTE 5.6 for suggested probabilistic fatigue inputs.)

In lieu of conducting flexural fatigue tests over the range of temperatures expected to occur in the field, all tests may be run at 70°F and the following procedures may be used in conjunction with Figures 5.6 and 5.7 to estimate the properties for other temperatures.

1. Construct a vertical line from the temperature of interest to the line plotted.
2. Construct a horizontal line from this intersection to the vertical axis.
3. Multiply the resulting number on this scale, times the value determined from tests at 70°F to estimate the fatigue property at the temperature of interest.

NOTES FOR CHAPTER 5

- NOTE 5.1 - Indirect tensile test procedures will be included as they are developed.
- NOTE 5.2 - The elastic compliance represents materials essentially elastic in nature such as cement-treated materials, open-graded granular materials, and fine-grained materials below optimum moisture content. The creep curve $D(t)$ is essentially a horizontal straight line. Its value, the elastic compliance, has an inverse equivalent to the Resilient, Dynamic or Magnitude of Complex Modulus. It can be estimated from the creep curve at .03 seconds provided the compliance is not highly dependent on time of loading as with bituminous concrete at high temperatures.
- NOTE 5.3 - Step 7 may be omitted if dynamic equipment is not available. In this case the permanent deformation properties are determined from the simplified procedure using results of the Incremental Static Test series.
- NOTE 5.4 - Step 9 may eventually be omitted when the appropriate temperature shift factor is known. Some standard values of are given in Table 6.6.
- NOTE 5.5 - The states of stress specified in this document are those which research indicates to be reasonably representative of those occurring in pavement structures.
- NOTE 5.6 - Suggested values for the probabilistic fatigue inputs are the following:
- COEFK1 = 0.48
- COEFK2 = 0.07
- K1K2CORL = (-0.867)

TABLE 5.1 - TEST TYPES FOR DETERMINING MATERIALS PROPERTIES
FOR INPUT TO VESYS IIM

TEST DESCRIPTION		MATERIAL PROPERTIES DETERMINED FOR EACH LAYER i		
BOUNDARY CONDITIONS	TYPE LOADING	CREEP COMPLIANCE $D(t)_i, i = 1,2,3$	PERMANENT DEFORMATION $\mu_i, \alpha_i, i = 1,2,3$	FATIGUE $K_1, K_2, i=1$
DIRECT COMPRESSION CYLINDER	DYNAMIC		X	
	INCREMENTAL STATIC- DYNAMIC	X	X	
* INDIRECT TENSION CYLINDER, CORE	DYNAMIC		X	X
	INCREMENTAL STATIC- DYNAMIC	X	X	X
FLEXURE BEAM	DYNAMIC ONLY			X

* Procedure is not included in this version of the manual

TABLE 5.2 - LIMITING STRAIN LEVELS FOR CONSISTENT RESULTS*

TEMPERATURE = 40⁰F

Results are similar for stress levels and stress states

TEMPERATURE = 70⁰F

<u>Type of Test</u>	<u>Limiting Strain Levels - micro inches per inch</u>
Unconfined	Axial tensile strains = 200 Axial compressive strains = 1200
Confined and Unconfined	Axial compressive strains = 300 Radial tensile strains = 25

TEMPERATURE = 100⁰F

<u>Type of Test</u>	<u>Limiting Strain Levels - micro inches per inch</u>
Unconfined	Axial tensile strains = 250 Axial compressive strains = 600
Confined and Unconfined	Axial compressive strains = 270 Radial tensile strains = 30

CONCLUSION

If the axial compressive strains are kept below 270 $\mu\text{in/in}$, the results are independent of the test method.

* For determination of Viscoelastic Functions
(From MR&D Final Report, Contract FH-11-7319)

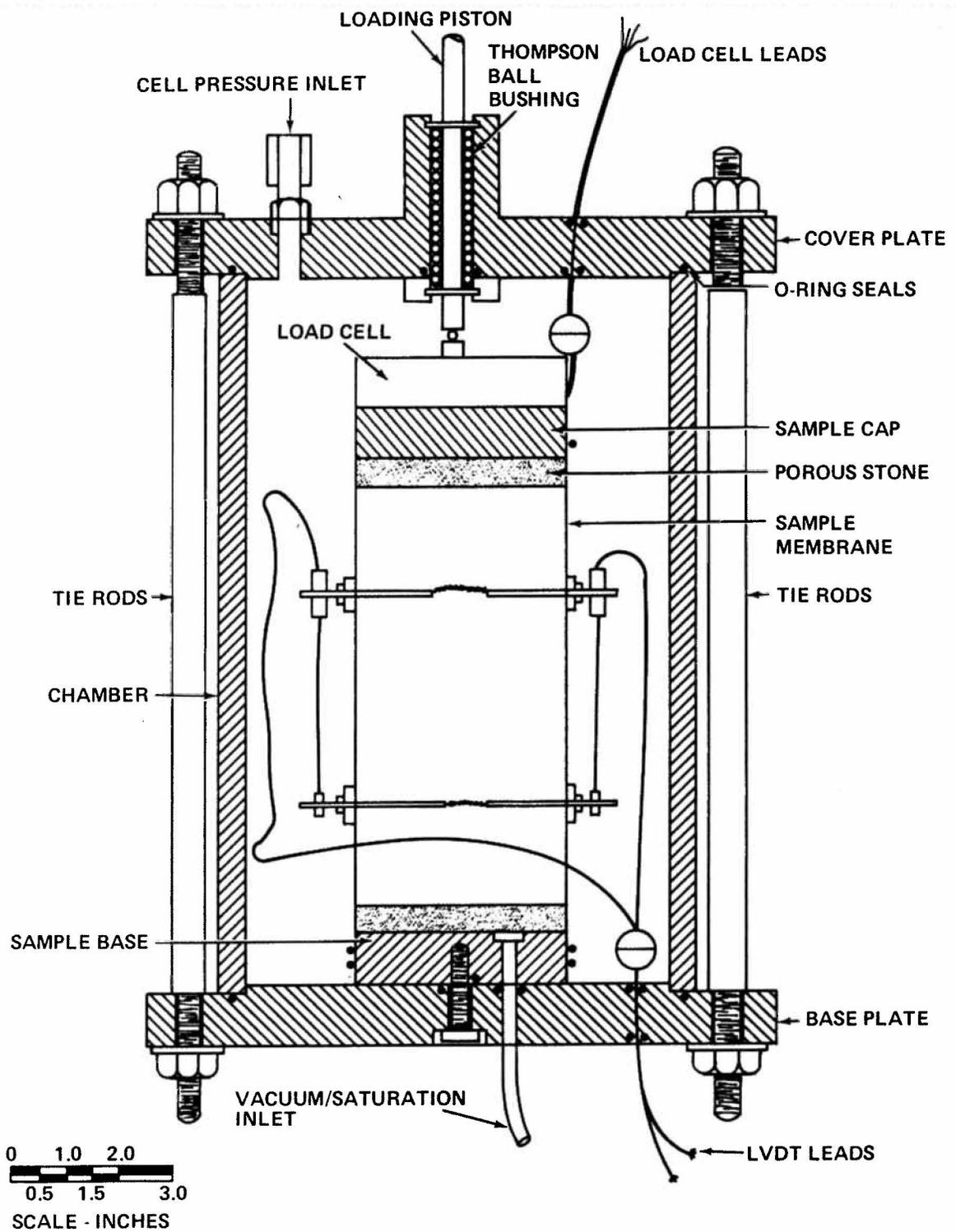
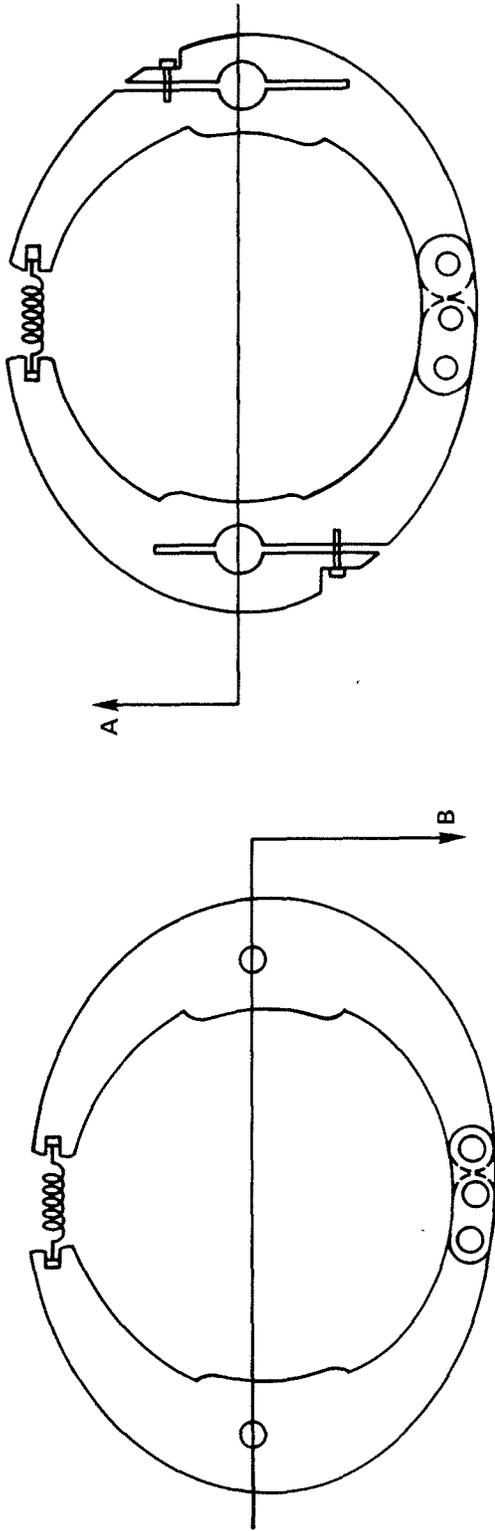


FIGURE 5.1 - TRIAXIAL CELL FOR TESTING CYLINDRICAL SPECIMENS



SCALE - INCHES

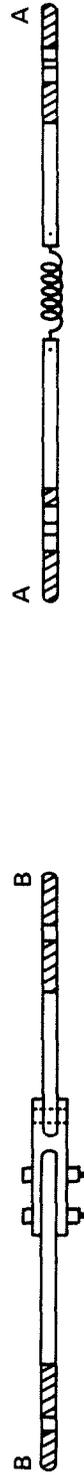
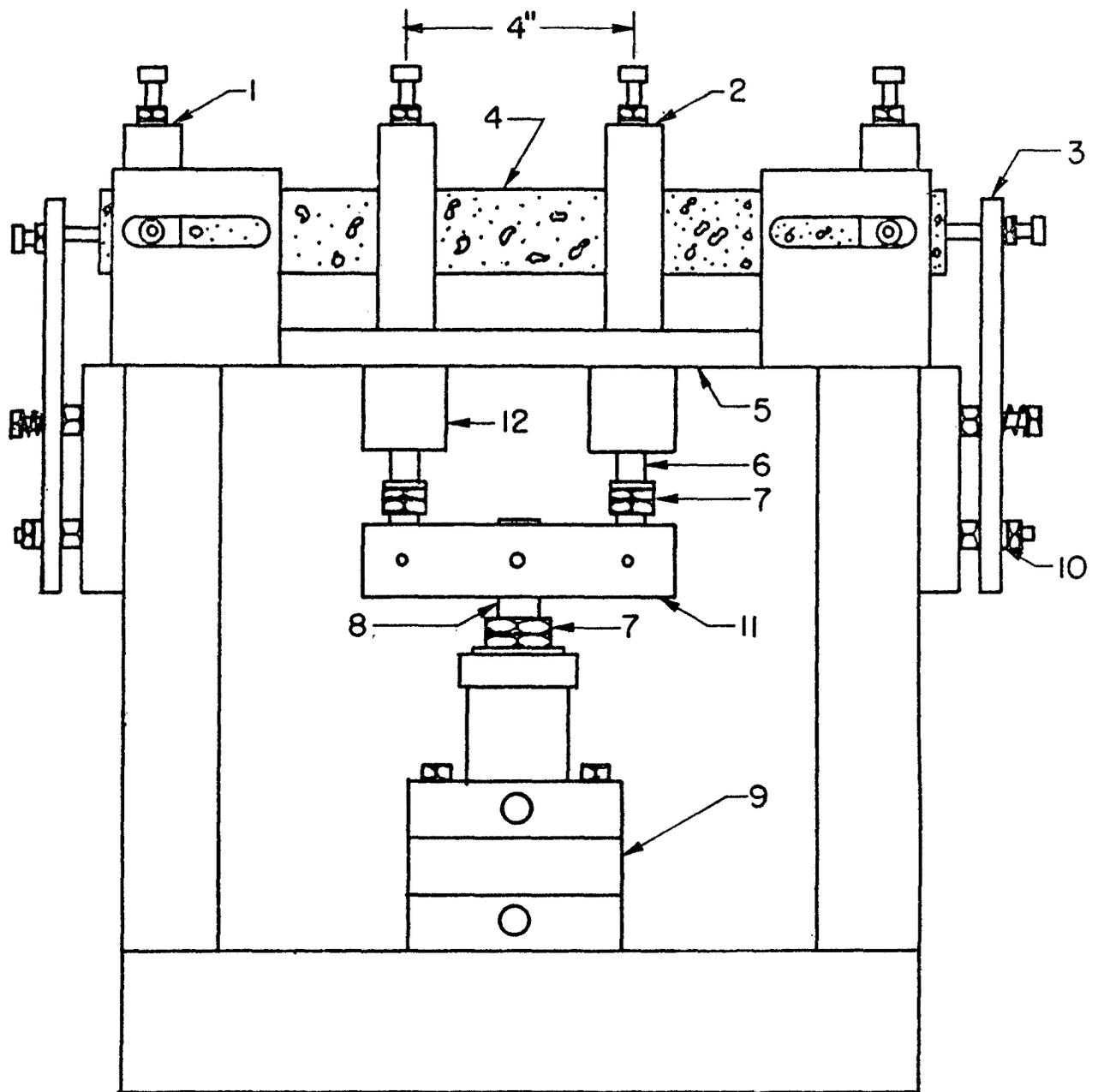


FIGURE 5.2 LVDT HOLDERS



Key:

- | | |
|-------------------|--------------------------------------|
| 1. Reaction clamp | 7. Stop nut |
| 2. Load clamp | 8. Piston rod |
| 3. Restrainer | 9. Double-acting, Bellofram cylinder |
| 4. Specimen | 10. Rubber washer |
| 5. Base plate | 11. Load bar |
| 6. Loading rod | 12. Thomson ball bushing |

Figure 5.3 Repeated Flexure Apparatus.

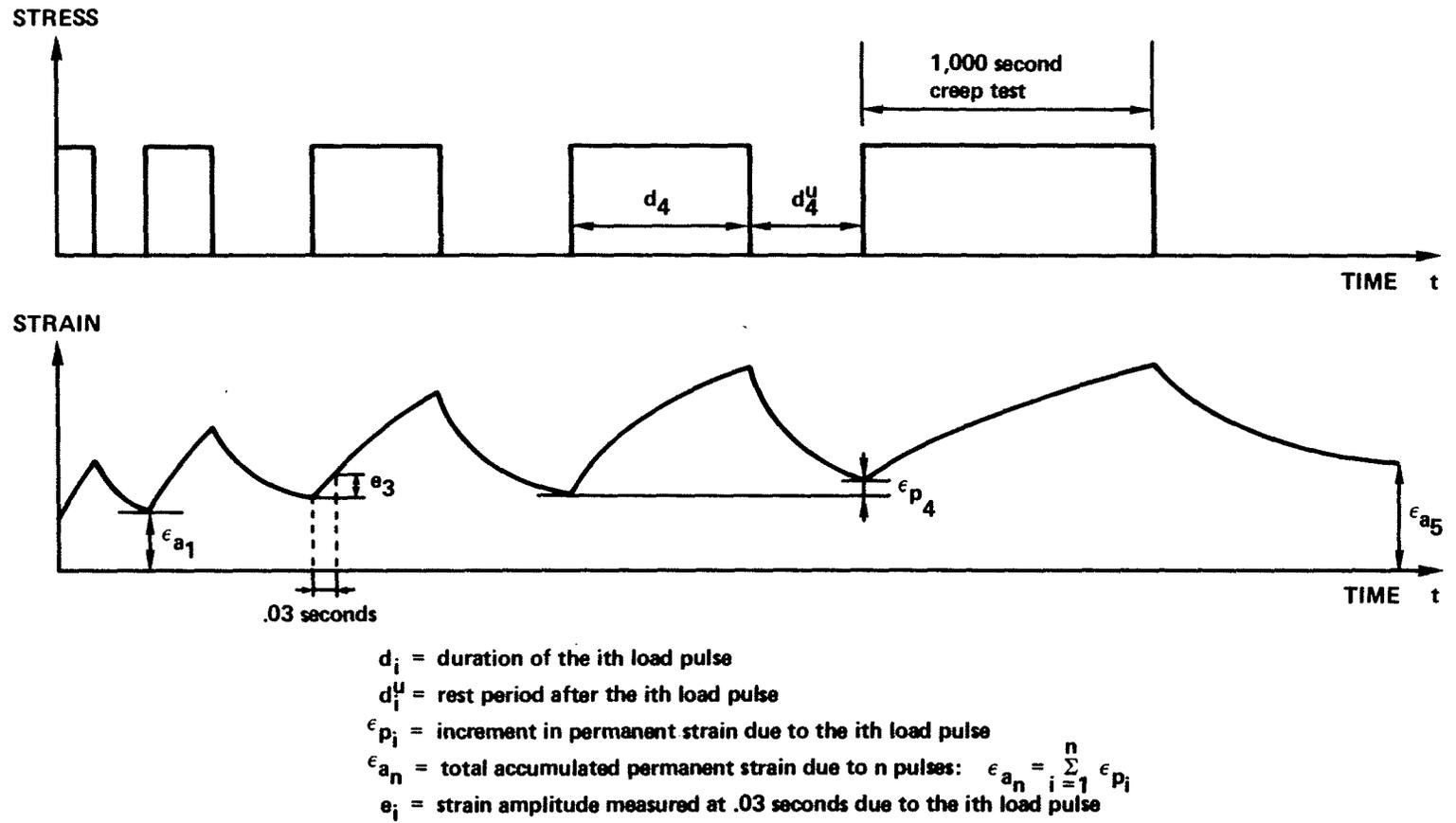


FIGURE 5.4 STRESS STRAIN OF INCREMENTAL STATIC TEST SERIES

INCREMENTAL STATIC-DYNAMIC TEST (CYLINDRICAL SPECIMENS)

Test Date _____
 Test No., Sample No. _____
 Material Description, Location, Etc. _____

Specimen Type: Core , Molded
 Specimen Size: Length: _____, Diameter _____
 Type Test: Direct Compression , Indirect Tension
Test Conditions
 Confining Pressure _____
 Load (Peak-Peak) _____
 Duration _____
 Rest Period _____
Material Conditions
 Temperature _____
 Moisture _____
 Density _____

INCREMENTAL STATIC		1,000 SEC. CREEP		DYNAMIC	
Duration (Sec.)	Permanent Deformation (in. x 10 ⁻⁶)	Compliance (psi ⁻¹ x 10 ⁻⁶)	Time (sec.)	Repetition	Permanent Deformation (in. x 10 ⁻⁶)
_____	_____	_____	.001*	_____	_____
_____	_____	_____	.003*	_____	_____
_____	_____	_____	.01*	_____	_____
_____	_____	_____	.03	_____	_____
_____	_____	_____	.1	_____	_____
_____	_____	_____	.3	_____	_____
_____	_____	_____	1	_____	_____
_____	_____	_____	3	_____	_____
_____	_____	_____	10	_____	_____
_____	_____	_____	30	_____	_____
_____	_____	_____	100	_____	_____
_____	_____	_____	1000	_____	_____

Creep Compliance from 1,000 sec. test at .03 sec. _____ psi⁻¹
 Inverse _____ psi
 Dynamic Modulus from Dynamic Test at 200 Repetitions _____ psi
 *Extrapolated from measured data.

Comments:

FIGURE 5.5 SUMMARY REPORT SHEET

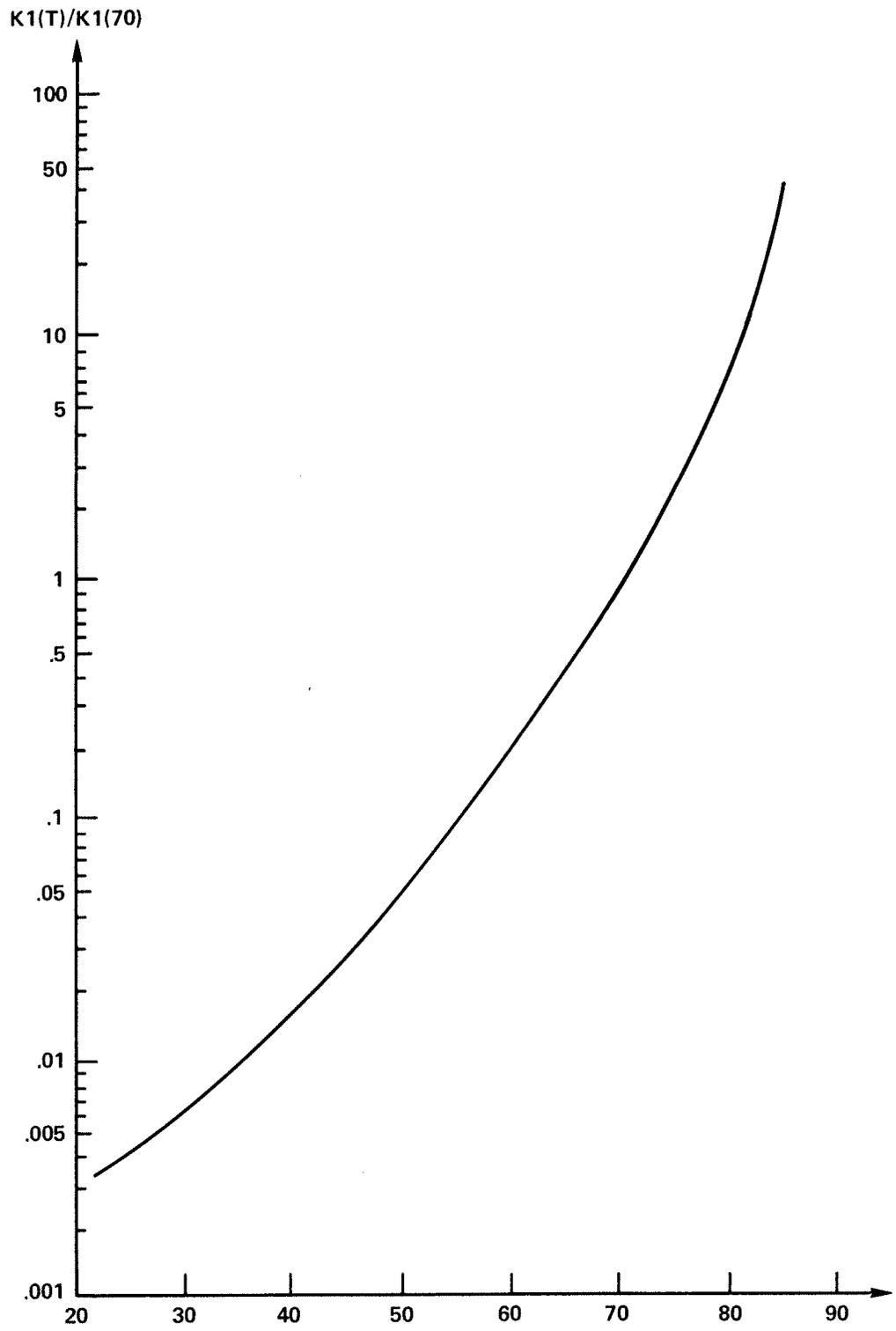


FIGURE 5.6 FATIGUE COEFFICIENT AS A FUNCTION OF TEMPERATURE

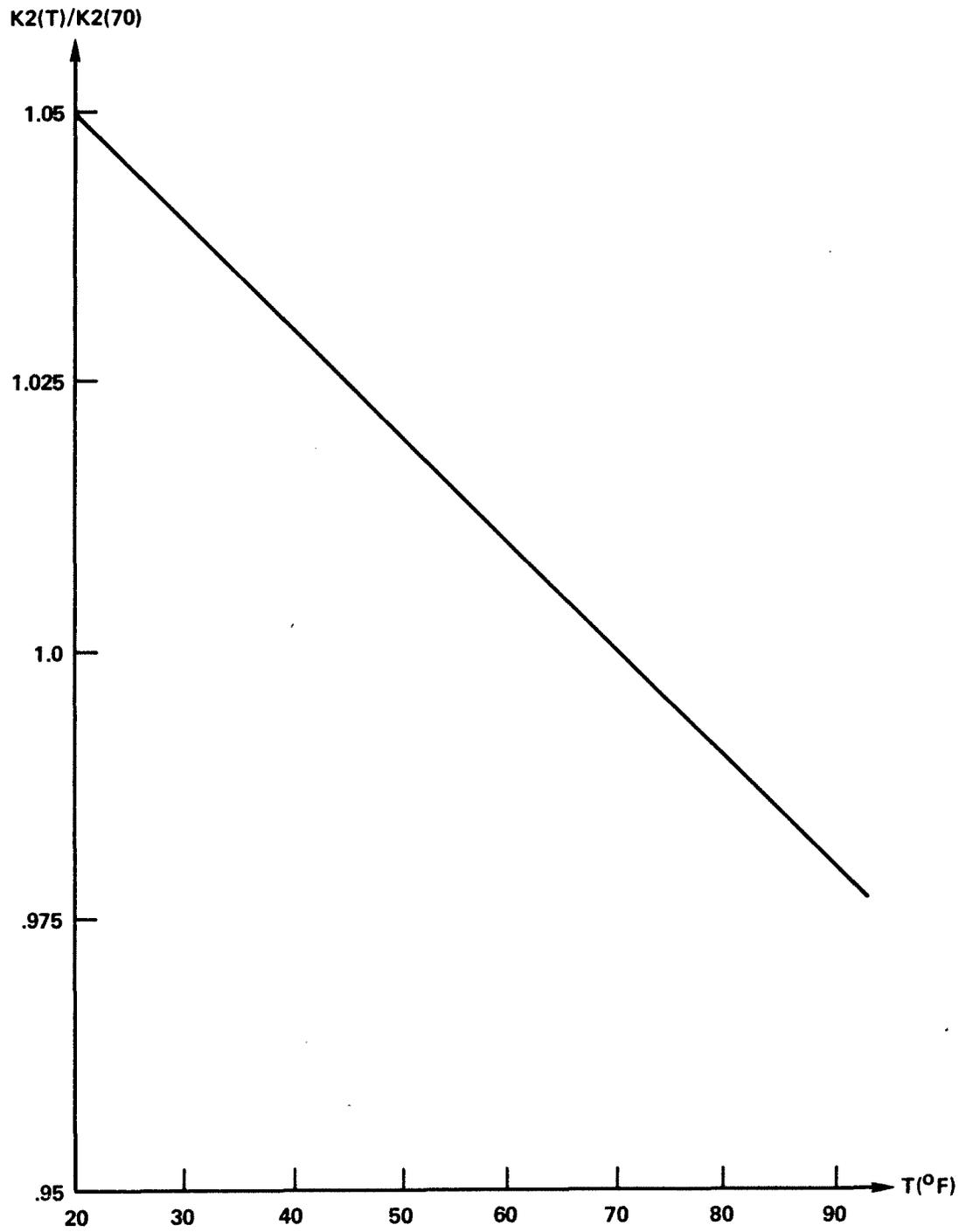


FIGURE 5.7 FATIGUE EXPONENT AS A FUNCTION OF TEMPERATURE

6.3 PREPARATION OF COMPUTER INPUT
(Refer to Articles 2.2 and 4.4)

6.3.1 Traffic Analysis Period (Article 2.2.1.2)

Step 1 - Conduct an analysis of distress and performance over a 20-year time span using a Type 1 analysis, TYPE 1.

Step 2 - Select time units in years, TUNITS 6.

Step 3 - Select 10 points, NTRANDOM 10 to look at accumulated damage over 20 years.

Step 4 - It is desired to examine distress at various points in the lifetime at years, TRANDOM 0.5, 1, 1.5, 2, 3, 4, 8, 12, 16, 20.

6.3.2. Traffic Characteristics

A. Traffic Rate (Article 2.2.1.3)

Step 1 - Anticipated traffic over the analysis period is obtained from planning as given in Table 6.1.

Step 2 - Percent heavy trucks is obtained from planning as given in Table 6.1.

Step 3 - Percent heavy trucks which will occupy the outer lane is also obtained from Planning as given in Table 6.1.

Step 4 - The average daily truck traffic ADTT is computed using equation 2.1 and is shown in Table 6.1.

Step 5 - Multiply ADTT by the average number of axles per truck to obtain the number of axles per day for each time increment.

There will be 10 traffic rates LAMBDA at each TRANDOM:

2000 2000 2000 2000 2000 2000 2500 3000 3500 4000

B. Mean and Variance of Axle Load Distribution (Article 2.2.4)

Step 1 - The mean and variance of the axle weight distributions is computed using equations (2.6) and (2.7), respectively, as shown in Table 6.2, part of which has been extracted from the W-4 Tables. The W-4 Table represents the number of single and tandem axles weighed and counted for vehicle types using a given roadway in service. If one can assume that a new road will have similar distributions

as those tabulated, then the W-4 Tables can be used as an estimating tool for predicting future weight distributions. The damaging effect of tandem axles, however, can be quite different than that due to single axles depending upon vehicle speed, geometry, and stiffness of the pavement.

Research efforts have shown that elastic layer theory can be used to determine an equivalent single axle weight which will cause similar stress or deformation in the pavement as the tandem axle configuration. A method for obtaining the mean and variance of the single axle weight distribution, adjusted to account for the effects of tandem axles, is given by equations (2.6) and (2.7). The fraction 1.5 in these equations represents an equivalent single load adjustment factor F.

Step 2 - The mean and variance of the intensity of repeated loadings are obtained using equations (2.8) and (2.9) as demonstrated in Table 6.3.

AMPLITUD	74.43
VCAMP	558

C. Mean and Variance of Duration of Axle Loadings

For a mean truck speed of 40 mph, the mean and variance of duration is computed using equations (2.4) and (2.5), respectively, as indicated in Table 6.4:

DURATION	.1
VCDUR	.54E-5

The mean duration of repeated axle loadings is an estimate of the pulse time over which a moving vehicle's wheel weight has a significant effect on the responses of various critical points in the pavement system.

Table 6.5 gives some values of duration for given values of vehicle speed, radius and X.

Equations (2.4) and (2.5) of Article 2.2.1.5 are based on X = 6 and r = 6 inches.

D. Tire-Pavement Contact

RADIUS	6
--------	---

6.3.3 System Geometry (Article 2.2.2)

TRIAL NO. 1	TRIAL NO. 2
THICK1 6	THICK1 3.5
THICK2 8	THICK2 18

6.3.4 Environment (Article 2.2.3)

Step 1 - It is desired to use an array of 12 mean monthly pavement temperatures throughout each year of the 20-year analysis period:

NTEMPS 12

Step 2 - Mean monthly temperatures at a depth of 2 inches have been estimated from a knowledge of local temperature variations and from past research investigations dealing with the distribution of temperature in asphalt concrete. These mean values in °F beginning with the month of January are input as:

TEMPS	49.7	53.3	59.5	68.6
	75.2	81.6	84.6	84.7
	78.9	70.1	59.1	52.3

6.3.5 Materials Properties (Article 2.2.5)

A. Primary Response Properties

Step 1 - The conduct of the Incremental Static-Dynamic Test on each layer material has yielded the curves shown in Figure 6.1.

Step 2 - Select the number of times and the times for which creep compliance is specified.

NTSTATIC	11				
TSTATIC		.1E-02	.3E-02	.1E-01	.3E-01
		.1E 00	.3E 00	.1E 01	.3E 01
		.1E 02	.3E 02	.1E 03	

Step 3 - Determine creep compliance.

LAYER 1 -	.37E-06	.52E-06	.86E-06	.145E-05
	.25E-05	.40E-05	.62E-05	.86E-05
	.12E-04	.16E-04	.19E-04	
LAYER 2 -	.17E-04		DO 11 TIMES	
LAYER 3** -	.20E-03	.21E-03	.22E-03	.24E-03
	.28E-03	.33E-03	.40E-03	.45E-03
	.50E-03	.55E-03	.60E-03	
LAYER 3* -	.22E-04		DO 11 TIMES	

* Subgrade at 16 percent moisture.

** Subgrade at 23 percent moisture.

VARCOEF1	.27
VARCOEF2	.2
VARCOEF3	.325

A method for estimating the coefficient of variation of compliance for asphalt concrete is given in Table 6.7 using the laboratory creep curves shown in Figure 6.2.

Step 4 - Although the program will automatically compute DELTAs, there are some curves for which large and unacceptable residuals will result. These residuals should be kept below 5 percent as printed on the curve fit output sheet. In order to keep residuals at a minimum, the user should be guided by the following:(6)

- a. Supply two time points (creep curve plots) per order of magnitude, evenly spaced on the log scale of time. A good set of values is .001, .003, .01, .03, .1, .3, 1, 3, 10, 30, 100.
- b. Conduct a Type 1 or Type 4 analysis to obtain the DELTAs provided by the computer. If any DELTA results in a residual greater than 5 percent, execute the following steps.
- c. Identify the time interval in which the fit is the poorest (where residuals are highest). Provide an extra DELTA for that interval, spacing the other DELTAs somewhat to prevent oscillation caused by the close proximity of neighboring δ 's. In order to select the extra δ for a certain time interval, it is necessary to know what will be the range of its effects. A useful rule of thumb is that a δ will have its influence on the fitted curve over the time range from $.05/\delta$ to $3.0/\delta$. If the predicted values differ from the observed curve most at a time t , then a δ whose value is $.69/t$ will have its range of influence centered about the region of the curve where the fit must be improved.
- d. Try the new DELTAs and times and if the error is still too large, repeat the process.
- e. Usually the following DELTAs can be used to give reasonable results with the times given in Step 2.

NDELTA 7

DELTA

0.1E+03 0.3E+02 0.8E+01 0.1E+01 0.1E+00 0.3E-01 0.0

Step 5 - Select β from Table 6.6, BETA = .113

In the VESYS program the input parameter Beta represents the time-temperature shifting principle. Investigators have demonstrated that asphalt mixes subjected to temperature increases experience an accelerated deformation process when subjected to load as if the time scale were compressed. For example, 1 hour at 70°F could be equivalent to 1 second at 90°F.

This relationship has been investigated by performing creep tests at different temperatures. These experiments are summarized by the time-temperature shift factors (a_T):

$$a_T = \frac{t_T}{t_{T_0}}$$

where t_T = time to obtain value of material property at temperature T

t_{T_0} = time to obtain the same value of material property at reference temperature T_0 .

Beta is defined by the following equation:

$$\beta = (-d \log a_T / dT)$$

Thus on a graph of temperature versus $\log a_T$, Beta is the absolute value of the slope of the line. Figure 6.7 plots temperature versus $\log a_T$ for VESYS default value for β of 0.113 and reference temperature of 70°F.

Table 6.6 is a summary of the Beta values found by various researchers.

B. Distress Properties

Step 1 - The conduct of fatigue tests, at 70°F, on the bituminous binder course has yielded the fatigue curve shown in Figure 6.3. Calculations are given in Table 6.8. Values of K1 and K2 are estimated for each monthly temperature. They are input in an array to coincide with the mean monthly temperature array. The following values of STRNCOEF (K1) and STRNEXP (K2) are estimated using Figures 5.6 and 5.7 and the temperatures from article 6.3.4.

STRNEXP	2.69	2.68	2.67	2.64
	2.63	2.61	2.60	2.60
	2.62	2.64	2.67	2.69
STRNCOEF	.462E-04	.728E-04	.155E-03	.799E-03
	.242E-02	.124E-01	.284E-01	.293E-01
	.568E-02	.932E-03	.151E-03	.657E-04

Step 2 - Estimate the coefficients of variation of K1 and K2 and the correlation between K1 and K2 (6). Some realistic values to use are:

coefficient of variation of K1 = .48
 coefficient of variation of K2 = .07
 correlation coefficient = -.867

Step 3 - The conduct of the Dynamic Series of the Incremental Static-Dynamic tests on each layer material using Procedure I has yielded the curves given in Figure 6.4. A similar curve for bituminous concrete is obtained from the results of the Incremental Static Series using the alternate Procedure II as shown in Figure 6.5. Calculations are given in Table 6.9.

GNU	.318	.055	.0357**
			.0075*
ALPHA	.756	.730	.643**
			.850*

6.3.6 Systems Properties (Article 2.2.6)

CORLCOEF	1
CORLEXP	.058

6.3.7 System Performance Bounds (Article 2.2.7)

Select an initial present serviceability index $PSI_1 = 4.8$ based on previous PSI measurement on newly constructed roads. The variation in previous PSI measurements indicates that the PSI of the proposed roadway, immediately after construction, will be within $\pm .29$ standard deviations

QUALITY0	4.8
STDEVO	.29

It is desired that a 50 percent level be used.

TOLERNCE	50
----------	----

* Subgrade at 16 percent
 ** Subgrade at 23 percent

6.4 SUMMARY OF DESIGN EXAMPLE

The VESYS program analyzes alternative flexible pavement designs by predicting the performance and distress of various pavements subjected to a set of loads over a specified life. Based on experience, specifications are generated concerning the levels of damage when maintenance and rehabilitation will be required. The engineer may then specify possible pavement designs and select the most feasible one, after a pavement analysis with the aid of VESYS, by weighing the impacts of the different actions. If the most desirable pavement of a group is unsatisfactory, new alternatives (in this case pavement sections) should be found and analyzed, or a new set of specifications could be generated. In this manner, assessment is used as a tool of management, and flexibility is achieved through evaluation and goal clarification. Figure 6.6 depicts the various procedures which may be used to build a model of the pavement system and solve it, with the aid of the VESYS program.

Table 6.10 lists the predicted number of years before maintenance may be required, for various distress parameters, as given in the VESYS output for the design example and based upon the set of performance criteria. From the table it appears that the initial thickness design (6-inch surface and binder, over an 8-inch base) is adequate to provide a 20-year life for a subgrade at 16 percent water content, but has only a 2-year expected life over clay at 23 percent. The respective lives for the 3.5-inch 18-inch thickness design on a clay subgrade at 16 percent and 23 percent water contents are 11 and 7 years.

Rather than formulate a new set of specifications, it is decided to search for a new thickness design and an analysis of a 6-inch 20-inch section on a subgrade at 23 percent yields an 8-year lifetime for the pavement.

Based upon this computer analysis it seems that the best choice for implementation is a pavement thickness design of 1 1/2-inch AC surface, 4 1/2-inch AC binder, and an 8-inch crushed stone base. In addition, it seems feasible and desirable to provide adequate subgrade soil moisture control to achieve a water content that we may expect (with high probability) to remain near the optimum when subjected to various environmental conditions.

A listing of computer input and output for the 6-inch 8-inch section on a subgrade at 16 percent is given in Table 6.11.

PLANNED IMPROVEMENTS

The FHWA Office of Research plans several major improvements and additions to the VESYS program. Among the more important changes will be:

- a. extension of the present three-layer analysis capability to include any number of layers of different materials,
- b. extension of the primary response model to include additional wheel loads and variable wheel load spacing,
- c. addition or modification of advanced models recently developed, and
- d. incorporation of the VESYS program into an overall system which will design an optimized pavement section as a function of cost, service life, and maintenance.

As a long range goal, the design procedure will become an integral part of an overall highway management system. Such a system will be capable of assessing the structural integrity of all types of pavements and providing an optimized design where cost of alternate designs and maintenance strategies are evaluated.

USERS

The VESYS structural subsystem, in the form of the VESYS IIM Computer Program, is currently being implemented by the Utah and Florida Highway Departments. They are applying the VESYS Program to actual pavement design problems using different environmental conditions, material's properties, and performance requirements in typical management situations. These States are also evaluating simplified test procedures that determine the elastic or visco-elastic properties of the pavement layers. This implementation effort will demonstrate the practicality of the program from a user's standpoint. The program has also been examined by Austin Research Engineers, Inc., in order to determine its sensitivity to broad ranges of realistic input values. In addition, it is currently being used by Pennsylvania State University under Highway Planning and Research (HP&R) Program activity to examine the performance of various pavement test sections on the Pennsylvania Department of Transportation test track facility in State College, Pennsylvania.

The primary emphasis of the implementation activities is to provide a basis for the modification and calibration of the VESYS structural subsystem. A continuing effort will be made to improve the predictive capabilities, simplify procedures and assist user agencies throughout this effort.

TABLE 6.1 TRAFFIC RATE

TIME INCREMENTS (i) YEAR	ADT (i) ALL TRAFFIC	(i) %TRUCKS ALL TRAFFIC	C(i) %TRUCKS DESIGN LANE	ADTT (i)	D(i) AVG. AXLES PER TRUCK	LAMBDA (i) AXLES/DAY
1 - 4	13,333	10	50	667	3	2,000
5 - 8	16,667	10	50	833	3	2,500
9 - 12	20,000	10	50	1000	3	3,000
13 - 16	21,875	10	40	875	4	3,500
17 - 20	25,000	10	40	1000	4	4,000

$$ADTT (i) = \frac{B(i)}{100} \times \frac{C(i)}{100} \times ADT (i)$$

$$LAMBDA (i) = ADTT (i) \times D(i)$$

TABLE 6.2 EXAMPLE FOR THE DETERMINATION OF AMPLITUDE AND VCAMP

From W - 4 Table:

AXLE LOAD IN KIPS SINGLE AXLE	TOTAL ALL TRUCKS AND COMBINATIONS PROBABLE NO. f_s	MIDPOINT OF LOAD GROUPS X_s	$(f_s X_s)$	$(f_s X_s^2)$
8 - 12	1362	10	13620	136200
12 - 16	519	14	7266	101724
16 - 18	343	17	5831	99127
18 - 19	96	18.5	1776	32856
19 - 20	39	19.5	760	14829
20 - 22	7	21.0	147	3087
22 - 24	3	23.0	69	1587
24 - 26	2	25	50	1250
TOTALS	$\Sigma f_s = 2371$		$\Sigma (f_s X_s) = 29,519$	$\Sigma (f_s X_s^2) = 390,660$

From W - 4 Table: TANDEM AXLE	PROBABLE NO. f_t	X_t	$(f_t X_t)$	$(f_t X_t^2)$
12 - 18	174	15	2610	39150
18 - 24	200	21	4200	88200
24 - 30	448	27	12096	326592
30 - 32	229	31	7099	220069
32 - 33	165	32.5	5362	174281
33 - 34	32	33.5	1072	35912
34 - 36	85	35.0	2975	104125
36 - 38	31	37.0	1147	42439
38 - 40	6	39.0	234	9126
40 - 42	3	41.0	123	5043
42 - 44	1	43.0	43	1849
44 - 46	0	45.0	0	0
46 - 50	2	48.0	96	4608
TOTALS	$\Sigma f_t = 1376$		$\Sigma (f_t X_t) = 36863$	$\Sigma (f_t X_t^2) = 1,051,402$

TABLE 6.3 EXAMPLE FOR DETERMINATION OF AMPLITUDE AND VCAMP

Using Equation (2.6)

$$\bar{X} = \frac{66342}{4435} = 14.96 \text{ kips}$$

Using Equation (2.7)

$$\sigma_x^2 = \frac{1,091,594}{4435} - 223.8 = 22.33 \text{ kips}$$

Using Equation (2.8) for $a = 100$ sq. inches

$$\bar{A} = \frac{14.96 * 1000}{200} = 74.43 \text{ psi}$$

Using Equation (2.9)

$$\sigma_A^2 = \frac{22.33 * 1,000,000}{40,000} = 558 \text{ psi}$$

TABLE 6.4
 EXAMPLE FOR DETERMINATION OF MEAN
 AND VARIANCE OF LOAD DURATION

For $\bar{s} = 40$ mph

$$\sigma_s^2 = .728 \text{ mph}^2$$

$$\bar{d}(s) = \frac{4}{s} = .1 \text{ seconds}$$

$$\sigma_d^2 = \frac{(19)(.728)}{2,560,000} = .0000054 \text{ seconds}^2$$

TABLE 6.5
 MEAN DURATION $d(r,s)$ SECONDS

r/s	X		
	3	6	9
.05	.02	.03	.05
.15	.05	.10	.15
.30	.10	.20	.30
.60	.20	.40	.60
1.20	.40	.80	1.2

TABLE 6.6
SUMMARY OF FINDINGS FOR BETA

STUDY	BETA VALUE
Fitzgerald, Lai	0.086
Nair, Smith, Chang	0.09
Chang, Nair, Smith	0.061
Pagen	0.147
van de Loo	0.17
Shook, Kallas	0.09 and 0.15
Range of Values	0.061 and 0.17
Mean Value	0.113

TABLE 6.7
CALCULATION OF VARIABILITY OF
MATERIAL RESPONSE PROPERTIES
(See FIGURE 6.2)

1. The standard deviation Compliance at 1000 s

$$\sigma_D = \frac{100-58}{2} = 21 \times 10^{-6} \text{ psi}^{-1}$$

2. The mean Compliance is:

$$\bar{D} = \frac{100 + 58}{2} = 79 \text{ psi}^{-1}$$

3. The coefficient of variation is

$$V_D = \frac{\sigma_D}{\bar{D}} = \frac{21}{79} = .27$$

4. V_D is obtained at two other times, .01 and 10 seconds and the average value is used as input.

TABLE 6.8
 CALCULATION OF K_1 and K_2
 (See FIGURE 6.3)

1. LET $K_1 = N_0 e_0^{K_2}$

where $K_2 = \left| \frac{1}{S} \right| = \left| \frac{dN}{de} \right|$

N_0, e_0 = number of repetitions and
 strain at the verticle reference axis

2. From a plot of e vs. N on log-log paper read K_2

$$K_2 = \frac{9.25''}{3.50''} = 2.64$$

3. Compute K_1

$$K_1 = (10^3) (5.7 \times 10^3)^{2.64}$$

$$= 8.85 \times 10^{-4}$$

TABLE 6.9
 CALCULATION OF GNU AND ALPHA
 (See FIGURE 6.4)

CALCULATION OF GNU AND ALPHA

MATERIAL	INTERCEPT I	SLOPE S	STRAIN e	$\mu = \frac{IS}{e}$	$\alpha = 1 - s$
ASPHALT	4.3×10^{-5}	0.244	3.3×10^{-5}	0.318	0.756
SUBBASE	6.1×10^{-5}	0.270	3×10^{-4}	0.055	0.730
CLAY 23%	1.3×10^{-4}	0.357	1.3×10^{-3}	0.0357	0.643
CLAY 16%	1.0×10^{-5}	0.150	2×10^{-4}	0.0075	0.850

TABLE 6.10 SUMMARY OF DESIGN EXAMPLE

WATER CONTENT OF CLAY SUBGRADE (%)	THICKNESS DESIGN (in.)	Approximate Years to Maintenance and Rehabilitation for Distress Types		
		CRACKING	RUT DEPTH	SLOPE VARIANCE
16	6 - 8	20	20	20
16	3.5 - 18	11	20	20
23	6 - 8	15	2	3
23	3.5 - 18	9	7	13
23	6 - 20	20	8	18

VESYS IIM: A PROBABILISTIC PREDICTIVE MODEL FOR PAVEMENT DESIGN

LATEST REVISION: January 22, 1976
Federal Highway Administration

DESIGN EXAMPLE: March 3, 1976

INPUT DATA VALUES FOR RUN: 1

TYPE	1										
ITYPES	1001000										
UNLOAD											
THICK1	0.6000E 01										
THICK2	0.8000E 01										
LOADING	0.1000E 01										
RADIUS	0.6000E 01										
ZPOINT	0.4000E 01										
NRPOINTS	1										
RPOINTS	0.0										
NTSTATIC	11	<i>(number of time points where creep compliance is measured)</i>									
TSTATIC	<i>(time points)</i>										
	0.1000E-02	0.3000E-02	0.1000E-01	0.3000E-01	0.1000E 00	0.3000E 00	0.1000E 01	0.3000E 01	0.1000E 02	0.3000E 02	0.1000E 03
LAYER1	<i>(surface creep compliance values)</i>										
	0.3700E-06	0.5200E-06	0.8600E-06	0.1450E-05	0.2500E-05	0.4000E 05	0.6200E-05	0.8600E-05	0.1200E-04	0.1600E-04	0.1900E-04
LAYER2	<i>(base creep compliance values)</i>										
	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04	0.1700E-04
LAYER3	<i>(subgrade creep compliance values)</i>										
	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04	0.2200E-04
VARCOEF1	0.2700E 00										
VARCOEF2	0.2000E 00	<i>(coefficients of variation for the creep compliance curves)</i>									
VARCOEF3	0.3250F 00										
NDELTAS	7	<i>(number of deltas)</i>									
DELTAS	0.1000E 03	0.3000E 02	0.8000E 01	0.1000E 01	0.1000E 00	0.3000E-01	0.0				

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES

STRNEXP	<i>(value of exponent in Miner's law for AC fatigue by monthly temperature)</i>										
	0.2690E 01	0.2680E 01	0.2670E 01	0.2640E 01	0.2630E 01	0.2610E 01	0.2600E 01	0.26200E 01	0.2620E 01	0.2640E 01	0.2670E 01
	0.2690E 01										
STRNCOEF	<i>(value of coefficient in Miner's law for AC fatigue by monthly temperature)</i>										
	0.4620E-04	0.7280E-04	0.1550E-03	0.7990E-03	0.2420E-02	0.1240E-01	0.2840E-01	0.2930E-01	0.5680E-02	0.9320E-03	0.1510E-03
	0.6570E-04										
COEFK1	0.3000E 00										
COEFK2	0.4000E-01	<i>(coefficients of variation and correlation coefficient of the fatigue properties)</i>									
K1K2CORL	-0.8670E 00										
GNU	<i>(permanent deformation property for each layer material)</i>										
	0.3180E 00	0.5500E-01	0.7500E-02								
ALPHA	<i>(permanent deformation property for each layer material)</i>										
	0.7560E 00	0.7300E 00	0.8500E 00								
CORLCOEF	0.1000E 01	<i>(roughness property coefficient B)</i>									
CORLEXP	0.5800E-01	<i>(roughness property exponent C)</i>									
NTEMPS	12	<i>(number of monthly temperatures)</i>									
TEMPS	0.4970E 02	0.5330E 02	0.5950E 02	0.6860E 02	0.7520E 02	0.8160E 02	0.8460E 02	0.8470E 02	0.7890E 02	0.7010E 02	0.5910E 02
	0.5230E 02										
REFTEMP	0.7000E 02	<i>(reference temperature)</i>									
BETA	0.1130E 00	<i>(time temperature shift factor for asphalt concrete)</i>									
NRANDOM	10	<i>(number of incremental analysis periods)</i>									
TRANDOM	<i>(incremental analysis periods)</i>										
	0.5000E 00	0.1000E 01	0.1500E 01	0.2000E 01	0.3000E 01	0.4000E 01	0.8000E 01	0.1200E 02	0.1600E 02	0.2000E 02	
TUNITS	6	<i>(specifies time units for incremental analysis periods, 6 = years)</i>									
LAMBDA	<i>(traffic rate for each incremental analysis period)</i>										
	0.2000E 04	0.2000E 04	0.2000E 04	0.2000E 04	0.2000E 04	0.2000E 04	0.2500E 04	0.3000E 04	0.3500E 04	0.4000E 04	
AMPLTUD	0.7443E 02	<i>(tire pavement contact pressure, psi)</i>									
VCAMP	0.5580E 03	<i>(variance of amplitude)</i>									
DURATION	0.1000E 00	<i>(time loading influences pavement due to moving traffic)</i>									
VCDUR	0.5400E-05	<i>(variance of duration)</i>									
QUALITYO	0.4800E 01	<i>(initial psi)</i>									
STDEVO	0.2900E 00	<i>(standard deviation of initial psi)</i>									
PSIFAIL	0.2500E 01	<i>(minimum acceptable psi)</i>									
TOLERNC	0.5000E 02	<i>(minimum acceptable probability that pavement is not in or below state PSIFAIL)</i>									

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES (Continued)

FITTED CREEP COMPLIANCE FUNCTIONS - DIRICHLET SERIES (7 deltas define 7 Dirichlet coefficients at Ref. Temp.)

I	G (I) LAYER 1	G (I) LAYER 2	G (I) LAYER 3	DELTA (I)
1	-0.58724E-06	0.0	0.0	0.10000E 03
2	0.16298E-07	0.0	0.0	0.30000E 02
3	-0.21742E-05	0.0	0.0	0.80000E 01
4	-0.37549E-05	0.0	0.0	0.10000E 01
5	-0.55544E-05	0.0	0.0	0.10000E 00
6	-0.66510E-05	0.0	0.0	0.30000E-01
7	0.19000E-04	0.17000E-04	0.22000E-04	0.0

COEFFICIENTS OF VARIATION: 0.270E 00 0.200E 00 0.325E 00

VALUES OF CREEP COMPLIANCE . . . WITH RESIDUALS (at Ref. Temp.)

TIME (SECONDS)	MEASURED	PREDICTED	% ERR	MEASURED	PREDICTED	% ERR	MEASURED	PREDICTED	% ERR
0.10E-02	0.37000E-06	0.37182E-06	-0.49	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.30E-02	0.52000E-06	0.51045E-06	1.84	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.10E-01	0.86000E-06	0.87364E-06	-1.59	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.30E-01	0.14500E-05	0.14404E-05	0.66	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.10E 00	0.25000E-05	0.24961E-05	0.16	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.30E 00	0.40000E-05	0.40394E-05	-0.98	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.10E 01	0.62000E-05	0.61376E-05	1.01	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.30E 01	0.86000E-05	0.86197E-05	-0.23	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.10E 02	0.12000E-04	0.12029E-04	-0.24	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.30E 02	0.16000E-04	0.16019E-04	-0.12	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0
0.10E 03	0.19000E-04	0.18669E-04	1.74	0.17000E-04	0.17000E-04	0.0	0.22000E-04	0.22000E-04	0.0

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES (Continued)

LAYER 1 THICKNESS = 6.0 INCHES
 LAYER 2 THICKNESS = 8.0 INCHES
 RADIAL POSITION = 0.0 INCHES
 VERTICAL POSITION = 0.0 INCHES
 LAYER OF INTEREST = 1
 LOADING IN PSI = 1.0

LAYER 1 THICKNESS = 6.0 INCHES
 LAYER 2 THICKNESS = 8.0 INCHES
 RADIAL POSITION = 0.0 INCHES
 VERTICAL POSITION = 6.0 INCHES
 LAYER OF INTEREST = 1
 LOADING IN PSI = 1.0

VARIABLE IS VERTICAL DISPLACEMENT (of surface due to a 1 psi static load at Ref. Temp.)

VARIABLE IS RADIAL STRAIN (at bottom of B.C. due to a 1 psi static load at Ref. Temp.)

TIME (SEC)	MEAN VALUE	COEF OF VAR
0.10E-02	0.53756E-04	0.22150E 00
0.30E-02	0.59410E-04	0.20896E 00
0.10E-01	0.69823E-04	0.19503E 00
0.30E-01	0.80639E-04	0.18563E 00
0.10E 00	0.93639E-04	0.17703E 00
0.30E 00	0.10636E-03	0.16910E 00
0.10E 01	0.11913E-03	0.16075E 00
0.30E 01	0.13113E-03	0.15286E 00
0.10E 02	0.14459E-03	0.14433E 00
0.30E 02	0.15889E-03	0.13548E 00
0.10E 03	0.17079E-03	0.12757E 00

TIME (SEC)	MEAN VALUE	COEF OF VAR
0.10E-02	0.57666E-06	0.20942E 00
0.30E-02	0.72759E-06	0.15284E 00
0.10E-01	0.10533E-05	0.98540E 01
0.30E-01	0.14467E-05	0.81128E-01
0.10E 00	0.19785E-05	0.84581E-01
0.30E 00	0.25271E-05	0.97505E-01
0.10E 01	0.30559E-05	0.11357E 00
0.30E 01	0.34996E-05	0.12893E 00
0.10E 02	0.39221E-05	0.14483E 00
0.30E 02	0.42747E-05	0.15888E 00
0.10E 03	0.44808E-05	0.16739E 00

CURVE-FITTED SYSTEM RESPONSE . . . DIRICHLET SERIES

I	G (I) SYSTEM	DELTA (I)
1	-0.23585E-04	0.10000E 03
2	-0.16678E-05	0.30000E 02
3	-0.24899E-04	0.80000E 01
4	-0.22891E-04	0.10000E 01
5	-0.20180E-04	0.10000E 00
6	-0.25712E-04	0.30000E-01
7	0.17079E-03	0.0

CURVE-FITTED SYSTEM RESPONSE . . . DIRICHLET SERIES

I	G (I) SYSTEM	DELTA (I)
1	-0.63840E-06	0.10000E 03
2	-0.13976E-06	0.30000E 02
3	-0.10622E-05	0.80000E 01
4	-0.96895E-06	0.10000E 01
5	-0.77611E-06	0.10000E 00
6	-0.38306E-06	0.30000E-01
7	0.44808E-05	0.0

PERMANENT DEFORMATION SYSTEM RESPONSE FACTORS

(These are system permanent deformation properties)

GNU = 0.5931E 00
 ALPHA = 0.2439E 00

GENERAL STRAIN RESPONSE DUE TO PEAK LOADING (HAVERSINE)

(due to a 0.1 sec. haversine load bottom of B.C.)

TEMPERATURE DEGREES-F	STRAIN INS./IN.	VAR STRAIN (INS./IN.)**2	NFAIL CYCLES	VAR NFAIL CYCLES**2
49.70	0.38855E-04	0.21827E-09	0.32853E 08	0.26023E 15
53.30	0.39968E-04	0.23096E-09	0.43587E 08	0.45804E 15
59.50	0.46802E-04	0.31674E-09	0.55672E 08	0.74723E 15
68.60	0.90162E-04	0.11759E-08	0.39283E-08	0.37183E 15
75.20	0.14196E-03	0.29145E-08	0.33601E 08	0.27182E 15
81.60	0.20103E-03	0.58442E-08	0.59302E 08	0.84569E 15
84.60	0.22646E-03	0.74159E-08	0.92178E 08	0.20422E 16
84.70	0.22730E-03	0.74713E-08	0.94196E 08	0.21326E 16
78.90	0.17715E-03	0.45386E-08	0.40880E 08	0.40209E 15
70.10	0.10084E-03	0.14707E-08	0.34272E 08	0.28298E 15
59.10	0.46005E-04	0.30603E-09	0.56732E 08	0.77597E 15
52.30	0.39551E-04	0.22617E-09	0.44582E 08	0.47920E 15

DAMAGE INDEX DIMENSIONLESS	VAR DAMAGE INDEX DIMENSIONLESS	AREA CRACKED SQ. YDS/1000 SQ. YDS.	TIME YEARS
0.14668E-01	0.25567E-04	0.0	0.50
0.26433E-01	0.43249E-04	0.0	1.00
0.41100E-01	0.68816E-04	0.0	1.50
0.52865E-01	0.86499E-04	0.0	2.00
0.79298E-01	0.12975E-03	0.0	3.00
0.10573E 00	0.17300E-03	0.0	4.00
0.23789E 00	0.44330E-03	0.0	8.00
0.39649E 00	0.83254E-03	0.0	12.00
0.58151E 00	0.13623E-02	0.0	16.00
0.79297E 00	0.20543E-02	0.0	20.00

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES (Continued)

PERMANENT DEFORMATION SYSTEM RESPONSE FACTORS

GNU = 0.5931E 00
 ALPHA = 0.2439E 00

SLOPE VARIANCE
 RADIANS*10**6

VAR SLOPE VARIANCE
 (RADIANS*10**6)**2

TIME
 YEARS

GENERAL DEFLECTION RESPONSE DUE TO PEAK LOADING (HAVERSINE)

TEMPERATURE DEGREES F	DEFLECTION INCHES	VAR DEFLECTION INCHES**2
49.70	0.3884E-02	0.2260E-05
53.30	0.3922E-02	0.2304E-05
59.50	0.4152E-02	0.2583E-05
68.60	0.5526E-02	0.4576E-05
75.20	0.6827E-02	0.6982E-05
81.60	0.8232E-02	0.1015E-04
84.60	0.8861E-02	0.1176E-04
84.70	0.8882E-02	0.1182E-04
78.90	0.7658E-02	0.8784E-05
70.10	0.5824E-02	0.5081E-05
59.10	0.4126E-02	0.2550E-05
52.30	0.3908E-02	0.2288E-05

0.23063E 00
0.40052E 00
0.45904E 00
0.56166E 00
0.68449E 00
0.78760E 00
0.11697E 01
0.15008E 01
0.18092E 01
0.21050E 01

0.24109E-01
0.72705E-01
0.95506E-01
0.14297E 00
0.21234E 00
0.28113E 00
0.62012E 00
0.10209E 01
0.14835E 01
0.20081E 01

0.50
1.00
1.50
2.00
3.00
4.00
8.00
12.00
16.00
20.00

<u>RUT DEPTH</u> INCHES	VAR RUT DEPTH INCHES**2	TIME YEARS
0.82924E-01	0.10301E-02	0.50
0.10928E 00	0.17888E-02	1.00
0.11699E 00	0.20503E-02	1.50
0.12941E 00	0.25084E-02	2.00
0.14268E 00	0.30570E-02	3.00
0.15324E 00	0.35175E-02	4.00
0.18675E 00	0.52241E-02	8.00
0.21154E 00	0.67029E-02	12.00
0.23226E 00	0.80802E-02	16.00
0.25052E 00	0.94009E-02	20.00

118

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES (Continued)

<u>SERVICEABILITY</u>	<u>VARIANCE OF SERVICEABILITY</u>	<u>TIME</u>
4.62354	0.09511	0.50
4.51701	0.10977	1.00
4.48352	0.11518	1.50
4.42799	0.12476	2.00
4.36610	0.13607	3.00
4.31739	0.14526	4.00
4.15676	0.17612	8.00
4.03635	0.19870	12.00
3.93556	0.21677	16.00
3.84647	0.23192	20.00

SERVICEABILITY FAILURE LEVEL IS 2.50000

MARGINAL STATE PROBABILITIES (Reliability = 1 - Probability pavement is in state 10 (PSI PSIFAIL))

STATE UPPER BOUNDS - 0.1E 51	4.74889	4.46778	4.18667	3.90555	3.62444	3.34333	3.06222	2.78111	2.50000
STATE LOWER BOUNDS - 4.74889	4.46778	4.18667	3.90555	3.62444	3.34333	3.06222	2.78111	2.50000	-0.1E 51

119

<u>STATE1</u>	<u>STATE2</u>	<u>STATE3</u>	<u>STATE4</u>	<u>STATE5</u>	<u>STATE6</u>	<u>STATE7</u>	<u>STATE8</u>	<u>STATE9</u>	<u>STATE10</u>	<u>TIME</u>	<u>RELIABILITY</u>
0.56995	0.30407	0.10876	0.01620	0.00099	0.00003	0.00000	0.0	0.0	0.00000	0.0	1.00000
0.34221	0.35104	0.22845	0.06834	0.00935	0.00058	0.00002	0.00000	0.0	0.00000	0.5	1.00000
0.24200	0.31706	0.28157	0.12689	0.02895	0.00333	0.00019	0.00001	0.00000	0.00000	1.0	1.00000
0.21714	0.30136	0.29062	0.14659	0.03860	0.00529	0.00038	0.00001	0.00000	0.00000	1.5	1.00000
0.18181	0.27336	0.29761	0.17767	0.05810	0.01039	0.00101	0.00005	0.00000	0.00000	2.0	1.00000
0.14970	0.24171	0.29526	0.20741	0.08374	0.01940	0.00258	0.00020	0.00001	0.00000	3.0	1.00000
0.12879	0.21779	0.28762	0.22586	0.10543	0.02922	0.00480	0.00047	0.00003	0.00000	4.0	1.00000
0.07913	0.15018	0.24228	0.25368	0.17240	0.07603	0.02174	0.00403	0.00048	0.00004	8.0	0.99996
0.05497	0.11159	0.20142	0.24742	0.20687	0.11772	0.04558	0.01200	0.00215	0.00028	12.0	0.99972
0.04033	0.08617	0.16833	0.23087	0.22231	0.15031	0.07134	0.02376	0.00555	0.00102	16.0	0.99898
0.03047	0.06803	0.14146	0.21121	0.22644	0.17432	0.09636	0.03823	0.01089	0.00259	20.0	0.99741

WARNING-RELIABILITY EXCEEDS THE SPECIFIED TOLERANCE THROUGHOUT THE PERIOD OF THIS ANALYSIS. IF AN ACCURATE ESTIMATE OF SERVICE LIFE IS REQUIRED, THEN THIS RUN SHOULD BE RESUBMITTED WITH ADDITIONAL TRANDOM POINTS, EXTENDING THE ANALYSIS BEYOND THE TIME AT WHICH RELIABILITY DROPS BELOW THE MINIMUM ACCEPTABLE LEVEL.

TABLE 6.11 PREDICTIVE DESIGN PROCEDURES (Continued)

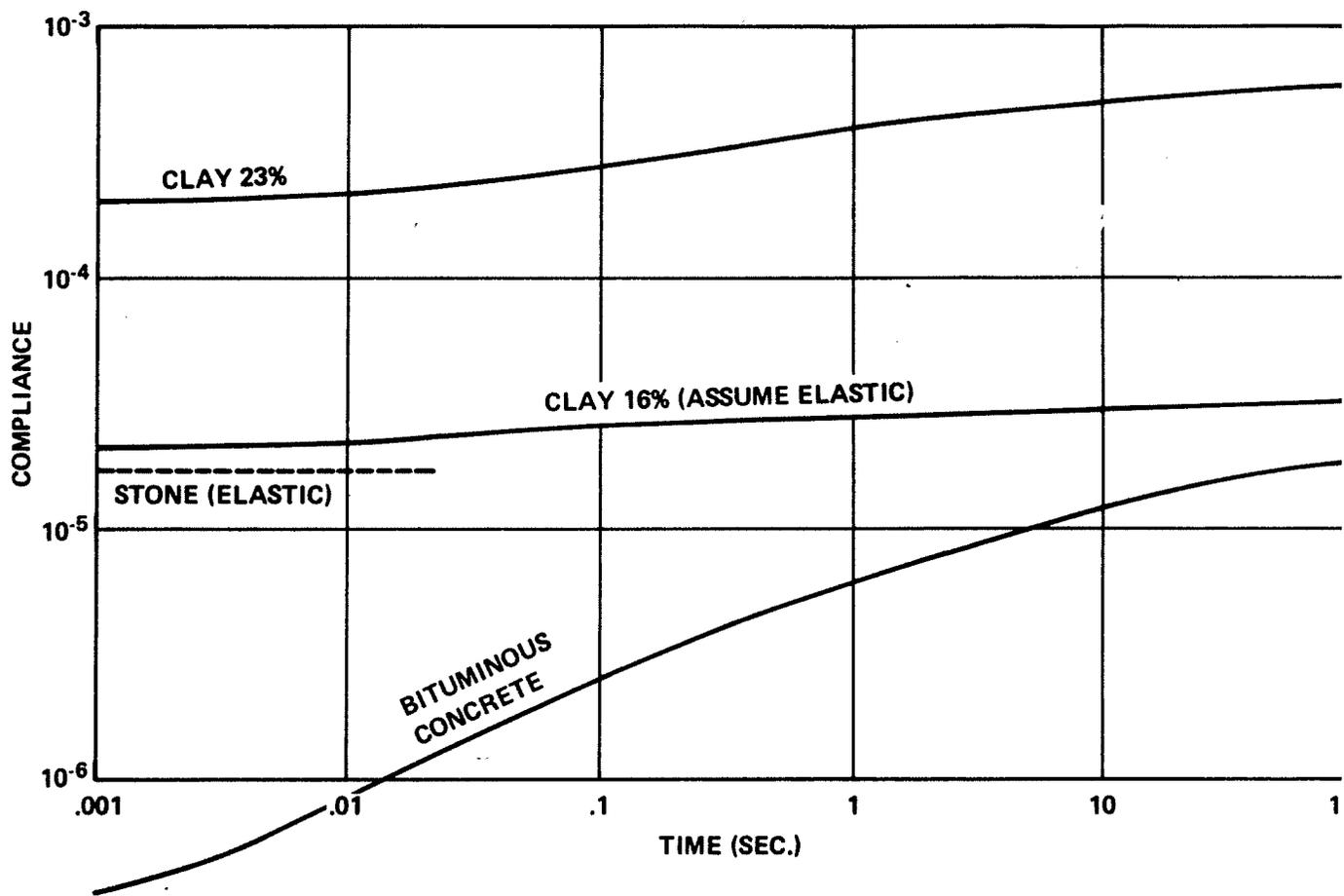


FIGURE 6.1 1000 SEC. CREEP TEST

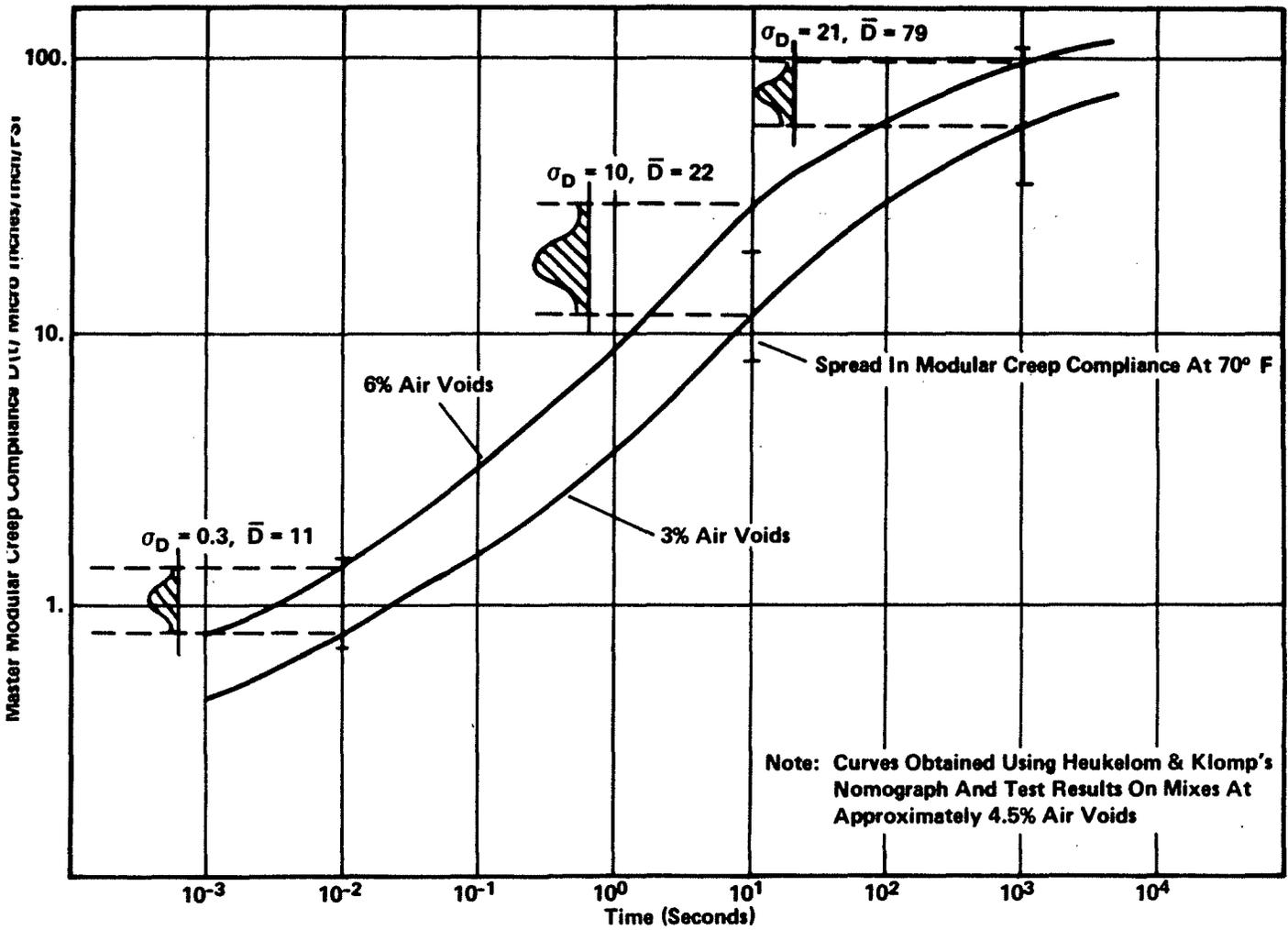


FIGURE 6.2 Unconfined Compressive Master Modular Creep Compliance $D(t)$ At Reference $T = 70^\circ F$

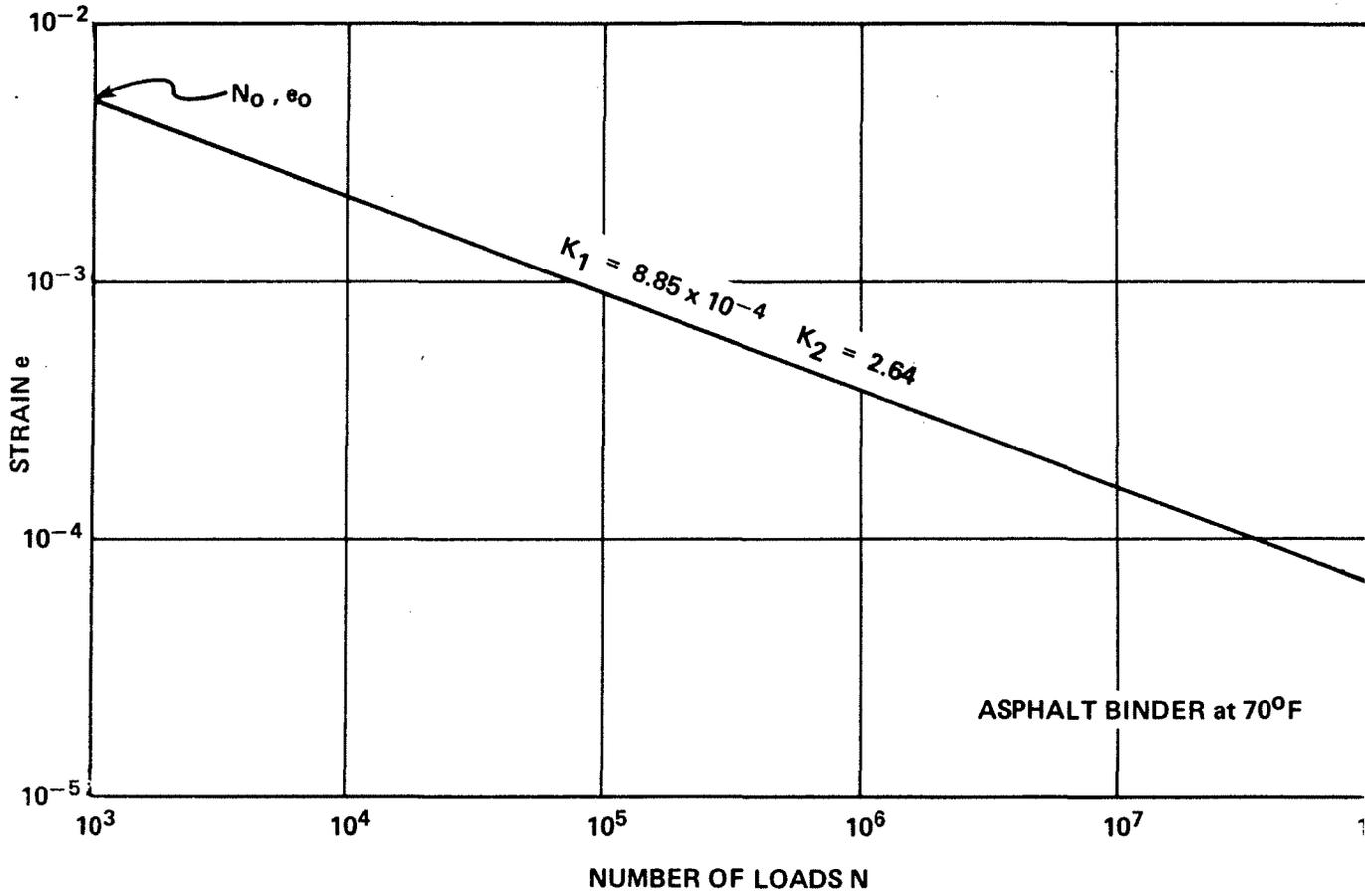


FIGURE 6.3 FLEXURAL FATIGUE TEST - AT 70° F

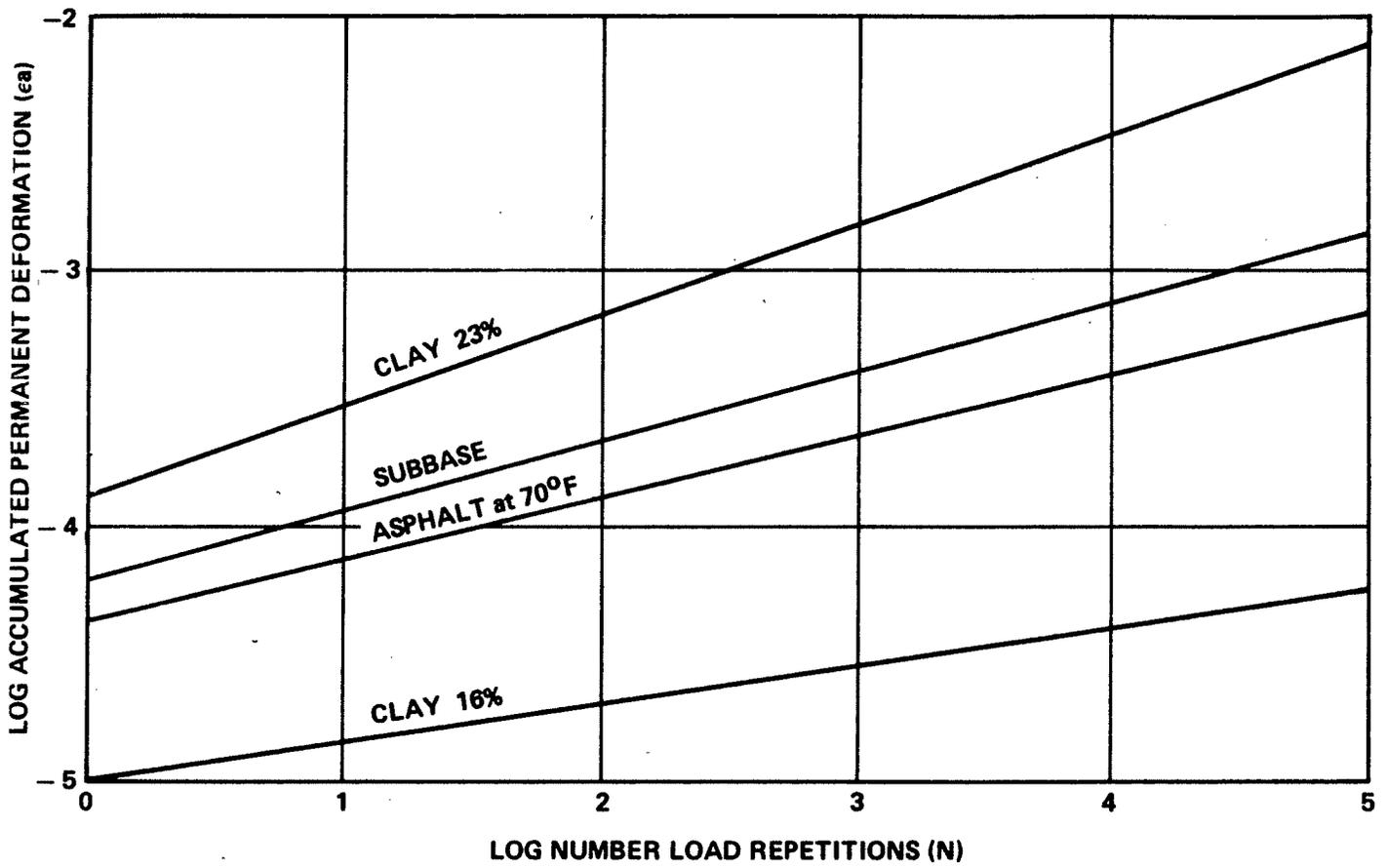


FIGURE 6.4 DYNAMIC SERIES OF INCREMENTAL STATIC-DYNAMIC TESTS

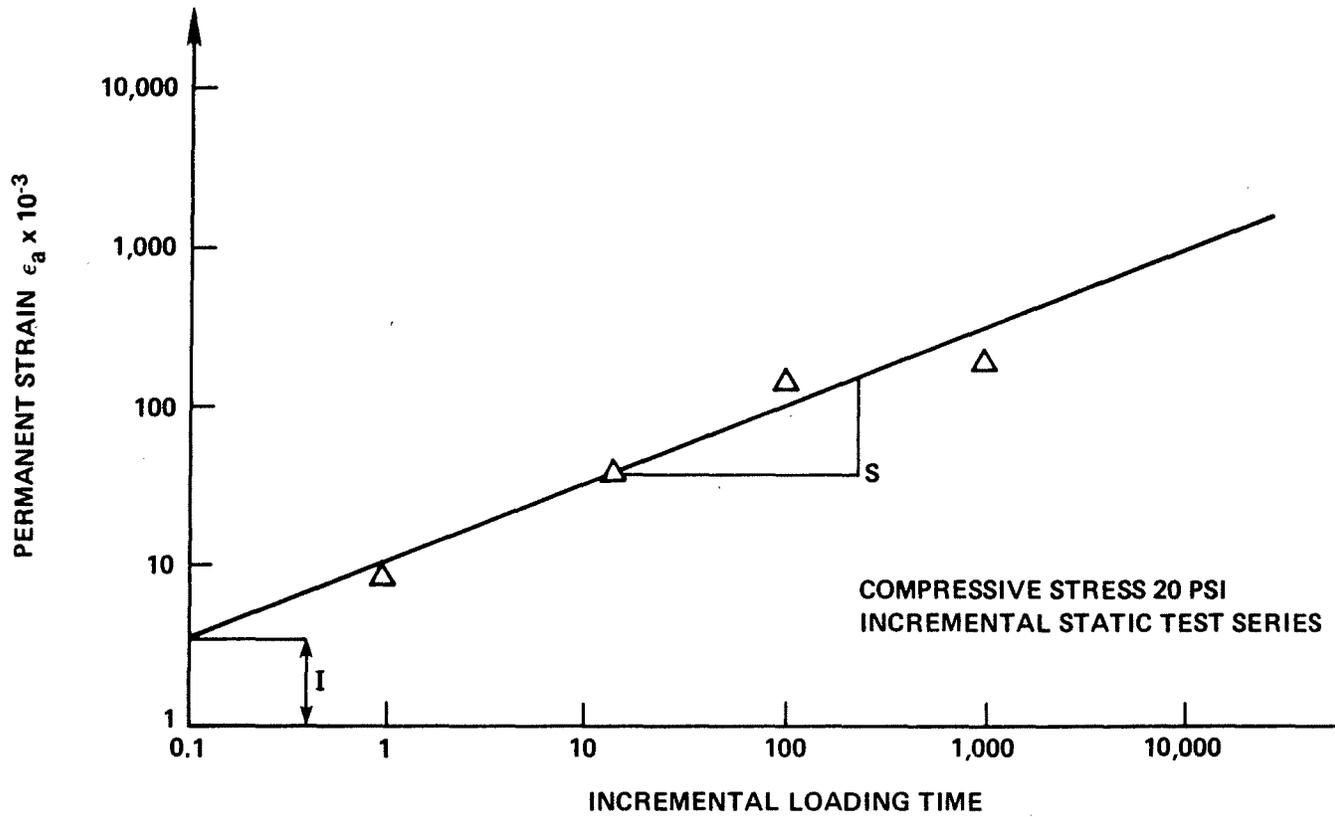


FIGURE 6.5 PERMANENT STRAIN CURVES FOR ASPHALT CONCRETE AT 70°F USING ALTERNATE PROCEDURE I

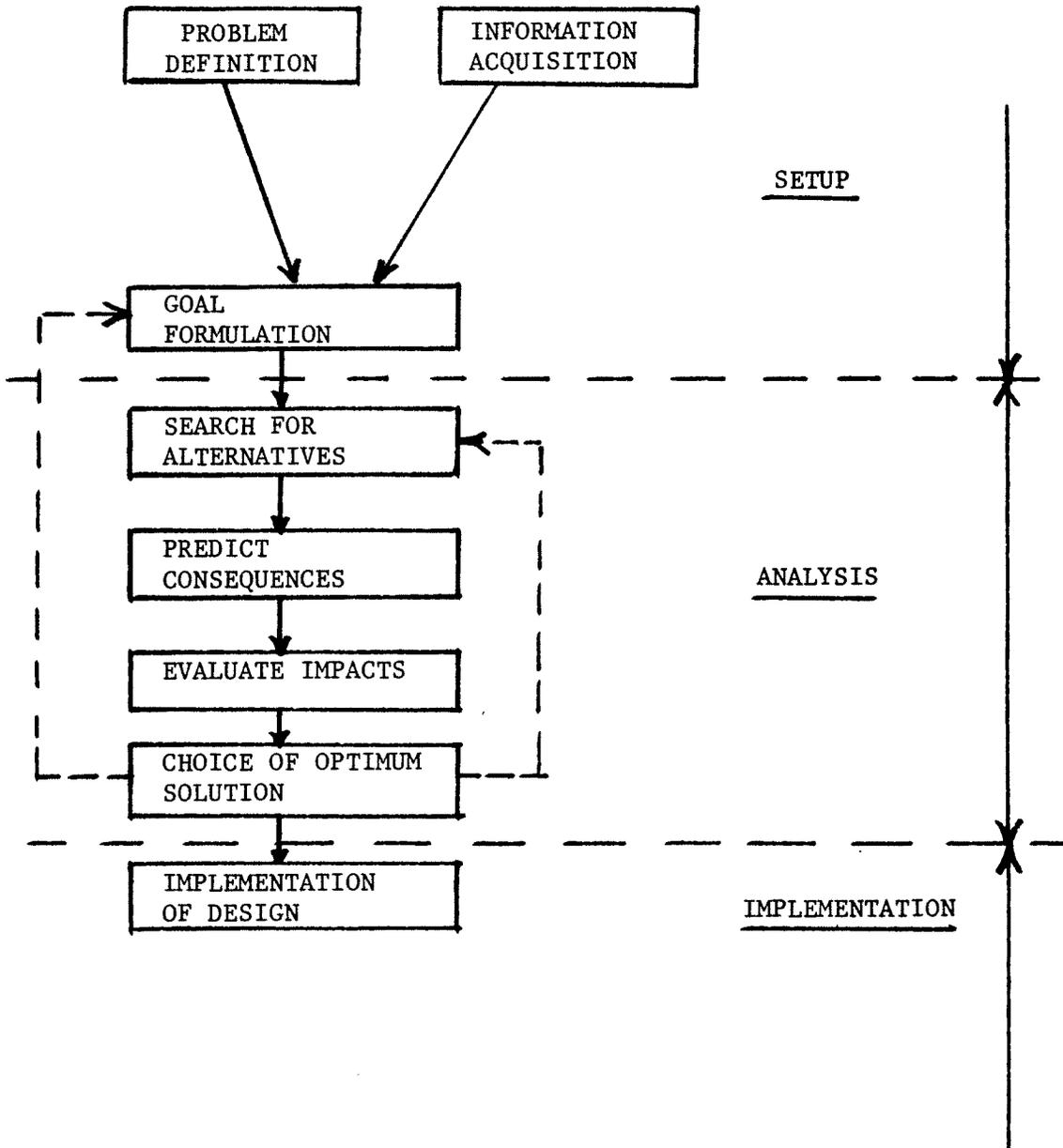


FIGURE 6.6 VESYS DESIGN PROCEDURES

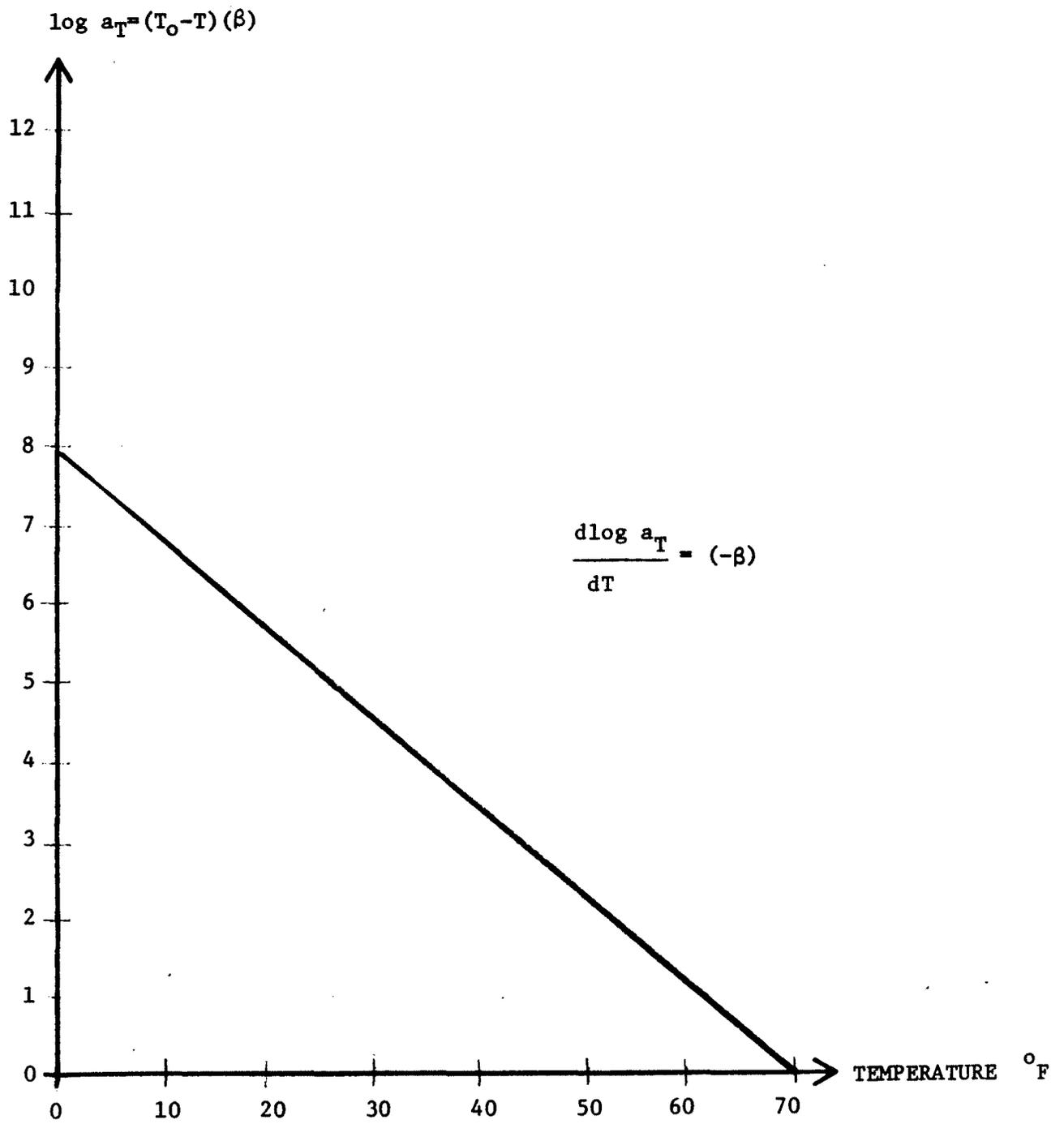


FIGURE 6.7 TIME TEMPERATURE SHIFT PRINCIPLE

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