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FLEXIBLE AND COMPOSITE STRUCTURES FOR PREMIUM PAVEMENTS

Volume 2 Design Manual

H.L. von Quintus, F.N. FINN, W.R. HUDSON, F.L. ROBERTS

~~NOVEMBER 1980~~

FINAL REPORT

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2600 DELLANA LANE • AUSTIN, TEXAS • 78746

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16. Abstract

This design manual presents the results of a detailed study to identify and design flexible and composite pavement configurations which will perform as premium or "zero-maintenance" pavements. This manual includes identification and classification of the pavement materials, design procedures for the selection of pavement configurations using wheel loads and environmental factors, and material and construction specifications necessary to achieve a "zero-maintenance" pavement. Six primary types of paving materials have been selected for use in this manual: 1) dense grade asphalt concrete, 2) portland cement concrete, 3) cement and asphalt stabilized materials, 4) granular and crushed aggregates, 5) lime, and 6) pozzolanic materials.

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PREFACE

The Federal Highway Administration has pursued for several years multiple research studies aimed at producing premium pavement structures for heavily traveled routes. The primary objective of the efforts is to minimize pavement maintenance, which disrupts traffic flow and thus creates hazards and high user costs. This general research effort has been designated as "Premium Pavements for Zero Maintenance." Its goal is the development of pavement structures that will be maintenance-free for a minimum of 20 years and will require only routine maintenance for 10 to 20 years thereafter.

This design manual has been prepared to provide information, specifications and thickness requirements for design of "zero-maintenance" flexible and composite pavements. Included in this manual are, 1) criteria for subsurface exploration, subgrade preparation and granular base requirements, 2) criteria for stabilized layers, 3) pavement thickness design recommendations and 4) criteria for considering environmental effects. The structural design of the pavement is concerned not only with minimizing cracking and rutting in a pavement structure but also considers environmental factors such as frost penetration, rainfall, and swelling soils. To accomplish the zero maintenance objective this manual considers the effects of factors such as time, traffic, pavement material properties, environmental conditions, and natural soil conditions. Additional factors influencing pavement performance, such as material and construction specifications and quality control, have also been included in development of this manual.

This is the second of two volumes; the first being Vol. I-FHWA-RD-81- , "Flexible and Composite Structures for Premium Pavements - Development of Design Procedure".

This manual was developed by a research team including Harold L. Von Quintus, Fred N. Finn, W. Ronald Hudson, Freddy L. Roberts, and Lee J. Ream with technical support from B. Frank McCullough, Thomas W. Kennedy and Professor Carl L. Monismith.

Financial support for the project was provided by the Federal Highway Administration, Office of Research and Development, Contract No. DOT-FH-11-9348. Technical coordination was provided by Mr. William J. Kenis, Sr., Contract Manager.

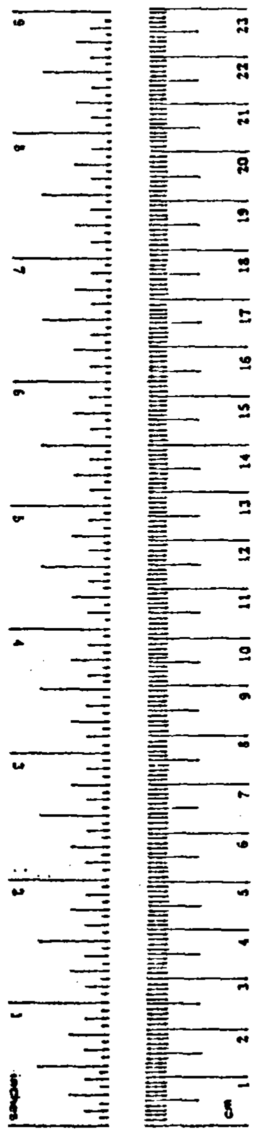
Austin Research Engineers Inc

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

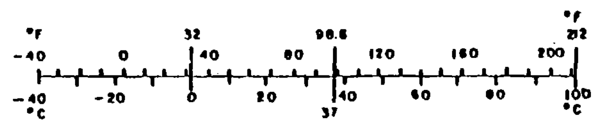
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECTION 1. INTRODUCTION

This design manual presents a method for designing premium flexible and composite pavements. A premium or "zero-maintenance" pavement is defined as a pavement structure which will perform free of structural maintenance for twenty years and will require only minimum maintenance for an additional ten to twenty years. In order to satisfy this requirement this manual incorporates and consolidates the best current flexible and composite pavement design and construction practices.

It should be emphasized that sound engineering must be used in designing not only premium pavements, but in selecting any pavement design strategy; and that it is difficult as a general design procedure to successfully couple the knowledge of performance of local materials and the service requirements for premium pavements. The structural design of premium pavements must consider not only minimizing cracking and rutting of the pavement structure but also the effects of environmental factors such as frost penetration, rainfall, and swelling soils. The effect of these environmental factors can be dominant ones that limit the maintenance-free life of a pavement.

This manual provides highway engineers with a systematic method for selecting a premium pavement design. The procedure is more complex than some empirically based systems, but is relatively easy to use. The manual includes a number of charts, figures, and worksheets along with a procedure for their use. On the basis of his design data the user selects a precalculated pavement cross section from a catalog of designs. The procedure includes a series of worksheets on which the designer can record the results of his step by step operations. For those who prefer traditional design charts, a series of nomographs for various conditions have been prepared and are included in a separate Volume I (Ref. 1[1]). In that same volume (Ref. 1), basic performance data from which the design manual was developed are clearly presented and explained.

The first part of the manual is an overview of the design system and contains an explanation of the procedure and a brief description of the factors considered in the preparation of the manual. Section 2 presents an explanation of the design inputs required for use of the procedure. Section 3 presents the "zero maintenance" design procedure and a description of each variable used in selecting the structural

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[1]Von Quintus, H.L., F.N. Finn, W.R. Hudson, and F.L. Roberts, "Flexible and Composite Structures for Premium Pavements, Volume 1, Development of Design Procedure, Final Report No. FHWA-RD-81-, Federal Highway Administration, November 1980.

crossection. Section 4 includes special considerations included in the design such as the use of shoulders, reinforcement in the concrete layers of composite pavements, and pavement drainage. Section 5 provides information on materials specifications and is extremely important in meeting the "zero-maintenance" criteria. Section 5 includes a discussion of the material properties used in development of the structural cross-sections and lists certain factors which can be varied to achieve desired material properties. Section 6 describes some of the construction specifications associated with each of the pavement layers and materials used to construct a "zero-maintenance" pavement. Included are construction specifications for 1) curing stabilized layers and portland cement concrete, 2) suggested gradation limits for drainage layers, 3) compaction requirements, and 4) other miscellaneous factors on construction and quality control which affect the pavement performance. Recognized applicable specifications for other aspects of the pavement structure should be used from established agency specifications. Section 7 contains a sample problem to demonstrate the applicability of the method.

PAVEMENT MODEL

A slightly modified version of the Federal Highway Administration's pavement model, VESYS III (Ref. 2[1]), was used as the basic model to develop the flexible pavement thickness requirements necessary to meet the "zero-maintenance" service life criteria. In VESYS the pavement structure is treated as a visco-elastic multi-layer system in which the materials are characterized by Young's modulus of elasticity, Poisson's ratio and other properties. All adjacent layers are assumed to be completely bound at the interfaces with the materials assumed to be homogeneous and isotropic. For composite pavements discrete element slab theory (Ref. 3[2]) was used to analyze the portland cement concrete layer. Use of the slab model, allows finite horizontal dimensions, consideration of boundary conditions, and consideration of different loading conditions (interior, edge, and corner) in the design process. The edge loading condition was selected for use in developing the thicknesses in these design configurations.

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[1]Kenis, W.J., "Predictive Design Procedures, VESYS Users Manual-An Interim Design Method for Flexible Pavements Using the VESYS Structural Subsystem", Report No. FHWA-RD-77-154, Federal Highway Administration, January 1978.

[2]Treybig, H.J., W.R. Hudson, and A. Abou-Ayyash, "Applications of Slab Analysis Methods to Rigid Pavement Problems", Research Report 56-26, Center for Highway Research, The University of Texas at Austin, May 1972.

The pavement cross-sections presented in this manual (Appendix A) have generally been developed using elastic layer theory, laboratory material properties, and rational performance criteria. The design parameters include 1) traffic, in terms of 18-kip (80 kN) equivalent single axle loads, which is simulated with a 9-kip (40 kN) wheel load uniformly distributed over one circular area, 2) subgrade material properties, 3) temperature, 4) moisture, and 5) paving material properties. The design system selected was based on an extensive review of pavement design principles and performance studies. Discussion of the development of this design manual including design criteria, material properties, environmental and other factors is contained in Volume I (Ref. 1).

PAVEMENT MATERIALS

Based on a review of current research describing performance of pavement materials, the project team selected a small number of candidate materials for use in this design manual. The selection of these materials for "zero-maintenance" is based on a combination of availability, economics, and previous experience. The selected materials have been classified according to their fundamental behavior and strength characteristics. Each pavement material is characterized by two parameters, strength and stiffness. The following materials are included: 1) portland cement concrete, 2) asphalt concrete, 3) crushed granular base and subbase materials, 4) stabilized or improved subgrade materials (with cement, asphalt, lime, lime-fly ash) and 5) stabilized base materials (with cement or asphalt). Each material selected is discussed in the section on material specifications.

DESIGN PRINCIPLES

The behavior of a pavement structure is dependent on the interaction between pavement response and strength of the various layers. Wheel loads induce stresses and strains in each layer which can result in deformation and cracking of bound materials. The accumulation of deformation and cracking of the pavement eventually becomes visible distress. Therefore, since pavement structural deterioration is normally associated with cracking and/or rutting, these two distress manifestations along with the accumulative damage concept have been used in designing the pavement structures.

Environmental factors may control the thickness design and material property requirements. Two environmental factors included are temperature and moisture. Temperature is considered because of 1) its effect on bituminous material properties, and 2) the frost effects to which a pavement structure might be subjected. Other moisture considerations included are a set of specific drainage requirements for the design of flexible and composite zero maintenance pavements.

DESIGN CRITERIA FOR ASPHALT CONCRETE

Four distress criteria have been selected for use in the structural design of these pavement cross sections. These include, 1) fatigue cracking, 2) rutting, 3) low temperature cracking, and 4) roughness. The limits set for each of these distress criteria were based on a thorough review of the literature and past research from both laboratory and field studies. Numerous pavement behavior variables or pavement structure responses have been used to predict rutting, cracking and roughness with time including: 1) asphalt concrete tensile strain, 2) portland cement concrete tensile stress, 3) surface deflection, and 4) subgrade vertical compressive strain. Associated with each of these responses are certain limiting criteria that have been applied in developing the design cross section. These criteria were developed based on data from conventionally designed pavement sections covering the range of design conditions. The design conditions included are strength variables, traffic applications, and environment. However, since few of these existing pavements have served as "zero-maintenance" pavements, these criteria and data are being significantly extrapolated. Therefore, some uncertainty in thickness requirements is associated with the design developed.

Material variability has, however, been considered in establishing thickness and material requirements for "zero-maintenance" pavements. Many pavements have required structural maintenance because of material property variations within a given project. Therefore, in developing the design cross-sections presented herein, a 90 percent confidence level was used.

Fatigue Cracking

Past observations of flexible pavement performance indicate that low levels of fatigue cracking can be tolerated before maintenance is required. In developing the design requirements for premium pavements, ten percent fatigue cracking in the wheel paths was selected as an allowable value for flexible pavements while five percent cracking was selected for composite pavements. The structural thickness requirements for flexible pavements were based on limiting asphalt concrete tensile strain (Ref. 4[1]) and for composite structures were based on a limiting concrete tensile stress (Ref. 5[2]). Relationships relating stress or strain for a given concrete strength or asphalt concrete modulus and performance were developed and are presented graphically in Figures 1.1 and 1.2 and are explained in Reference 1.

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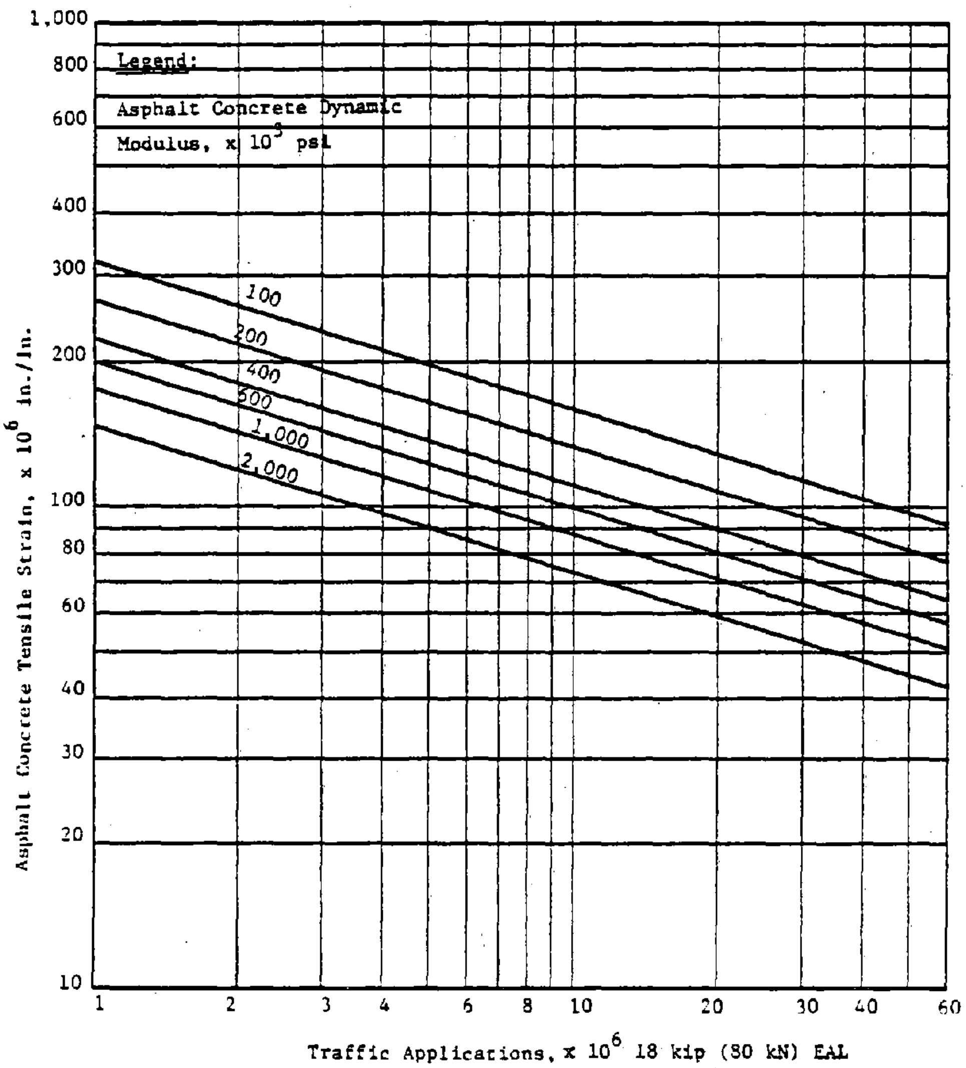
[1]Finn, F.N., C. Saraf, R. Kulkarni, K. Nair, W. Smith, and A. Abdullah, "Development of Pavement Structural Subsystems", Final Report, NCHRP Project 1-10B, National Cooperative Highway Research Program, Highway Research Board, February 1977.

[2]Treybig, H.J., B.F. McCullough, P. Smith, and H. Von Quintus, "Overlay Design and Reflection Cracking Analysis for Rigid Pavements, Volume 1, Development of New Design Criteria", Final Report No. FHWA-RD-77-66, Federal Highway Administration, August 1977.



1 in. = 2.54 cm 1 psi = 6.89 kPa

Figure 1.1 Asphalt Concrete Fatigue Curves Used to Establish the Structural Thickness Requirements (Ref. 1).

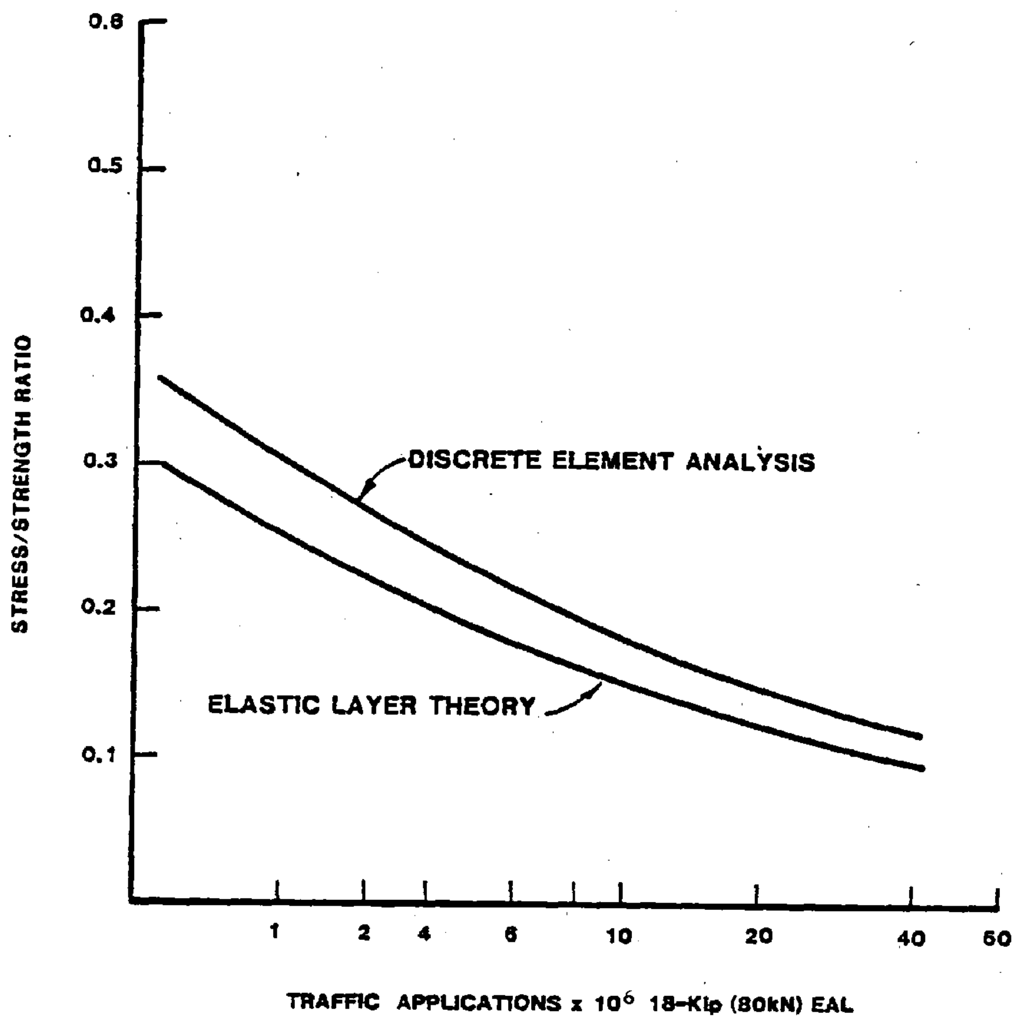


Figure 1.2 Portland Cement Concrete Fatigue Curves Used to Establish the Structural Thickness Requirements (Ref. 1).

Rutting

Past observations of flexible pavement rutting have been correlated to maintenance needs. These studies indicate that 0.4 inch (1 cm) rut depth requires no maintenance. Hence, a rut depth of 0.4 inch (1 cm) was selected as the limiting criteria which could not be exceeded for both the flexible and composite pavement structures.

Transverse Cracking

Some temperature related cracking must be expected in asphalt concrete pavements and certainly a small amount of temperature related cracking will generally not be detrimental to the performance of the pavement structure. Therefore in developing the material requirements for the asphalt concrete surface, an allowable crack spacing of 30 ft (9 m) was used in the design manual (Ref. 1). However, if special subgrade conditions exist where cracking must be eliminated, special considerations must be applied in the design of zero-maintenance pavements.

Surface Deflection

Surface deflection has been related to field performance (Ref. 6[1]). Hence, Figure 1.3 was used to determine the permissible surface deflection, depending on the desired traffic level, for developing the zero-maintenance cross-sections.

Subgrade Vertical Compressive Strain

Field studies have also shown that certain levels of permissible subgrade vertical compressive strains can be related to adequate performance (Ref. 7[2]). Since this strain is a function of the traffic level and modulus of the existing subgrade materials, a relationship was developed for use in developing the thickness requirements for the pavement structure as shown in Figure 1.4.

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[1]Lister, N.W. and C.K. Kennedy, "A System for the Prediction of Pavement Life and Design of Pavement Strengthening", Volume 1, Fourth International Conference Structural Design and Asphalt Pavements, The University of Michigan, August 1979.

[2]Barker, W.R. and W.N. Brabston, "Development of a Structural Design Procedure for Flexible Airport Pavements", FFA Report No. FAA-RD-74-199, U.S. Army Engineer Waterways Experiment Station, Federal Aviation Administration, September 1975.

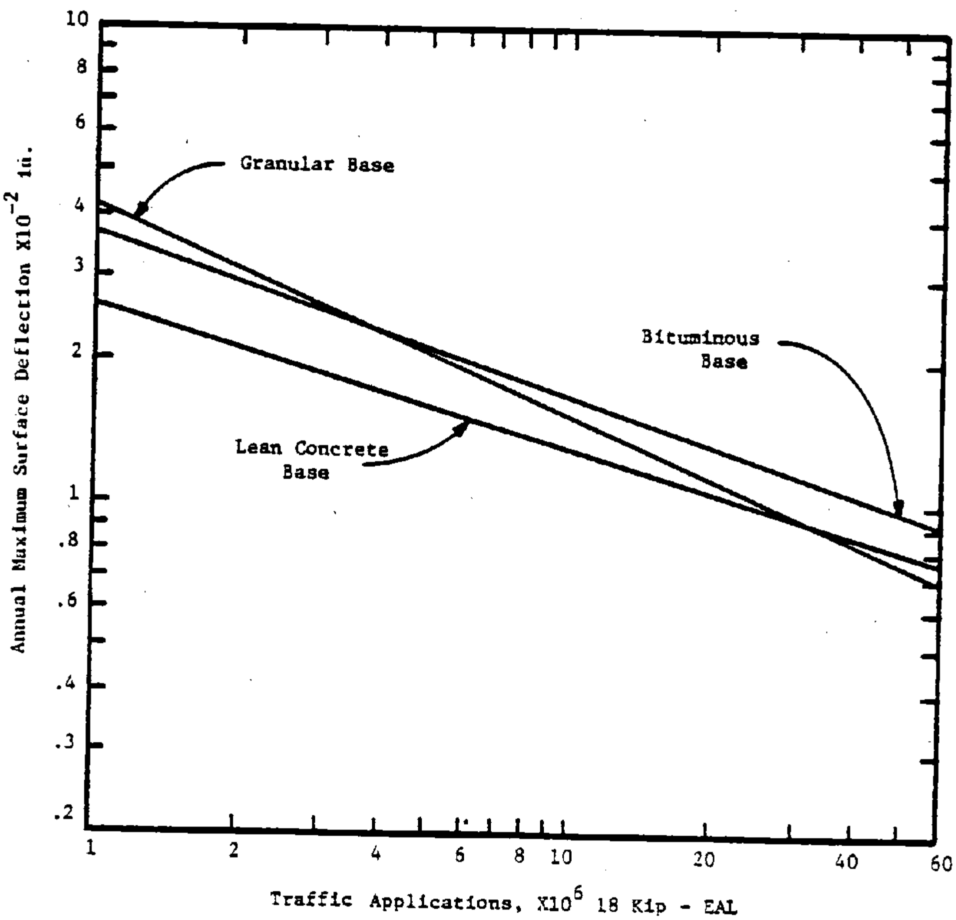
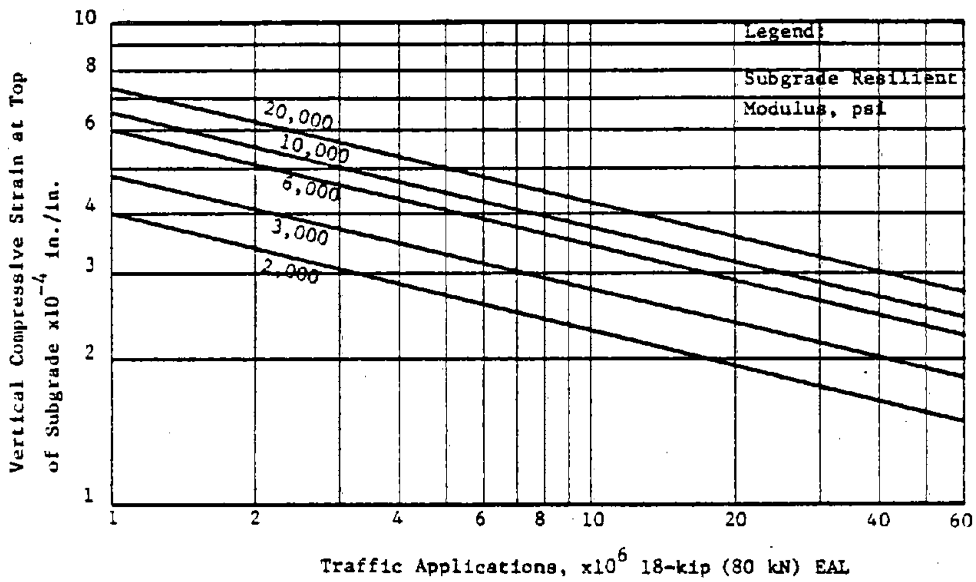


Figure 1.3 Allowable Maximum Surface Deflection Used to Develop the Structural Cross-Section for Each Pavement Type (Ref. 6).



1 in. = 2.54 cm
1 psi = 6.89 kPa

Figure 1.4 Allowable Subgrade Vertical Strain Used to Develop the Structural Cross-Section for the Zero-Maintenance Pavement.

Roughness

Representatives from several state highway agencies have indicated that for Interstate highways when the present serviceability index (PSI) reaches a value of 3.0 they expect that maintenance activities begin to be required. Since the premium pavements dealt with in this design manual require service standards similar to those for Interstate highways, a limiting PSI value of 3.0 was selected for use in developing these design cross-sections.

CLIMATIC FACTORS

In this design manual two climatic factors that influence the structural behavior of a pavement are considered, temperature and rainfall. Temperature influences not only the stiffness and fatigue properties of many materials but is also a major factor in frost penetration and freeze-thaw characteristics. Rainfall or moisture conditions also influence the stiffness and stress-sensitivity of unbound pavement materials.

Temperature Effects

Temperatures within a pavement structure usually vary widely throughout the year and affect many material property and environmental variables. The effect of temperature on asphalt concrete pavements is especially important since the fatigue characteristics of bituminous concrete are temperature dependent. Hence, fatigue damage depends not only on the strain at the bottom of the asphalt concrete layer, but also upon the temperature of the asphalt concrete layer. This design manual requires determination of pavement temperature for each season using a procedure developed by Barber (Ref. 8[1]).

Only the effect of temperature on frost penetration is considered for subgrade materials. The present criteria for determining minimum required thicknesses for frost penetration have been developed and are included in the FAA Advisory Circular AC-150/5320-6B (Ref. 9[2]) and in the Department of Army Technical Manual TM5-818-2 (Ref. 10[3]). Since the subgrade may become weakened during the spring-thaw, frost penetration

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[1]Barber, E.S., "Calculations of Maximum Pavement Temperatures from Weather Reports", Bulletin 168, Highway Research Board, 1957.

[2]FAA Advisory Circular, AC-150/5320-6B, "Airport Pavement Design and Evaluation", Department of Transportation, Federal Aviation Administration, May 28, 1974.

[3]"Soils and Geology - Pavement Design for Frost Conditions", TM 5-818-2, Department of the Army Technical Manual, Headquarters, Department of the Army, July 1965.

must be considered in design of the pavement structures. This occurs because even though the thaw period generally occurs over a relatively short period of time, the weakened subgrade condition can continue for many months. For simplicity, the length of the thaw period was initially selected as one month. However, if the strength loss is large, a longer period of reduced strength may occur as the strength values increases at a decreasing rate. In considering the frost effects on pavement materials the design manual was developed based on two conditions. These are: 1) design for total protection of the subgrade and 2) design for partial protection that permits some reduction in strength of frost susceptible subgrades. In estimating the depth of frost penetration, the procedure reported by Aldrich (Ref. 11[1]) was used to develop the design charts.

Moisture Effects

In the characterization of unbound materials, the strength and stiffness vary with variations in moisture content. To minimize these effects, this design procedure has included a requirement that good drainage of the pavement structure be provided. Hence, a reduction in strength of unbound materials was not used in the development of the design cross sections. This drainage system is assumed to remain serviceable for the complete design period (30 to 40 years). It should be understood that to meet these design conditions, a granular base material should never be placed over a less porous or stabilized material without sufficient drainage.

The resilient modulus of subgrade soils is normally very sensitive to changes in moisture content. Since moisture contents in the subgrade soil may increase with time, subgrade materials must be characterized not at the moisture content at construction but at a higher level. Because drainage is required, the subgrade has been characterized at a moisture content slightly above the construction optimum but not at saturation. However, if frost is allowed to penetrate the subgrade material, the strength will vary as discussed in later sections of this report.

[1]Aldrich, C.P., Jr., "Frost Penetration Below Highway and Airfield Pavements", HRB Bulletin No. 135, Highway Research Board, 1956.

SECTION 2. DESIGN INPUTS

In order to use this design manual, the designer must collect basic information on 1) environmental factors, including temperature and air freezing index, 2) natural or existing soil properties, and 3) traffic. A worksheet for tabulating this information (Worksheet A) is given in Figure 2.1.

ENVIRONMENTAL FACTORS

In this design manual temperatures are used to modify asphalt concrete properties and determine depth of frost penetration. The temperature values required are: 1) mean annual air temperature (MAAT) 2) warmest mean monthly air temperature (WMMAT) and 3) the coldest mean monthly air temperature (CMMAT). These air temperatures are obtained from climatological records (Ref. 12[1]) and then recorded on Worksheet A (Figure 2.1). These temperature values are used to reflect the effects of other environmental factors, such as solar radiation, daily temperature variations, and minimum design temperature for specific areas in the U.S. Hence, the effect that these different environmental variables have on pavement material properties are quantified collectively and simplified for use in the design procedure. For a detailed description of these terms and their effects, the designer is referred to Volume 1 (Ref. 1).

Air freezing index values are less readily available than the temperature information. Hence, Figure 2.2 can be used to estimate air freezing index for various locations in the U.S. This value is also recorded on Worksheet A (Figure 2.1).

NATURAL SOIL PROPERTIES

The subgrade modulus is used in this manual as one of the principal design parameters. Since the modulus of most subgrade soils is dependent on the state of stress, the subgrade modulus should be based on in-situ or expected field conditions; e.g. a moisture content and density which the soil is likely to reach under the pavement structure. This equilibrium moisture content is usually similar to that found at a depth of about 3 feet (1 m) in the natural soil. An appropriate method for determining the modulus of the subgrade is described in Appendix B. In

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[1]"Local Climatological Data", Annual Summaries for 1977, Part I and II, National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, North Carolina, 1977.

"ZERO-MAINTENANCE" DESIGN

INPUT-WORKSHEET A

Project:______________________ Date:______________________

Location:____

ENVIRONMENTAL DATA

(1) Mean Annual Air Temperature (MAAT), °F	
(2) Warmest Mean Monthly Air Temperature (WMMAT), °F . .	
(3) Coldest Mean Monthly Air Temperature (CMMAT), °F . .	
(4) Mean Monthly Air Temperature Change, (MMATC), °F (MMATC = WMMAT - CMMAT)	
(5) Design Air Freezing Index (Figure 2.2)	

NATURAL SOIL DATA

	Soil I	Soil II	Soil III
(6) Boring Number			
(7) Boring Location			
(8) Soil Type: Unified Soil Classification and P. I. ( ) . . .	( )	( )	( )
Percent finer than 0.02 mm . . .			
Frost Soil Classification (Table 2.2, Figure 2.3)			
(9) Subgrade Stiffness (Appendix A) .			
(10) Water Table Depth, ft.			

TRAFFIC DATA

(11) Design Applications 18-kip (80 kN) Equivalent Axle Loads (EAL) in Design Lane (Worksheet B, Figure 2.4)	

Figure 2.1 Worksheet Tabulating the Input Information Required to Use This Design Manual.

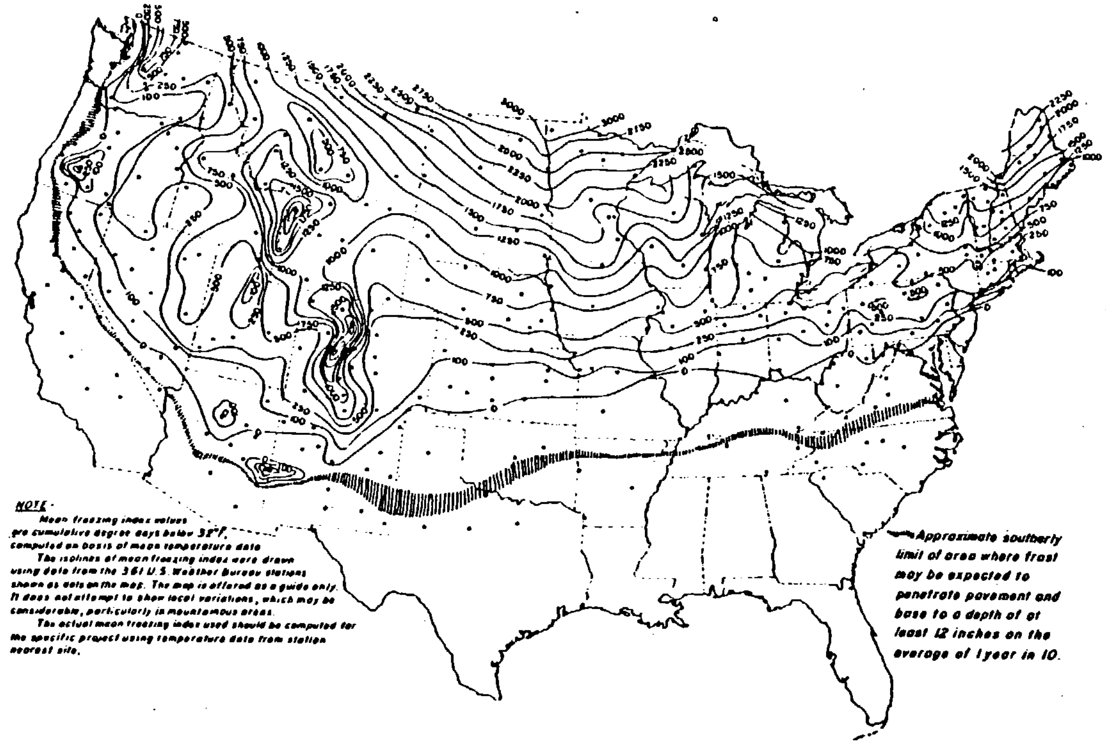

Figure 2.2 Distribution of Design Air Freezing Index Values in the Continental United States (Ref. 11).

Appendix B the resilient modulus is determined a function of stress and confining pressure. The test should be performed on undisturbed specimens or on specimens which are recompacted to a moisture content and density which are similar to in-situ conditions under the actual pavement. Suggested steps which can be followed to obtain information on natural soil properties are presented below:

1. Make a complete and thorough investigation of the topographic and subgrade conditions.

2. Conduct exploratory borings at a spacing and depth prescribed by the engineer. The spacing and depth of these borings are dependent on the variability of the existing soil conditions, both vertically and horizontally. These borings should also be used to determine the water table depth. Take sufficient and appropriate auger, split tube, or undisturbed samples at all representative subsoil layers. Prepare boring logs and soil profiles.

3. Classify all soils using the Unified soil classification system. Table 2.1 relates the Unified soil classification of a material to the relative value of a material for use as a pavement. The modified Proctor moisture-density test should be used to determine the compaction characteristics for soil and untreated pavement materials. The degree of compaction required or the in-place density should be expressed as a percentage of the maximum density from the modified Proctor test.

4. Determine the frost susceptibility of all soils encountered. Table 2.2 and Figure 2.3 can be used as an aid in assigning a soil to a frost group using the Corp of Engineers procedure (Ref. 10). For a detailed discussion of frost susceptibility of soils relative to frost heave and the resulting strength reduction please see Volume 1 (Ref. 1).

5. Examine the boring logs, soil profiles, and classification tests and select representative soil layers for design testing. Using the procedures outlined in Appendix B, determine a resilient modulus for each type of subgrade soil encountered.

6. Use the soil profile to relate resilient modulus to each type of subgrade soil encountered along the alignment. Select a design subgrade resilient modulus that is representative of each boring. For design purposes it is recommended that the weakest subgrade layer be selected as the design resilient modulus, unless the material is removed, improved or stabilized.

Record the selected soil properties on Worksheet A which has columns for three different soil types.

TABLE 2.1 SUMMARY OF SOIL CHARACTERISTICS AS A PAVEMENT MATERIAL

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Gravel and Gravelly Soils	GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	None to very slight	Almost None	Excellent
	GP	Poorly graded gravels or gravel-sand mixtures little or no fines	Good to excellent	None to very slight	Almost None	Excellent
	GM *d	Silty gravels, gravel-sand silt mixtures	Good to excellent	Slight to medium	Very slight	Fair to poor
	GM u		Good	Slight to medium	Slight	Poor to practically impervious
	GC	Clayey gravels, gravel-sand-clay mixture	Good	Slight to medium	Slight	Poor to practically impervious
Sand and Sandy Soils	SW	Well-graded sands or gravelly sands, little or no fines	Good	None to very slight	Almost None	Excellent
	SP	Poorly graded sands or gravelly sands, little or no fines	Fair to good	None to very slight	Almost None	Excellent
	SM *d	Silty sands, sand-silt mixtures	Fair to good	Slight to high	Very Slight	Fair to poor
	SM u		Fair	Slight to high	Slight to medium	Poor to practically impervious
	SC	Clayey sands, sand-clay mixtures	Poor to fair	Slight to high	Slight to medium	Poor to practically impervious

TABLE 2.1 SUMMARY OF SOIL CHARACTERISTICS AS A PAVEMENT MATERIAL (CONTINUATION)

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Silts and Clays LL is less Than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sand or clayey silts with slight plasticity	Poor to fair	Medium to very high	Slight to medium	Fair to poor
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays silty clays, lean clays	Poor to fair	Medium to high	Slight to medium	Practically impervious
	OL	Organic silts and organic silt-clays or low plasticity	Poor	Medium to high	Medium to high	Poor
Silts and Clays LL is greater Than 50.	ME	Inorganic silts, micaceous or diatomaceous fine sand or silty soils, elastic silts	Poor	Medium to very high	High	Fair to poor
	CH	Inorganic clays of high plasticity, fat clays	Poor to fair	Medium to very high	High	Practically impervious
	OH	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Medium	High	Practically impervious
Highly Organic Soils	Pt	Peal and other highly organic soils	Not suitable	Slight	Very high	Fair to poor

* d is used when the liquid limit is 25 or less and the plasticity index is 5 or less.
u is used in all other cases.

TABLE 2.2. FROST DESIGN SOIL CLASSIFICATION (REF. 10)

Frost Group	Kind of Soil	Percentage Finer than 0.02 mm by Weight	Typical Soil Types Under Unified Soil Classification System
F1	Gravelly soils	3 to 10	GW, GP, GW-GM, GP-GM
F2	(a) Gravelly soils	10 to 20	GM, GW-GM, GP-GM
	(b) Sands	3 to 15	SW, SP, SM, SW-SM, SP-SM
F3	(a) Gravelly soils	Over 20	GM, GC
	(b) Sands, except very fine silty sands	Over 15	SM, SC
	(c) Clays, PI 12	--	CL, CH
F4	(a) All silts	--	ML, MH
	(b) Very fine silty sands	Over 15	SM
	(c) Clays, PI < 12	--	CL, CL-ML
	(d) Varved clays and other fine-grained banded sediments	--	CL and ML; CL, ML, and SM; CL, CH, and ML; CL, CH, ML, and SM

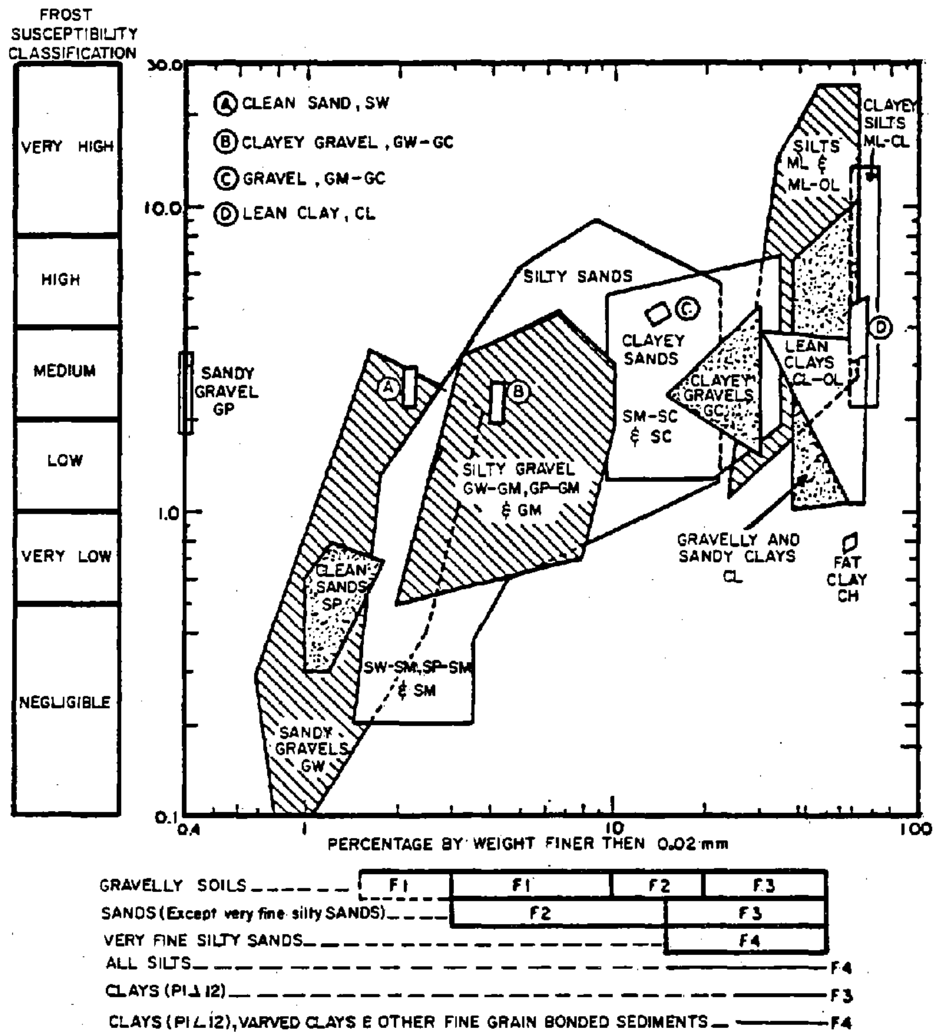

Figure 2.3. Average Rate of Heave VS. Percentage Finer than 0.02 mm for Natural Soil Gradations (Ref. 10).

TRAFFIC

Traffic is usually expressed in 18-kip (80 kN) equivalent single-axle loads as presented in the AASHTO Interim Guide (Ref. 13[1]) and as developed at the AASHO Road Test (Ref. 14[2]). In this design manual, total traffic is also expressed as the number of 18-kip (80 kN) equivalent axle loads (EAL) which occur during the minimum 20 year maintenance-free design life. The design lane traffic may be computed using Traffic Worksheet B contained in Figure 2.4. The projected number of axles for each load category is listed on Worksheet B. The number of axles in each axle load category is then multiplied by a load conversion factor to obtain the equivalent number of 18-kip (80 kN) single axle loads. For simplicity the AASHTO equivalency factor for a terminal serviceability of 3.0 can be used and are provided in Appendix C. The number of 18-kip (80 kN) single axle loads are summed to obtain the total axles per lane per day. The cumulative number of axles during the design life is calculated by multiplying the number per day for the design lane by a summation factor from Table 2.3 and recorded on Worksheets A and B.

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[1]"AASHTO Interim Guide for Design of Pavement Structure 1972", American Association of State Highway and Transportation Officials, Washington, D.C., 1974.

[2]"The AASHO Road Test, Report 5 - Pavement Research", HRB Special Report 61E, Highway Research Board, Washington, D.C., 1962.

"ZERO-MAINTENANCE" DESIGN

TRAFFIC-WORKSHEET E

Project:______________________ Date:______________

Location:______________

(1) Axle Load L, kips	(2) Projected Number of Axles per day (Design Lane), N	(3) Equivalency Factor, E (Appendix B)	(4) Projected Equivalent Number of 18 kip (80 kN) axles per day (Design Lane), Ne

(5) Total Projected Number of Equivalent 18-kip (80 kN) axles per day (Design Lane) ______________

(6) Total Projected Number of Equivalent 18 kip (80 kN) per year (Design Lane), (5)x365= ______________

(7) Growth Rate Projected for Design Period ______________

(8) Design Life of Pavement for Zero-Maintenance, Years ______________

(9) Traffic Summation Factor (Table 2.5) ______________

(10) Total Projected Number of 18-kip (80 kN) axles in Design Lane, (6)x(9) = ______________

Figure 2.4 Worksheet for Obtaining the Design Number of 18-kip (80kN) Equivalent Axle Loads.

TABLE 2.3 TRAFFIC SUMMATION FACTORS*

Growth Rate, % \ Design Life, Years	15	20	25	30	35	40
1	16	22	28	35	42	49
2	18	25	33	41	51	62
3	19	28	38	49	62	78
4	21	31	43	58	76	99
5	23	35	50	70	93	127
6	25	39	58	84	118	164
7	27	44	68	101	148	214
8	29	49	79	122	186	280
9	32	56	92	149	235	365
10	35	63	108	181	298	487

$$* F_Y = \sum_{n=1}^{Y} \left(1 + \frac{r}{100}\right)^n$$

r = Rate of Growth, %
n = Time Interval (1 Year)
Y = Design Life, years

SECTION 3. STRUCTURAL THICKNESS

This chapter contains the basic step-by-step procedure to be used in developing a design configuration for a project using information from the design charts, tables, and worksheets contained in this chapter, the designer will be able to go to Appendix A and select a design cross-section that will meet the design criteria for premium pavements within the limits of confidence of the input data.

A comprehensive series of research and performance studies were examined and/or conducted to develop the design procedures presented herein. While a large number of variables and a large number of combinations of factors were considered, all have several things in common. Zero-maintenance traffic levels are always very high. Only materials with good engineering properties are satisfactory for use in zero-maintenance pavements. After consideration of the ranges of values appropriate for these two factors, it was determined that many of the potential solutions fell within a restricted range of material properties and design thicknesses. Under these conditions, the best method of presentation was selected to be a catalogue of designs based on the limiting criteria, the design parameters associated with a mechanistic design procedure and combined with experience. Such a catalogue is presented here for use in Appendix A.

The catalogue of designs contained in Appendix A was developed from previous experience and optimization of various criteria using the mechanistic procedure discussed in detail in Volume 1 (Ref. 1). The catalogue of designs includes combinations of predetermined 1) traffic conditions, 2) environmental conditions, 3) materials and 4) subgrade conditions. Even though the method is applicable to most situations, it is recommended that the designer review the basic mechanistic procedures included in Volume 1 (Ref. 1) before using the method.

The basic selection of pavement design strategies for premium pavements is accomplished using the Cross Section Worksheet C contained in Figures 3.1 and 3.2. The information and guidelines for use of the worksheet are described below.

PAVEMENT TYPE

The engineer should select a pavement type for use in the calculation sequence to follow. He may select a design that consists of either full depth or conventional asphalt concrete, including various layer configurations or perhaps use low modulus continuously reinforced or jointed concrete pavement as the load carrying layer in a composite pavement configuration. Once the pavement type has been selected, based largely on service life of the various pavement types under very heavy traffic situations, the pavement type selected should be entered in the cross-section Worksheet C line (1).

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C*

Project ______________________________ Date ____________

Location ____

(1) Pavement Type: ______________________________

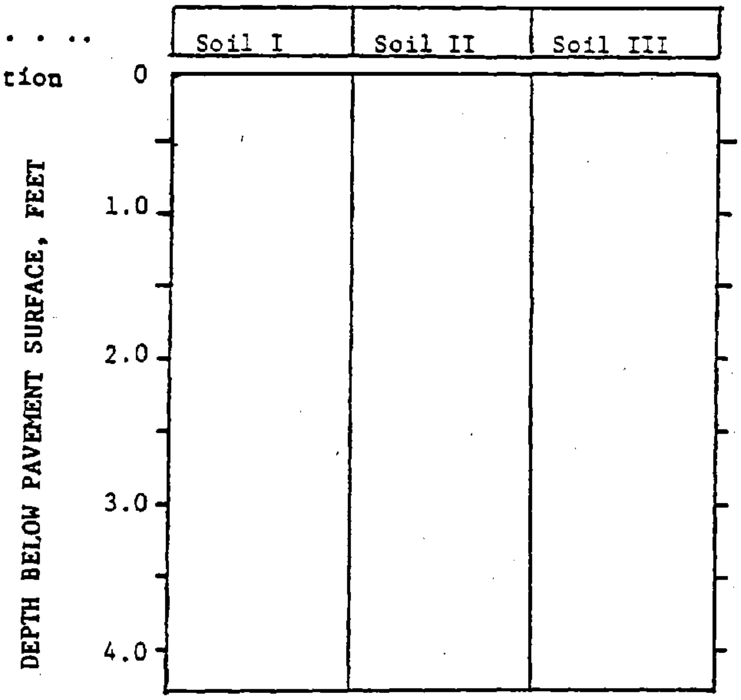
(2) Environmental Region No. (Figure 3.3)... ____________

(3) Asphalt Cement Grade (Figure 3.6). . ____________

(4) Effective Asphalt Concrete Modulus
(Figure 3.7 line 13), psi ____________

(5) Design Section . . . . . .

(6) Cross-Section Selection
(Appendix A)



	Soil I	Soil II	Soil III
(7) Frost Penetration Below Pavement Surface (Figure 3.15 - 3.17) feet			
(8) Increased Thickness of Non-Frost Susceptible Material (Figures 3.15 - 3.20).			

1 psi = 6.89 kPa
1 ft = 0.3048 m

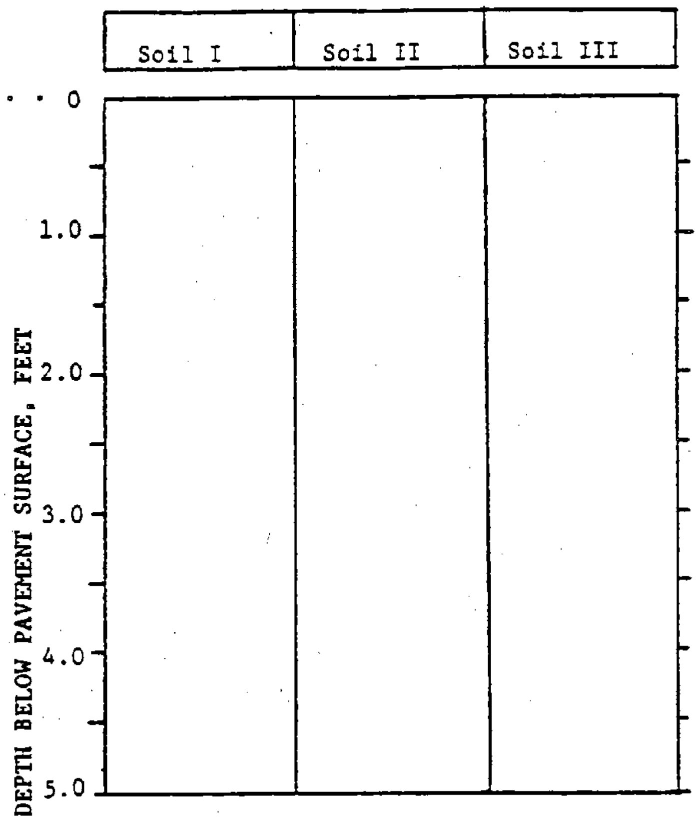
*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure 3.1 Worksheet for Determining the Initial Zero-Maintenance Structural Cross-Section.

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C *

(9) Cross-Section Thickness Determination, (6), (7), (8) in . . . .



1 ft = 0.3048 m
1 in = 2.54 cm

*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure 3.2 Worksheet for Determining the Final Zero-Maintenance Structural Cross-Section.

In this volume, the definition for each of the pavement types considered are listed below:

1. A full depth pavement is defined as a pavement in which asphalt mixtures are used for all courses or layers above the subgrade material or improved subgrade material.

2. A conventional pavement is defined as a pavement composed of layers of asphalt mixtures supported by untreated layers of aggregate placed on the subgrade material.

3. A composite pavement is defined as a pavement composed of a wearing surface of asphalt mixtures placed on a relatively rigid supporting layer of stabilized material which may or may not be supported by untreated aggregate on the subgrade material.

TEMPERATURE

The effect of temperature on the response of a pavement structure is considered by the use of an environmental region designation. The relationships shown in Figure 3.3 are used along with local temperatures to determine a region number. These temperature data can be secured either through offices of the National Oceanic and Atmospheric Administration (Ref. 12) or the local U.S. Weather Bureau. To determine the region number for a particular construction site, values for the mean annual air temperature, the warmest mean monthly air temperature (WMMAT), and the coldest mean monthly air temperature (CMMAT) must be secured. The Figure 3.3 relationships are then used along with the mean annual air temperature and the mean monthly air temperature variation (WMMAT - CMMAT) to establish the region number for the site. This region number is then entered into Worksheet C line (2).

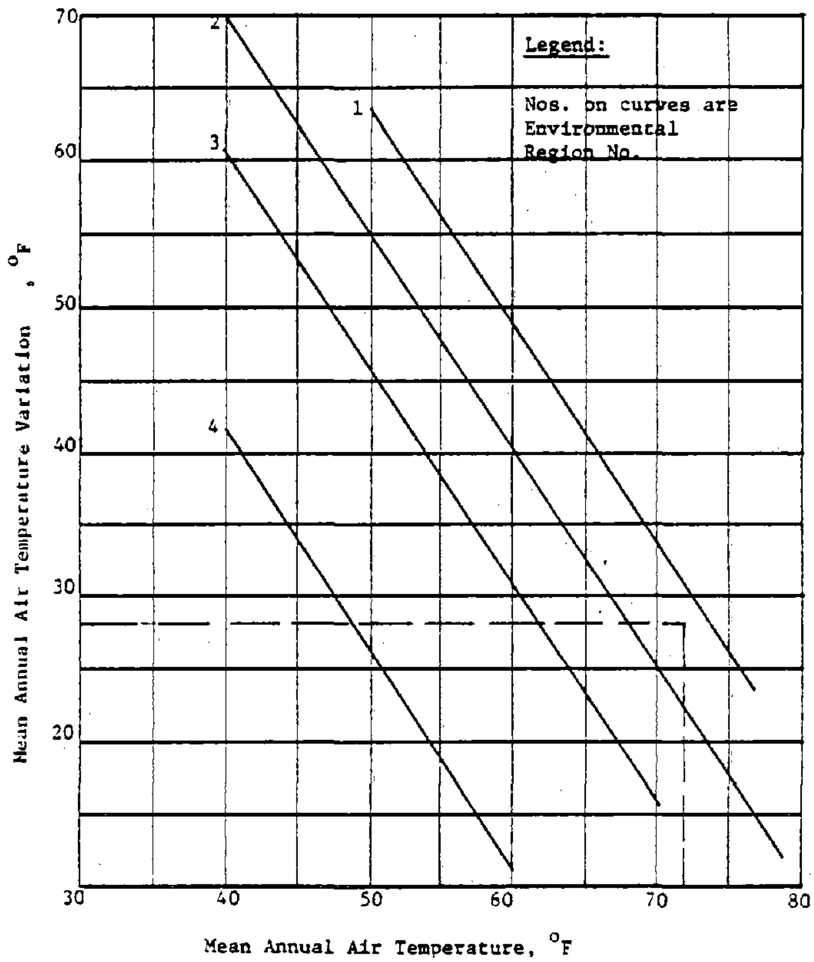
ASPHALT CEMENT GRADE

Figure 3.4 or 3.5 is used to estimate the minimum pavement temperature expected for a particular mean annual air temperature and environmental region. This minimum pavement temperature is then used in Figure 3.6 so that the asphalt cement grade selected will meet the low temperature cracking criteria built into the design procedure.

EFFECTIVE ASPHALT CONCRETE MODULUS

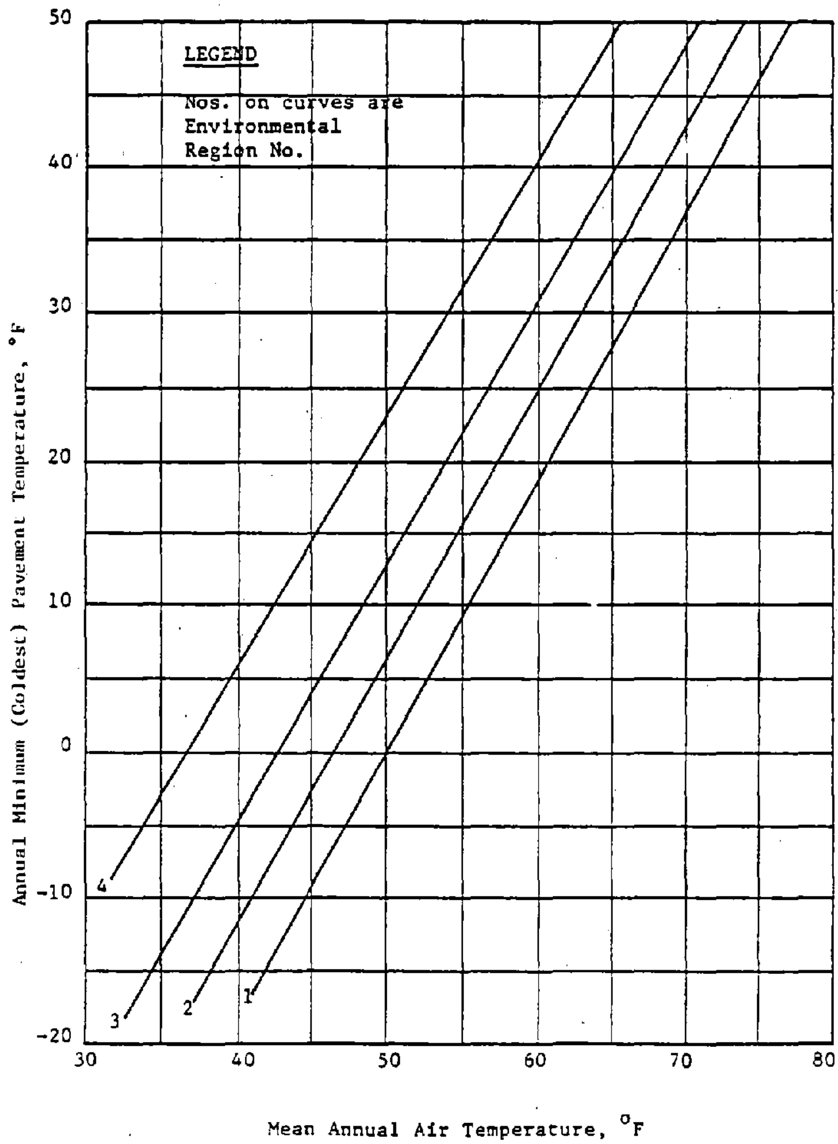
Variations in ambient temperature produce significant changes in the modulus of asphalt concrete materials. A procedure was developed that includes a weighted mean asphalt concrete modulus that is determined for each asphalt cement type and climate. The term effective or weighted mean asphalt concrete modulus was developed to consider the effects of temperature variations on fatigue cracking. These effects

Example:
Mean monthly maximum temperature - 81°F
Mean monthly minimum temperature - 53°F
Mean monthly variation - 28°F
Mean annual temperature - 72°F
Environmental Region 1



°C = (°F - 32)/1.8

Figure 3.3 Determination of the Environmental Region Number



°C = (°F - 32)/1.8

Figure 3.4 Estimation of the Annual Minimum (Coldest) Pavement Temperature for Dry Environments (Average Yearly Rainfall < 12 in).

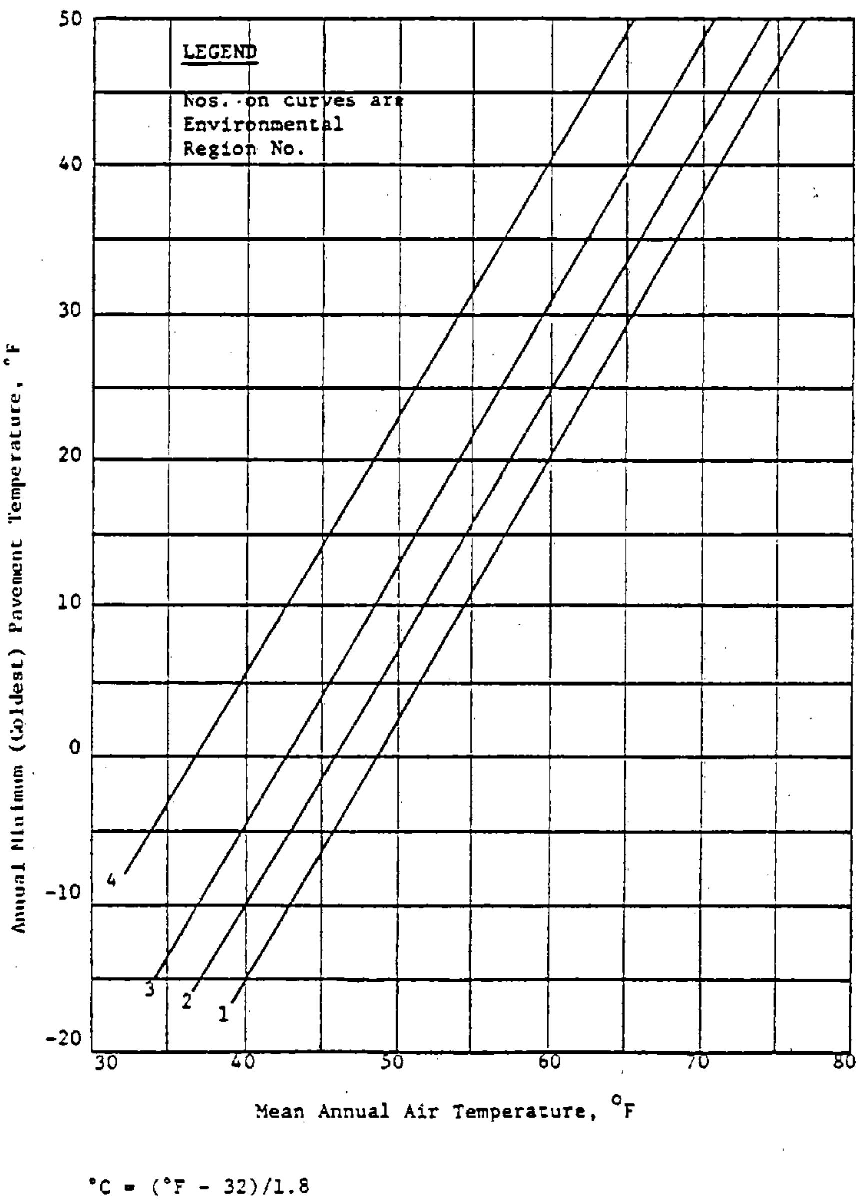
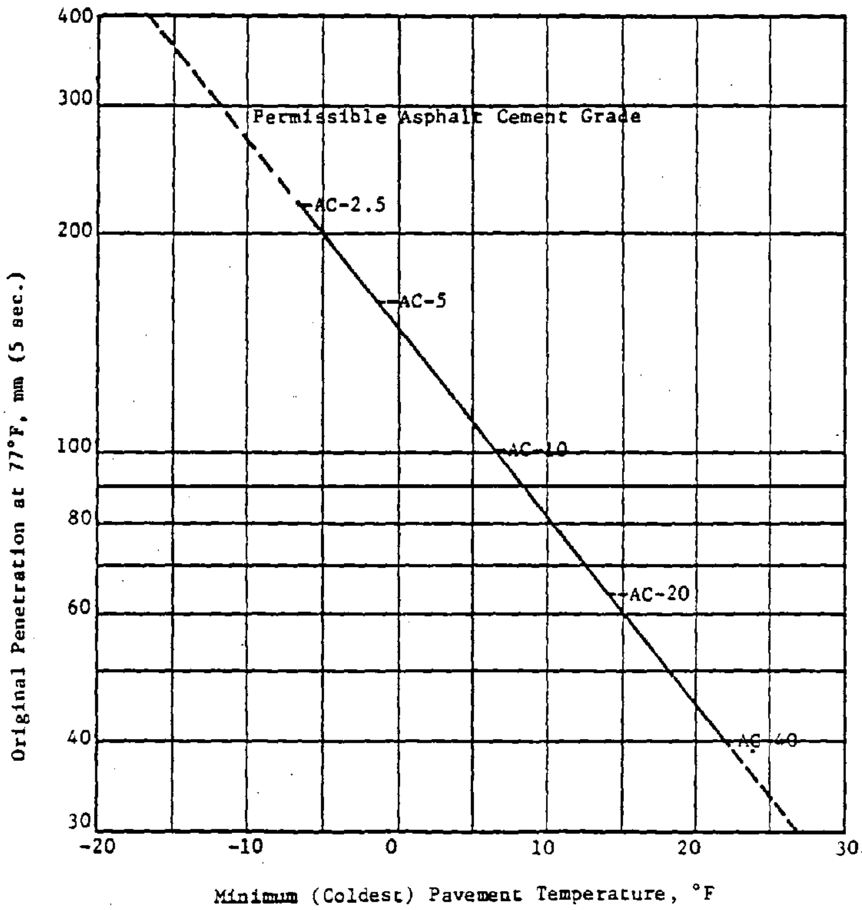


Figure 3.5 Estimation of the Annual Minimum (Coldest) Pavement Temperature for Wet Environments (Average Rainfall > 12 in).



°C = (°F − 32)/1.8

Figure 3.6 Determination of the Asphalt Cement Grade or the Allowable Original Penetration for Asphalt with a Penetration Index of −1.0.

cannot be adequately determined simply by averaging the asphalt concrete modulus over all seasons because of the interaction of temperature and modulus with the fatigue damage produced in the pavement. The effective asphalt concrete modulus for a particular asphalt mix and climate is computed using Worksheet D (Figure 3.7). First the seasonal pavement temperature values are determined using one of Figures 3.8 thru 3.12. Using each seasonal pavement temperature and the viscosity of the asphalt cement, asphalt concrete modulus is determined from Figure 3.13 as developed from relationships reported by Witczak (Ref. 15[1]) and contained in Appendix D. These modulus values for each temperature are entered in Worksheet D. For each asphalt concrete modulus a fatigue factor is then determined from Figure 3.14. The asphalt concrete modulus is then multiplied by the appropriate fatigue factor and recorded on Worksheet D. These products are then summed and divided by the sum of the fatigue factors to obtain an effective asphalt concrete modulus that is representative of a climate and mix. This effective asphalt concrete modulus is used to select the appropriate initial cross section and is recorded in line 4 of Worksheet C, Figure 3.1.

Figure 3.13 was developed for a particular material gradation, asphalt, and mix design. If other gradations or asphalt contents are selected, Appendix D can serve as a guide to develop a similar set of temperature-modulus relationships. In order to make direct use of viscosity values on Figure 3.13, it would be necessary to measure the viscosity at two temperatures. By plotting this information on the ASTM standard viscosity-temperature chart for asphalt (ASTM D 2493) it would be possible to estimate the viscosity at 70°F (21°C). If such information is not available, an approximation similar to that contained in Figure 3.13 can be used to relate asphalt grade and viscosity.

CROSS SECTION SELECTION

Using the total projected traffic, effective asphalt concrete modulus, and the subgrade modulus, an initial cross section can be selected from the catalog of design charts presented in Appendix A and entered in Worksheet C.

ADJUSTMENT FOR FROST SUSCEPTIBILITY

Using one of Figures 3.15 thru 3.17, the frost penetration below the pavement surface is estimated for the pavement cross section using the natural soil type and the environmental region. If the subgrade

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[1]Witczak, M.W., "Development of Regression Model for Asphalt Concrete Modulus for Use in MS-1 Study", The Asphalt Institute, College Park, Maryland, January 1978.

PREMIUM PAVEMENT DESIGN

EFFECTIVE MODULUS WORKSHEET D

Project:____________________ Date:____________________

Location:____

(1) Mean Annual Air Temperature Worksheet A, °F . . . . __________

(2) Mean Yearly Temperature Change, °F . . . . . . __________

(3) Environmental Region (Figure 3.3) . . . . __________

(4) Minimum Pavement Temperature, (Figure 3.4, 3.5), °F . . . . __________

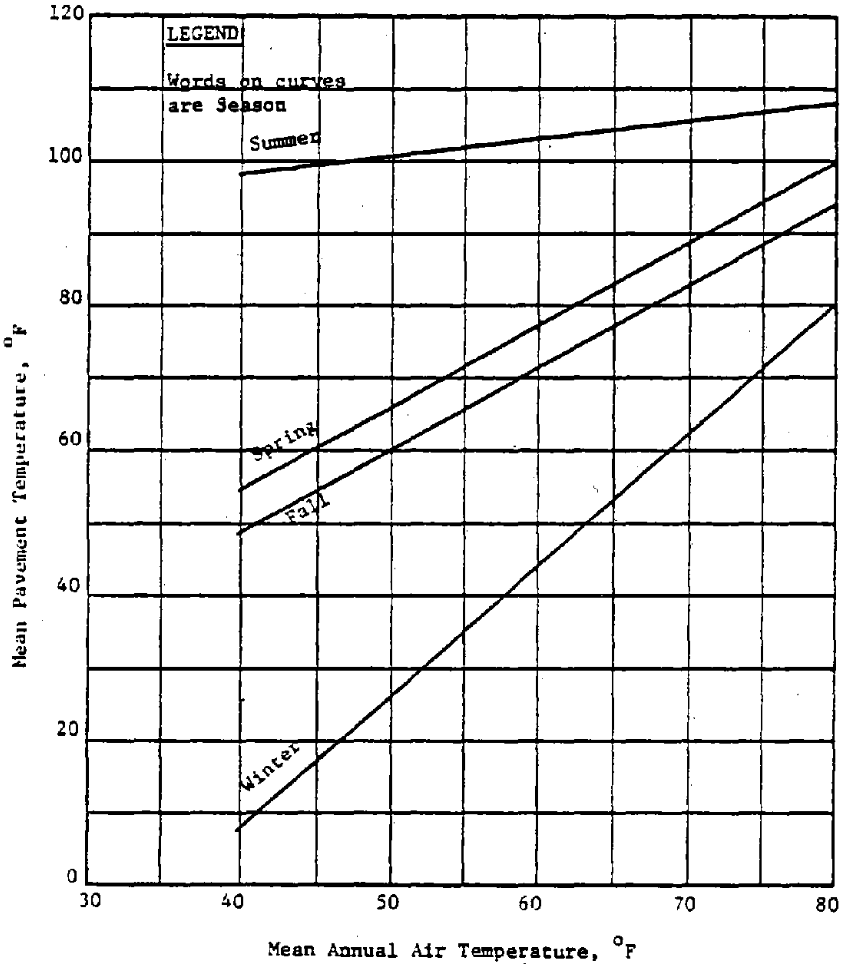
(5) Allowable Minimum Original (Figure 3.6) Penetration . . . . __________

(6) Asphalt Cement Grade . . . . __________

(7) Season	(8) Mean Pavement Temperature (Figure 3.8 - 3.12) °F	(9) Asphalt Concrete Modulus (Figure 3.13) psi	(10) Fatigue Factor (Figure 3.14)	(11) (9) x (10)
Fall				
Winter				
Spring				
Summer				
(12) Total				
(13) Asphalt Concrete Effective Modulus, psi (Σ(11)÷Σ(10))				

°C = (°F - 32)/1.8 1 psi = 6.89 kPa

Figure 3.7 Worksheet for Computing the Asphalt Concrete Effective Modulus.



°C = (°F - 32)/1.8

Figure 3.8 Estimation of the Mean Pavement Temperature for Environmental Region No. 1.

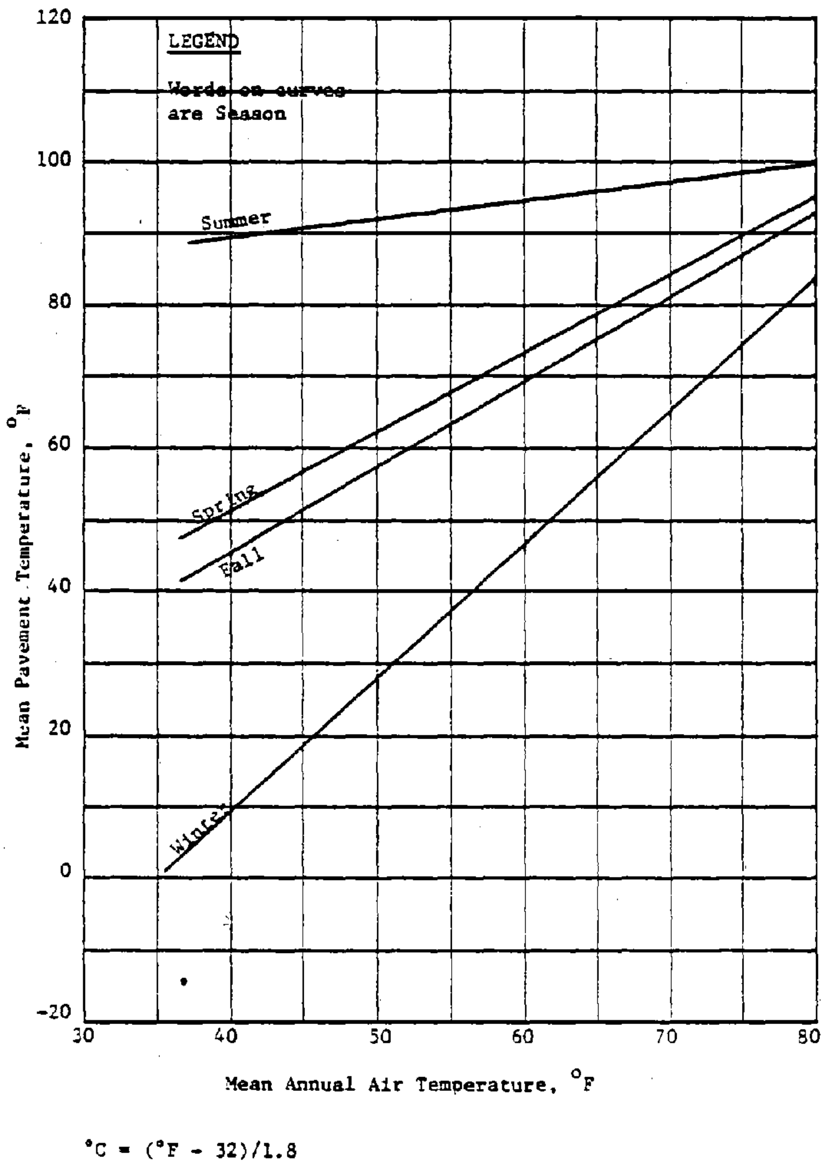


Figure 3.9 Estimation of the Mean Pavement Temperature for Environmental Region No. 2.

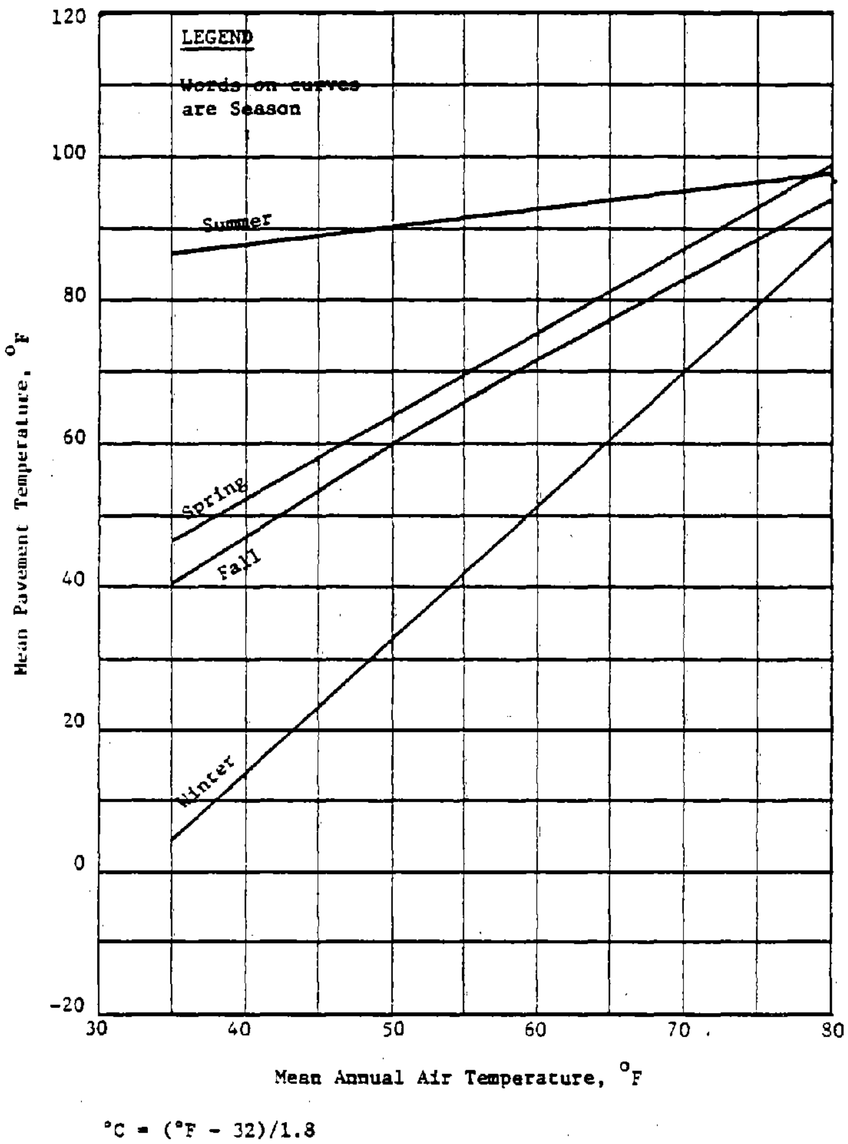


Figure 3.10 Estimation of the Mean Pavement Temperature for Environmental Region No. 3 Under Dry Conditions (Average Yearly Rainfall < 12 in).

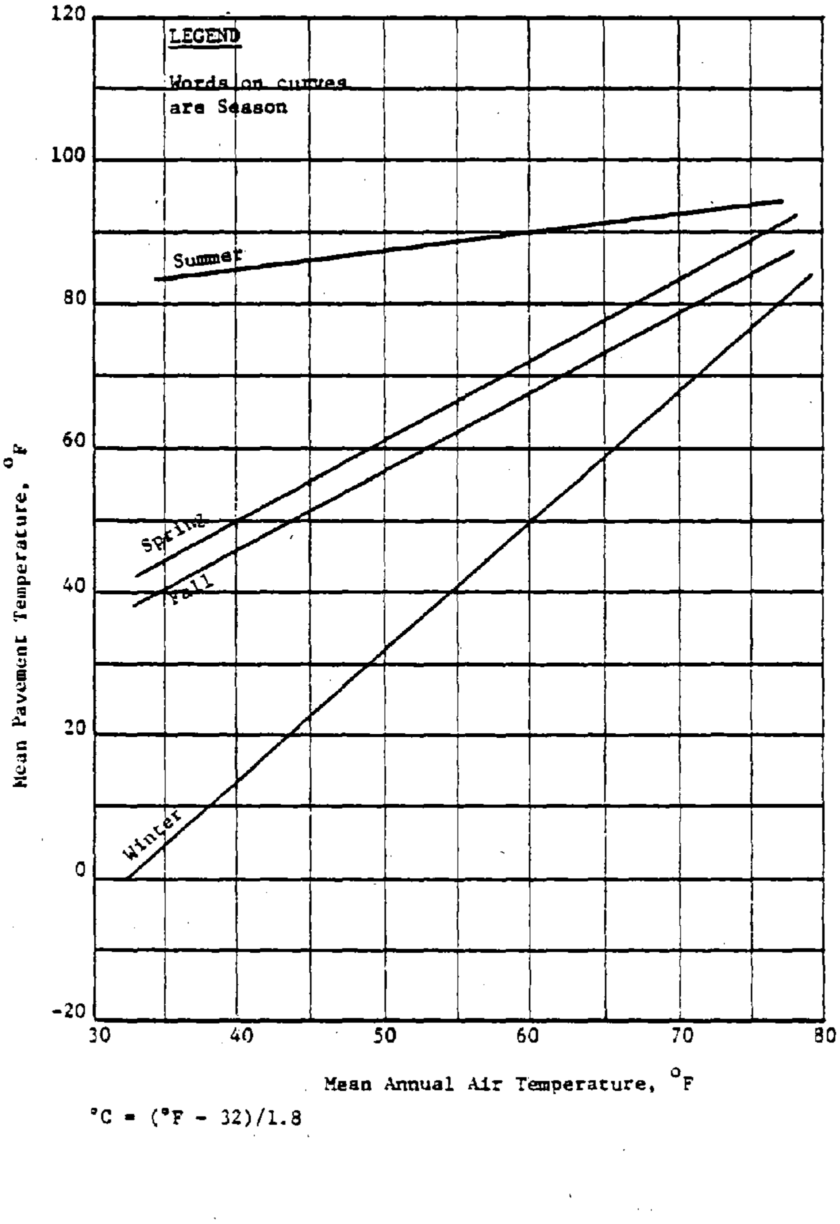
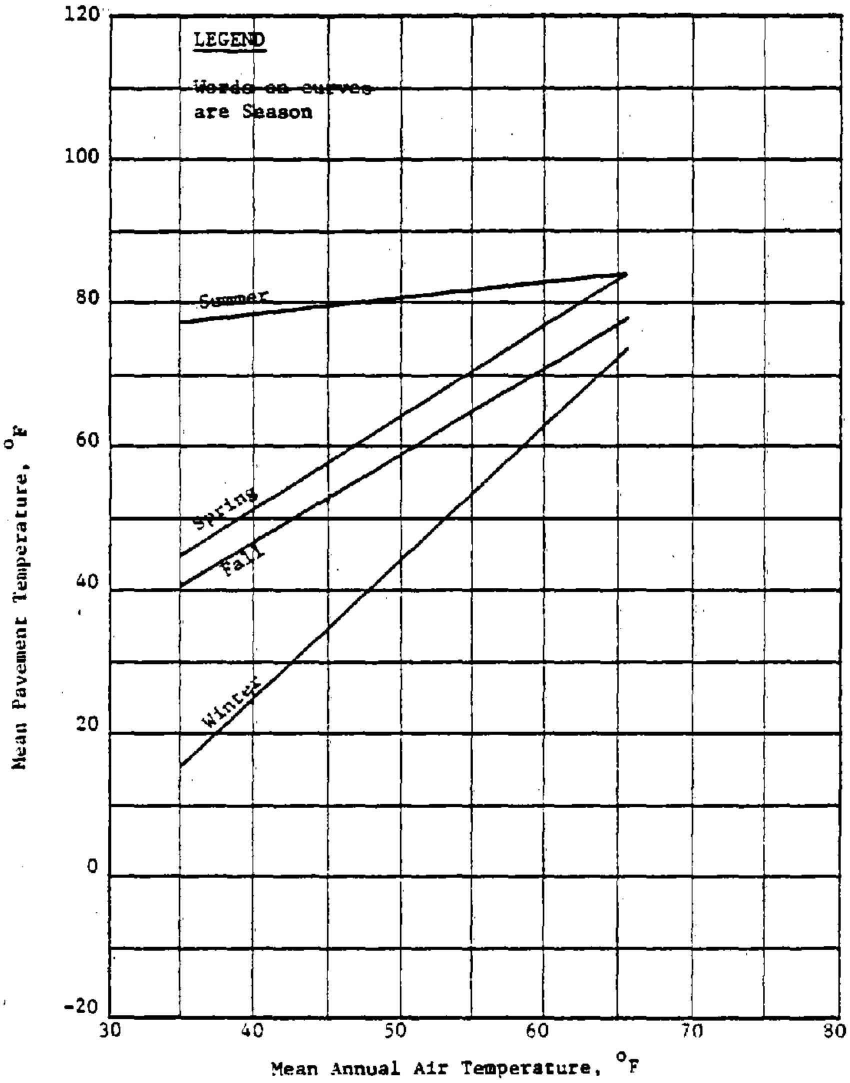


Figure 3.11 Estimation of the Mean Pavement Temperature for Environmental Region No. 3 Under Wet Conditions (Average Yearly Rainfall > 12 in).



°C = (°F - 32)/1.8

Figure 3.12 Estimation of the Mean Pavement Temperature for Environmental Region No. 4.

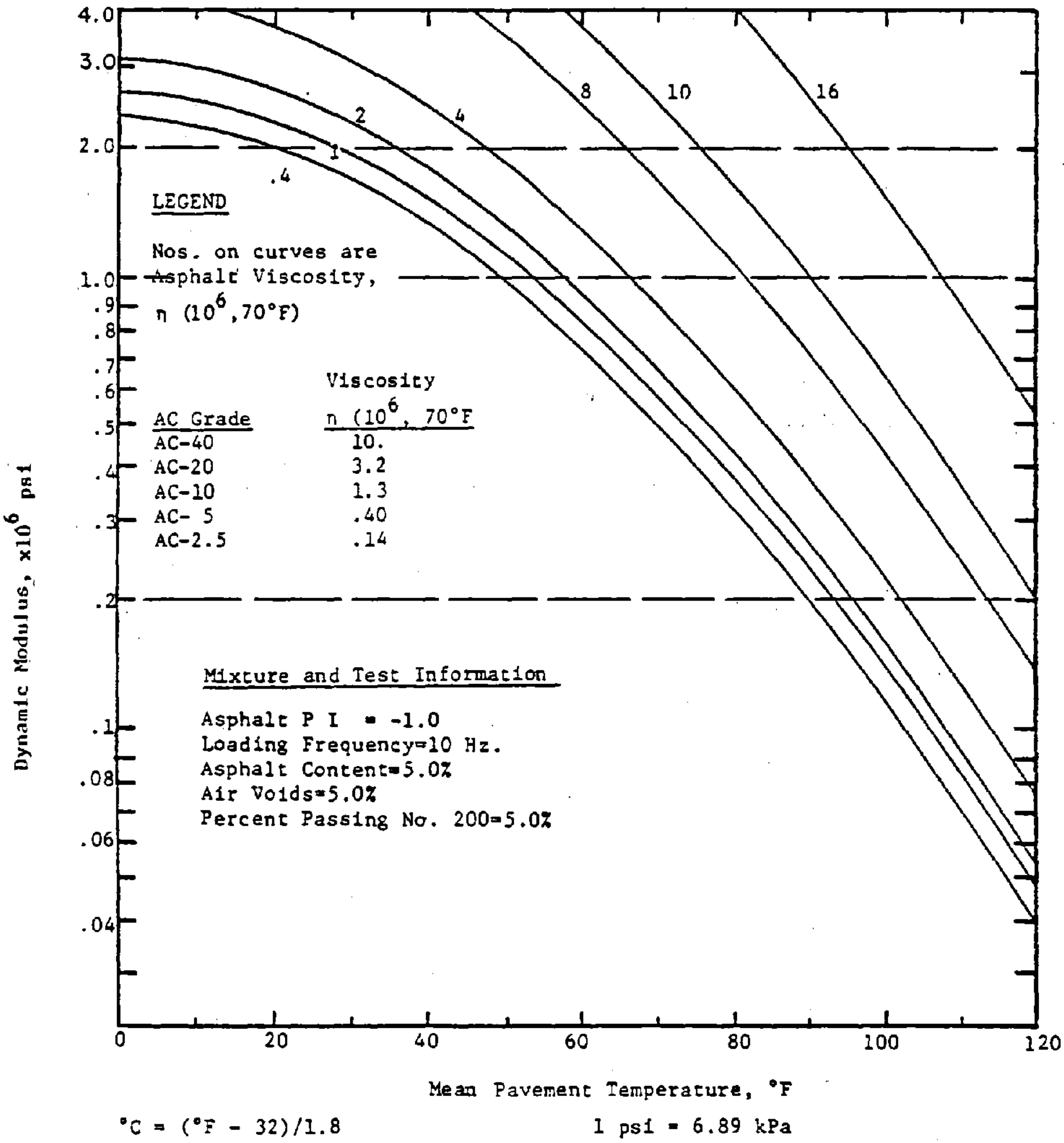


Figure 3.13 Estimation of the Asphalt Concrete Dynamic Modulus as a Function of Mean Pavement Temperature (Ref. 15).

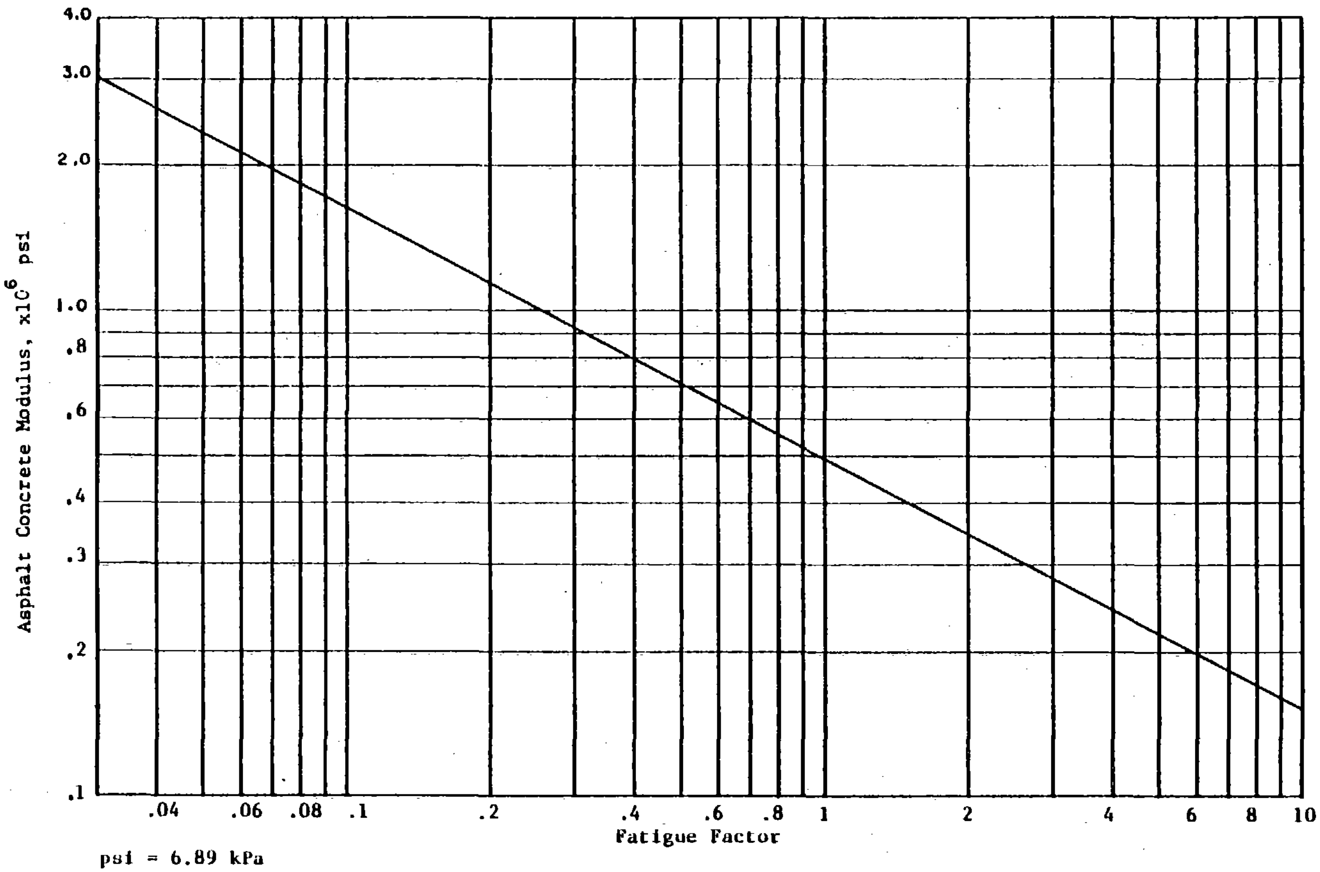
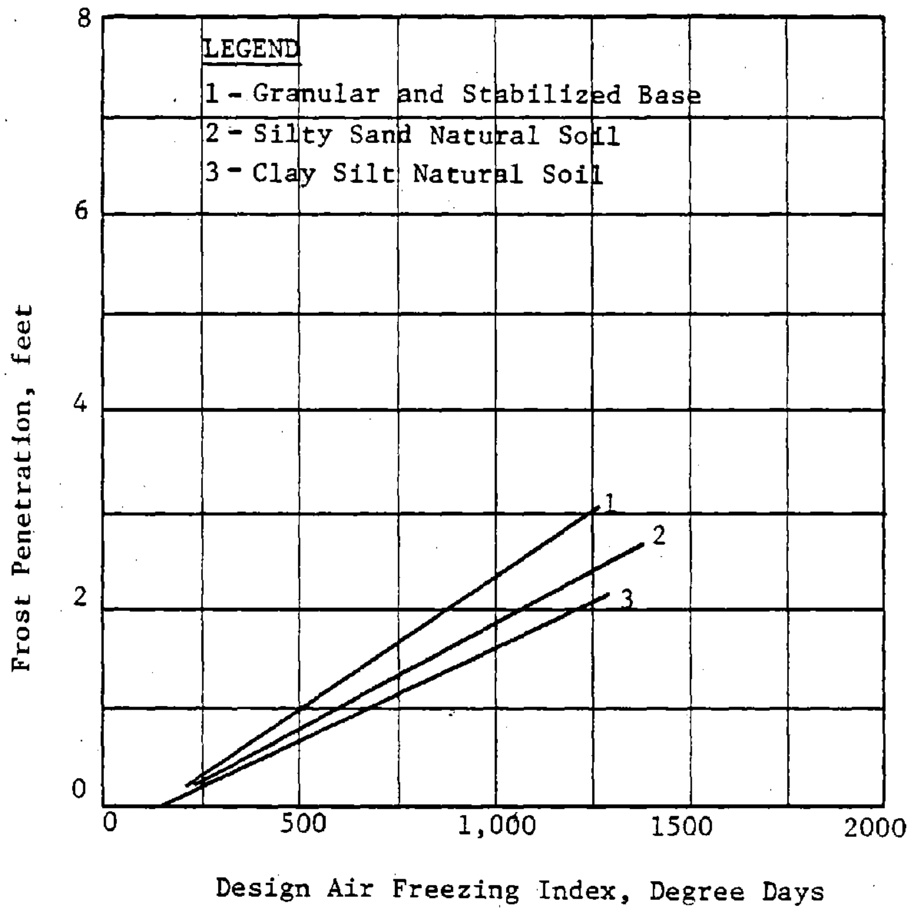


Figure 3.14 Estimation of the Fatigue Factor



1 ft = 0.3048 m

Figure 3.15. Determination of the Frost Penetration into Different Materials Below the Pavements Surface for Environmental Region No. 1.

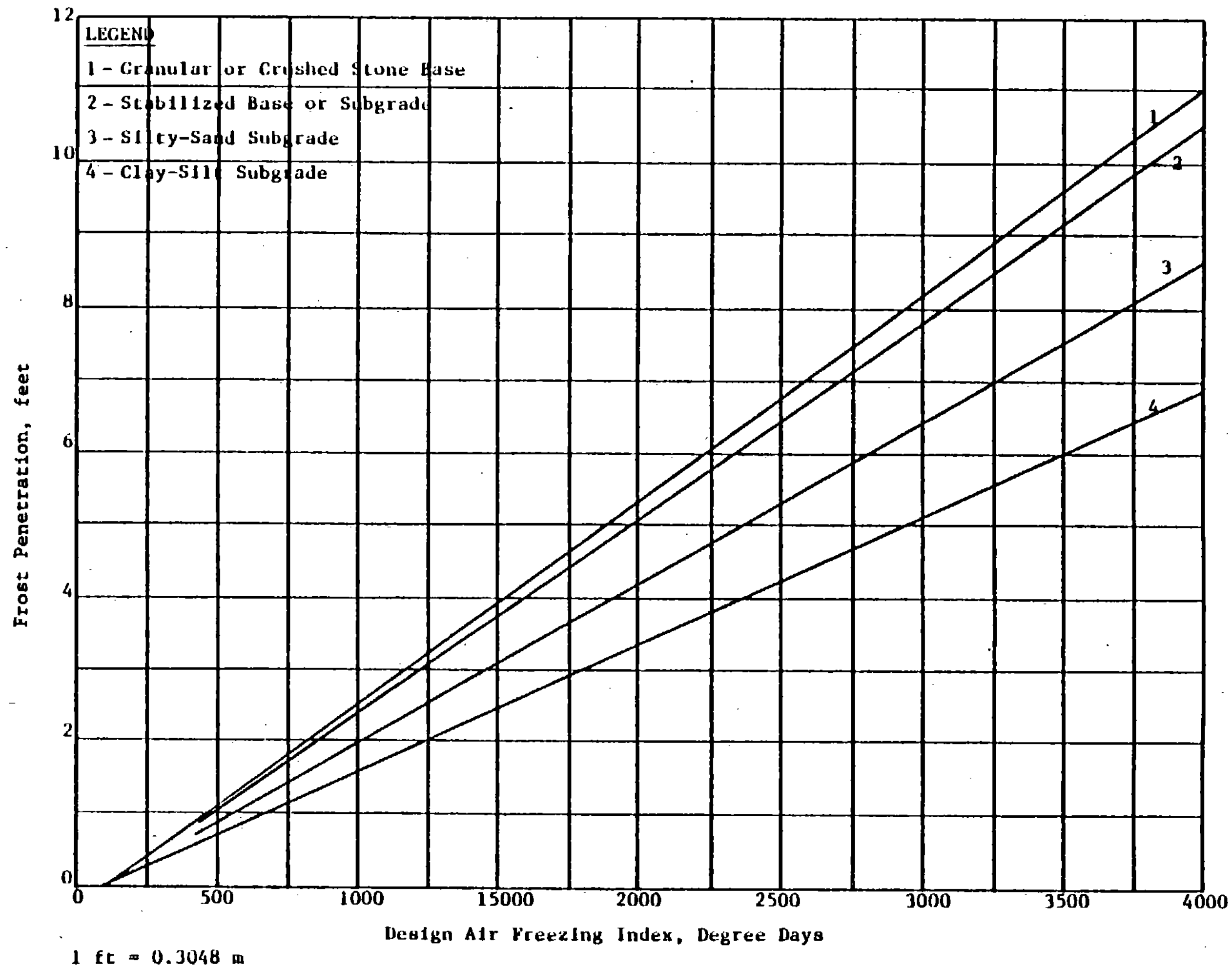


Figure 3.16 Determination of the Frost Penetration into Different Materials Below the Pavement Surface for Environmental Region No. 2.

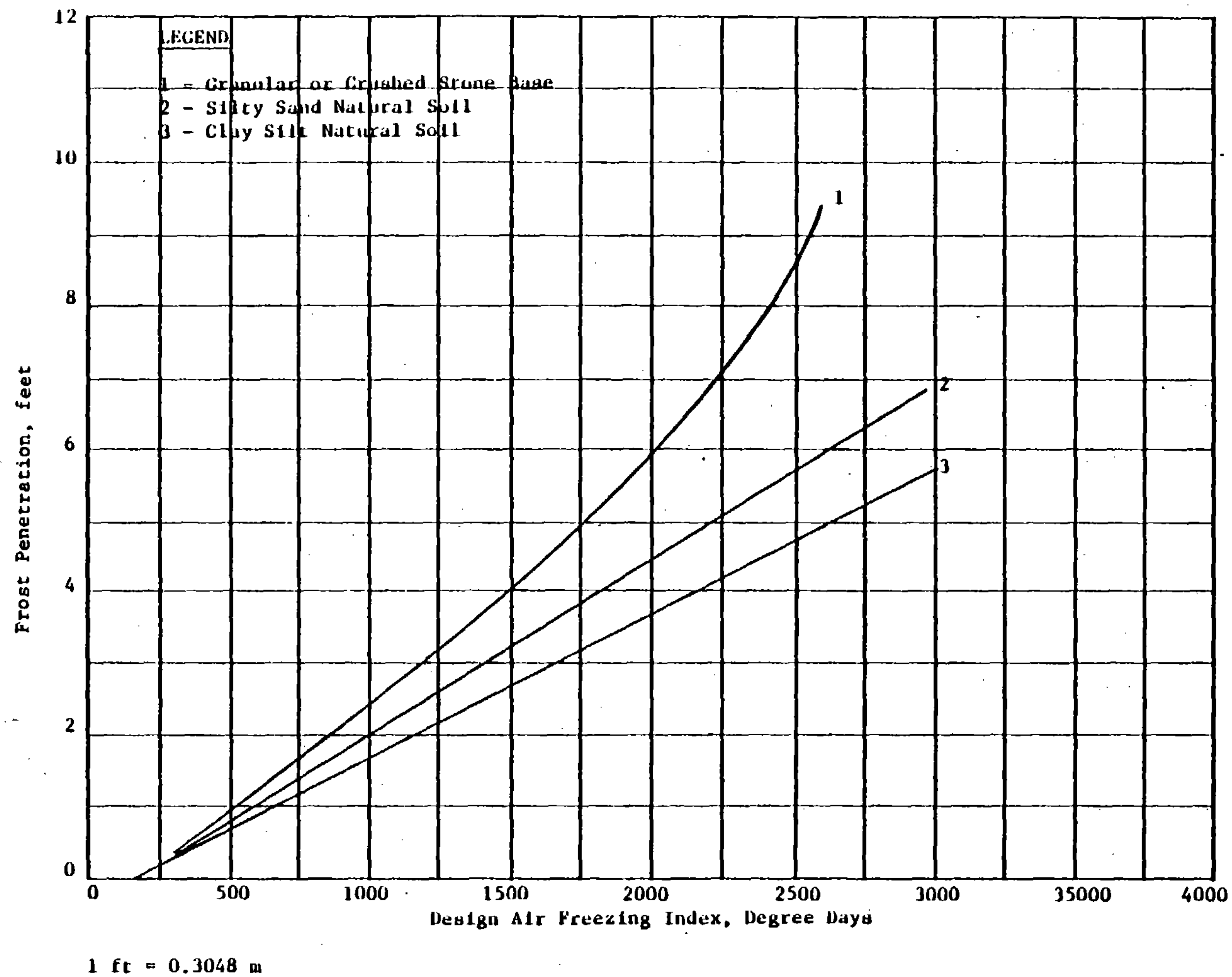


Figure 3.17 Determination of the Frost Penetration into Different Materials Below the Pavement Surface for Environmental Region No. 3.

soil is frost susceptible, two design alternates are possible. The engineer may elect to either totally protect the subgrade from frost penetration or he may elect to increase the structural thickness to account for reduced strength values occurring during spring thaw. Tables 3.1 and 3.2 provide suggestions to assist the engineer in choosing between full and partial protection from frost penetration. Among the factors that affect this decision are soil classification, strength during the thaw period, water table location, pavement type and soil modulus.

If the engineer elects to fully protect the subgrade from frost penetration, Figures 3.15 thru 3.18 can be used to estimate the additional thickness of non-frost susceptible materials required as a part of the pavement structure. Figure 3.18 is included to demonstrate a type of nomograph that has been developed to design the thickness of insulation materials used in Finland (Ref. 16[1]). Full protection is especially suggested for the combinations using granular layers in the asphalt pavement. A decrease in the stiffness of subgrade soils due to spring-thaw will result in a stiffness reduction of the granular materials which may not be recovered with time.

If the engineer desires to analyze the partial protection alternate, Figures 3.19 and 3.20 should be used to estimate the increased damage that occurs as a result of reduced strength during the spring thaw period. After evaluation of both the partial protection and full protection alternatives the engineer can select the most cost effective design.

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[1]Orama, R., "Thermal Protection of Finnish Roads", Proceedings, Symposium on Frost Action on Roads, Organization for Economics Cooperation and Development, 1974.

TABLE 3.1 COVER REQUIREMENTS FOR FROST PENETRATION OF PREMIUM FLEXIBLE PAVEMENTS

PAVEMENT TYPE	WATER TABLE DEPTH, FT.	NATURAL SOIL RESILIENT MODULUS x 10³ PSI	SOIL CLASSIFICATION[1] / THAW STRENGTH, % OF FALL VALUE: F-1 100	F-1 70	F-1 40	F-2 100	F-2 70	F-2 40	F-3 100	F-3 70	F-3 40	F-4 100	F-4 70	F-4 40
FULL-DEPTH	2	> 10		▧	▧		▧	▧		▧	▧	▧	▧	▧
FULL-DEPTH	2	< 10		▧	▧		▧	▧	▧	▧	▧	▧	▧	▧
FULL-DEPTH	3	> 10			▧			▧		▧	▧	▧	▧	▧
FULL-DEPTH	3	< 10			▧			▧	▧	▧	▧	▧	▧	▧
FULL-DEPTH	6	> 10									▧	▧	▧	▧
FULL-DEPTH	6	< 10							▧	▧	▧	▧	▧	▧
FULL-DEPTH	10	> 10									▧	▧	▧	▧
FULL-DEPTH	10	< 10							▧	▧	▧	▧	▧	▧
FULL-DEPTH	20	> 10								▧	▧	▧	▧	▧
FULL-DEPTH	20	< 10						▧	▧	▧	▧	▧	▧	▧
CONVENTIONAL	2	> 10		▧	▧		▧	▧		▧	▧	▧	▧	▧
CONVENTIONAL	2	< 10		▧	▧		▧	▧	▧	▧	▧	▧	▧	▧
CONVENTIONAL	3	>10		▧	▧		▧	▧		▧	▧	▧	▧	▧
CONVENTIONAL	3	< 10		▧	▧		▧	▧	▧	▧	▧	▧	▧	▧
CONVENTIONAL	6	>10			▧			▧		▧	▧	▧	▧	▧
CONVENTIONAL	6	< 10			▧			▧	▧	▧	▧	▧	▧	▧
CONVENTIONAL	10	>10								▧	▧	▧	▧	▧
CONVENTIONAL	10	<10						▧	▧	▧	▧	▧	▧	▧
CONVENTIONAL	20	>10								▧	▧	▧	▧	▧
CONVENTIONAL	20	<10					▧	▧	▧	▧	▧	▧	▧	▧

▧ FULL PROTECTION FROM FROST PENETRATION **REQUIRED**

☐ PARTIAL PROTECTION—INCREASED STRUCTURAL THICKNESS

1 ft = 0.3048 m

1 psi = 6.89 kPa

[1]Refer to Table 2.2 and Figure 2.3 for soil classification information.

TABLE 3.2 COVER REQUIREMENTS FOR FROST PENETRATION OF PREMIUM COMPOSITE PAVEMENTS

PAVEMENT TYPE	SUBGRADE RESILIENT MODULUS x 10 PSI	WATER TABLE DEPTH FT.	F-1			F-2			F-3			F-4		
SOIL CLASSIFICATION[1] →			F-1			F-2			F-3			F-4		
THAW STRENGTH OF FALL VALUE % →			100	70	40	100	70	40	100	70	40	100	70	40
LOW MODULUS CRCP	2	>10		▧	▧		▧	▧		▧	▧	▧	▧	▧
		<10		▧	▧		▧	▧	▧	▧	▧	▧	▧	▧
	3	>10			▧			▧		▧	▧	▧	▧	▧
		<10			▧			▧	▧	▧	▧	▧	▧	▧
	6	>10								▧	▧	▧	▧	▧
		<10						▧	▧	▧	▧	▧	▧	▧
	10	>10								▧	▧	▧	▧	▧
		<10						▧	▧	▧	▧	▧	▧	▧
	20	>10								▧	▧	▧	▧	▧
		<10						▧	▧	▧	▧	▧	▧	▧
LOW MODULUS PLAIN CONC	2	>10		▧	▧		▧	▧		▧	▧	▧	▧	▧
		<10		▧	▧		▧	▧	▧	▧	▧	▧	▧	▧
	3	>10			▧			▧		▧	▧	▧	▧	▧
		<10			▧		▧	▧	▧	▧	▧	▧	▧	▧
	6	>10								▧	▧	▧	▧	▧
		<10					▧	▧	▧	▧	▧	▧	▧	▧
	10	>10								▧	▧	▧	▧	▧
		<10					▧	▧	▧	▧	▧	▧	▧	▧
	20	>10								▧	▧	▧	▧	▧
		<10					▧	▧	▧	▧	▧	▧	▧	▧

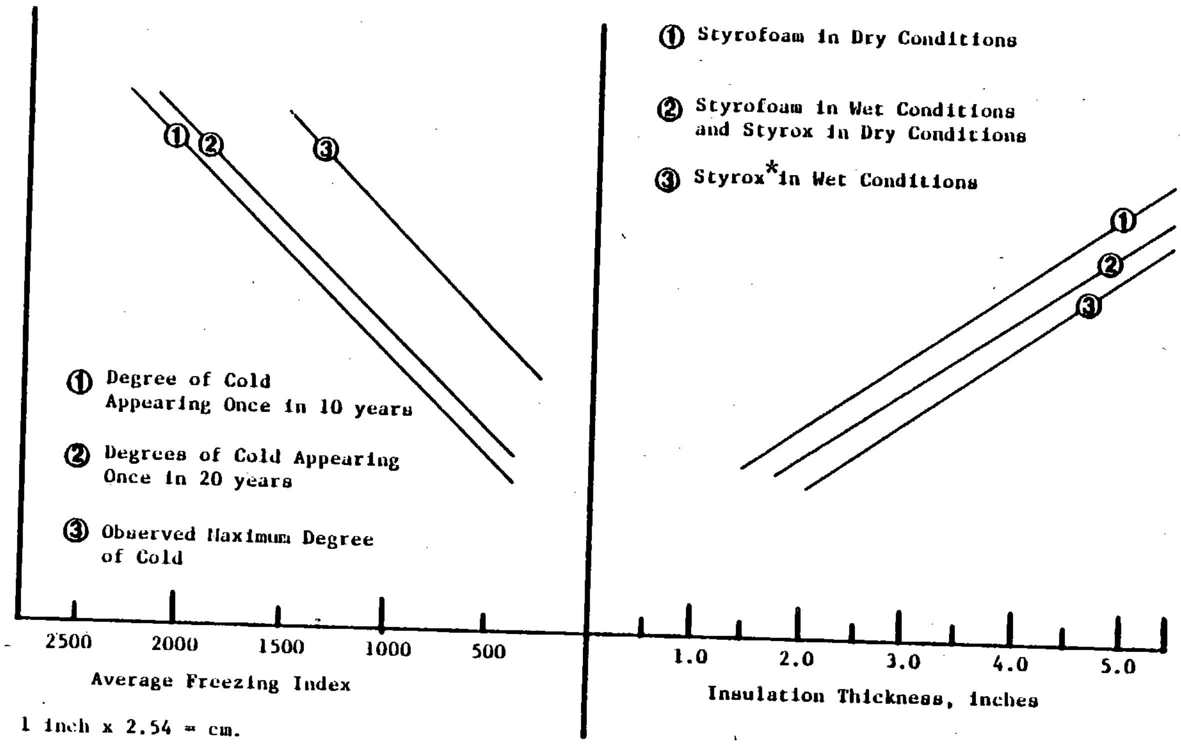
▧ FULL PROTECTION FROM FROST PENETRATION REQUIRED

▭ PARTIAL PROTECTION–INCREASED STRUCTURAL THICKNESS

1 ft = 0.3048 m

1 psi = 6.89 kPa

[1] Refer to Table 2.2 and Figure 2.3 for soil classification information.



*Styrox is a type of foam insulation used in Finland.

Figure 3.18 Design of Insulation Thickness (Ref. 16).

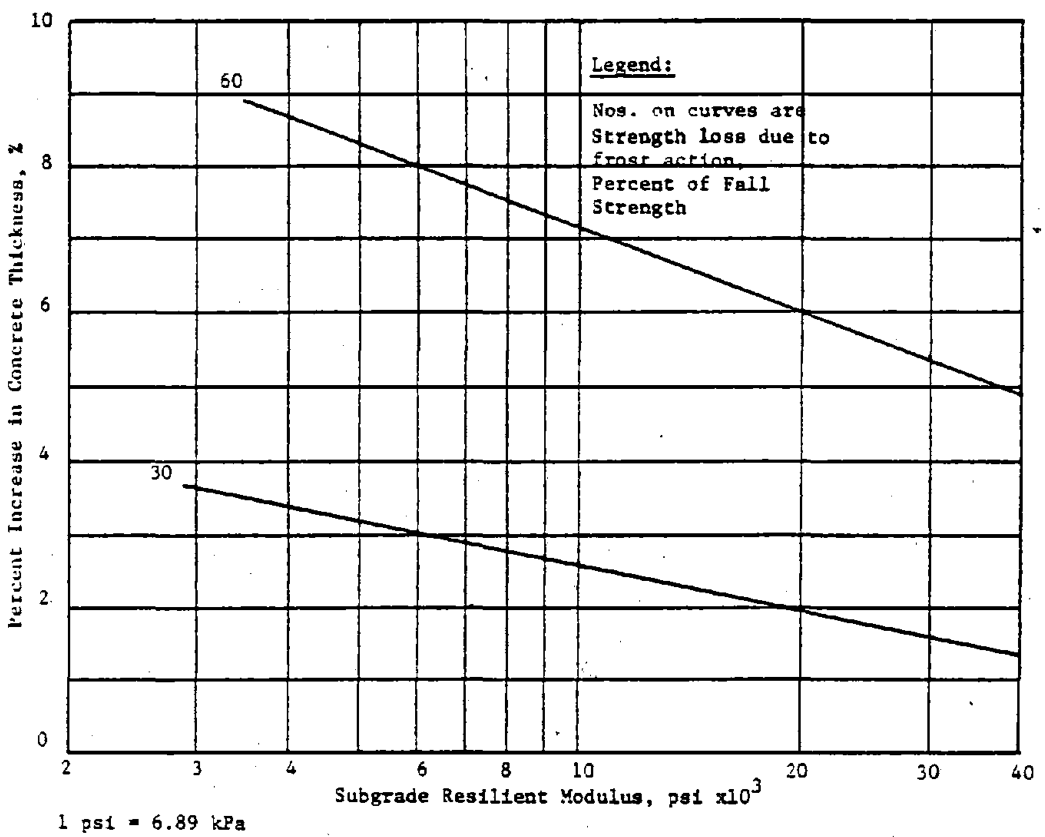


Figure 3.19 Increase in Structural Thickness of Composite Pavements for Different Levels of Frost Damage

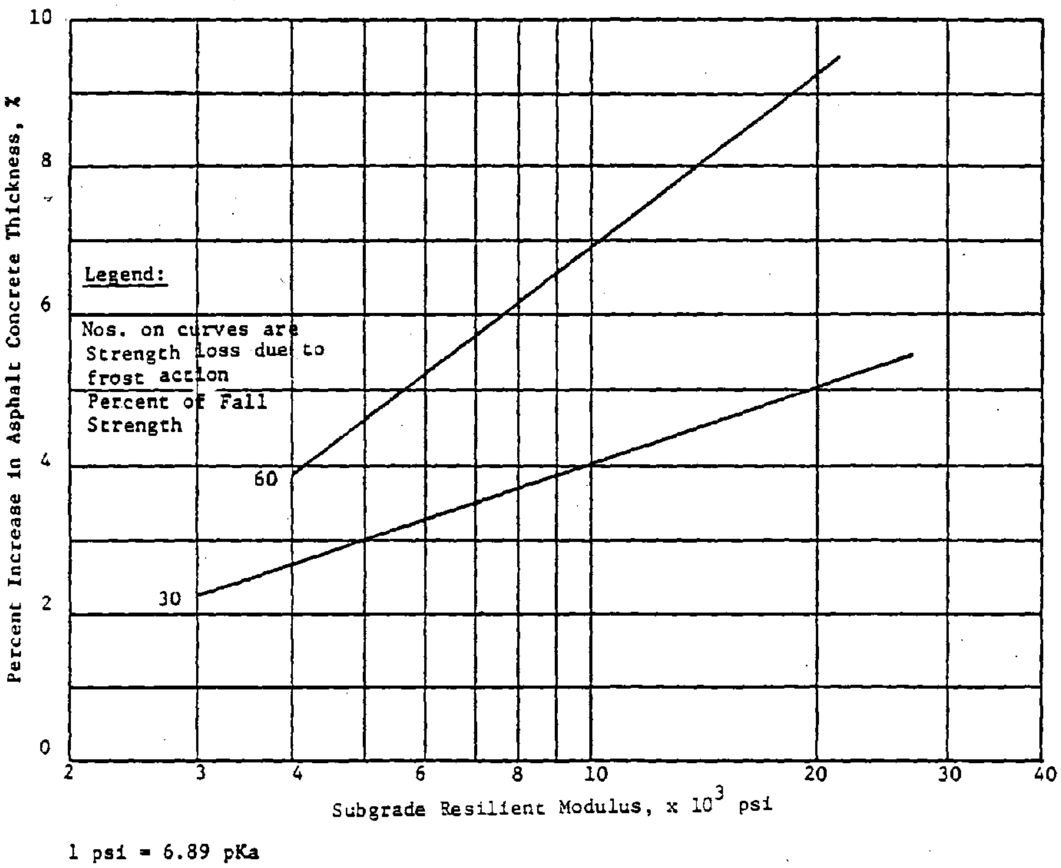


Figure 3.20 Increase in Structural Thickness of Flexible Pavement for Different Levels of Frost Damage.

SECTION 4. SPECIAL DESIGN CONSIDERATIONS

As previously discussed very stringent criteria must be met for a pavement structure to serve as a premium pavement for zero-maintenance. Not only must the strength and thicknesses of the structural layers be adequate but all components must be carefully designed in order to satisfy this zero-maintenance criteria. Special considerations should also be directed toward the adequacy of: 1) shoulders, 2) reinforcement in composite pavements, 3) joints in composite pavements, 4) sub-surface and surface drainage, and 5) anchorage of concrete layers.

SHOULDERS

Shoulders should be designed to provide zero-maintenance since their repair normally will disrupt traffic in the adjacent lane. In order to assure that the shoulders remain maintenance free during the minimum 20 year design period the following guidelines are suggested. Additional information on design and construction of shoulders can be found in References 17[1] and 18[2].

Flexible Pavements

The thickness of the asphalt concrete shoulder should be equal to the structural thickness of the pavement. Generally, the width of the asphalt concrete outer lane should extend at least 2 feet beyond the edge lane stripe and then taper to a thickness of approximately 80 percent of the outer lane at the shoulders edge. Other pavement layers should extend the full width to the shoulders if possible, unless either edge drains or a drainage blanket are provided.

Composite Pavements

As was suggested for flexible pavements, the full thickness of the concrete layer should extend two feet beyond the outer lane marking and then taper to 80 percent of the thickness at the shoulder edge. Other pavement layers should extend the full width to the shoulder edge. For the concrete layer, the shoulder should be tied to the outer lane. Generally, 30 inch long, No. 4 or 5 deformed bars spaced 30 inches center-to-center should be adequate to tie the shoulder and outer lane together.

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[1]Barksdale, R.D. and R.G. Hicks, "Improved Pavement Shoulder Joint Design", Final Report NCHRP Project 14-3, National Cooperative Highway Research Program, June 1975.

[2]"Design and Use of Highway Shoulders", NCHRP Synthesis of Highway Practice No. 63, National Cooperative Highway Research Program, August 1979.

REINFORCEMENT

Some reinforcement will be required for concrete layers used in composite pavement constructions. For jointed concrete sub-surface layers, load transfer devices are suggested for most situations to prevent potential faulting and subsequent reflection of cracks to the surface. For most situations the joint spacing should not exceed 20 feet in order to reduce the horizontal movements at the joints. In continuously reinforced concrete (CRC) sub-surface layers longitudinal steel runs continuous throughout the length of the pavement. In CRC sub-surface layers transverse reinforcement is provided for most pavements. Other uses of reinforcement occur at terminal anchorages, construction joints, and edges of pavements with tied shoulders as previously discussed.

Longitudinal Steel

The longitudinal reinforcement of the CRC base should be designed to:

1) hold the transverse cracks tightly closed,

2) obtain load transfer by aggregate interlock,

3) keep the steel stress below the fracture point, and

4) insure that the resulting crack spacing is within a range exhibiting good past performance.

To determine levels of steel reinforcement for a CRC base, limits on acceptable levels of crack width, crack spacing, and steel stress have been established which minimize distress manifestations prevalent in CRC pavement. These distress manifestation levels are based on both theoretical considerations and field performance studies and have been used to estimate the required reinforcement that will produce satisfactory performance when the pavement is subjected to the anticipated environmental and axle loading conditions.

Crack width should be minimized to control crack spalling and water infiltration at the crack. Water infiltration is directly proportional to the permanent crack width. The limiting crack width is determined with Figure 4.1 using a design temperature drop. This design temperature drop is the difference between the average expected concrete curing temperature and the expected minimum temperature during the design year. The average concrete curing temperature may be estimated as the average daily high temperature for the hottest month of the construction period expected for the design. The design minimum temperature is the average daily low temperature for the coldest month. Temperature data may be obtained from government weather records. An initial estimate of the required percent longitudinal steel is made using equation 4.1.

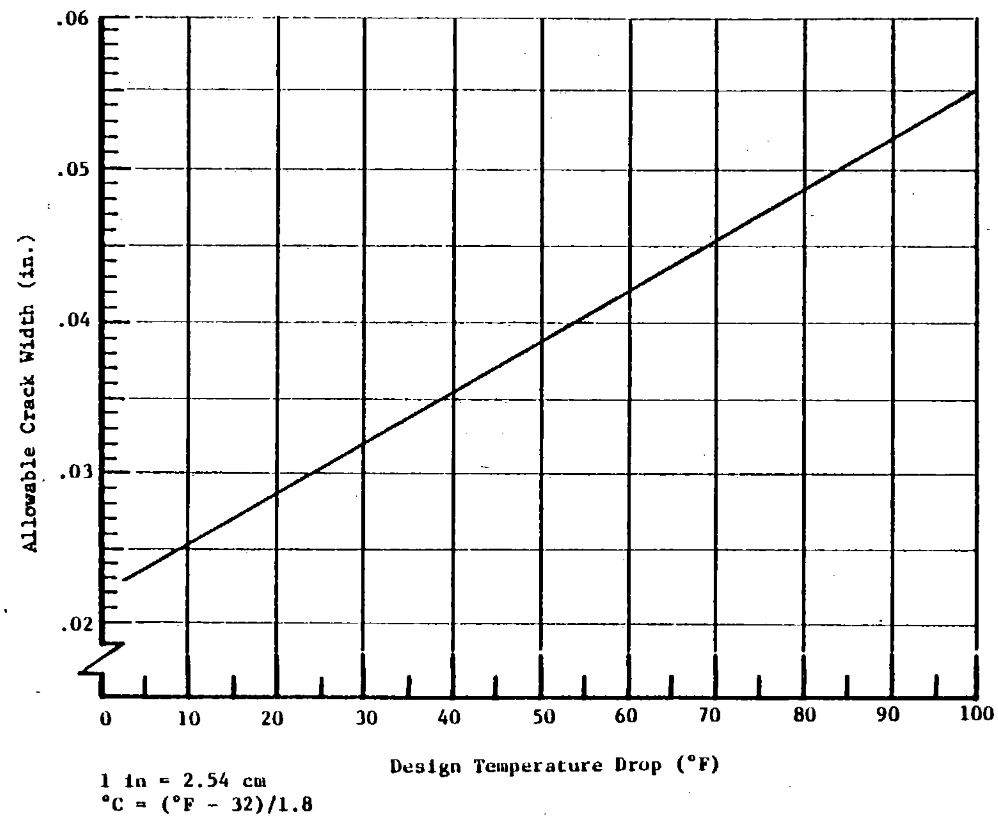

Figure 4.1 Limiting Crack Width for Design Temperature Drop

$$CW = \frac{0.00583 \left(1 + \frac{f_t}{1000}\right)^{6.53} (1 + \phi)^{2.20}}{(1 + p)^{4.55}} \qquad (4.1)$$

where:

CW = Maximum crack width (Figure 4.1), inches

f_t = 28-day concrete tensile strength, psi measured by direct or indirect methods

ϕ = Longitudinal Bar Diameter, inches

p = Longitudinal percent steel, %

This initial estimate is then used in equations 4.2 and 4.3 to insure that the required percent steel satisfies the crack spacing and steel stress criteria.

$$\overline{X} = \frac{0.702 \left(1 + \frac{f_t}{1000}\right)^{6.70} (1 - \phi)^{2.19}}{(1 + p)^{4.60}} \qquad (4.2)$$

where:

$\overline{X}$ = Allowable crack spacing, feet (Recommended criteria = 3 to 8 ft.).

$$\sigma_s = \frac{29{,}700 \left(1 + \frac{\Delta T}{100}\right)^{0.425} \left(1 + \frac{f_t}{1000}\right)^{4.09}}{(1 + p)^{2.74}} \qquad (4.3)$$

where:

ΔT = Design Temperature Drop, °F

σ_s = Allowable Steel Stress, psi (Recommended criteria - less than 0.9 of the yield strength).

The development of these design equations is discussed in Volume 1 (Ref. 1). Iterative solutions using variations in the percent longitudinal steel shall be performed until the three criteria of allowable crack width, crack spacing, and steel stress are met.

Transverse Steel

The design of transverse reinforcement is based on the amount of reinforcement required to hold the longitudinal crack at the center of the pavement closed. The required amount of transverse steel may be determined using the nomograph in Figure 4.2. The nomograph is based on a concrete with unit weight of 144 pcf (2307 kg/m^2). The steel percentage may be adjusted for different unit weight concrete using equation 4.4.

$$P_{tc} = P_t \left(\frac{W_t}{144}\right) \qquad (4.4)$$

where:

P_{tc} = corrected percent transverse steel,

P_t = percent transverse steel computed above, and

W_t = unit weight of concrete, pcf.

Other Reinforcement

To design other reinforcement for composite pavements such as construction and contraction joints or the steel needed at terminal anchorages, the designer is referred to References 19[1] and 20[2].

For composite pavements which contain a low modulus jointed concrete base, dowels are recommended in transverse contraction and construction joints when the subgrade is not stabilized and the water table is near the surface. The design and placement of dowels is discussed in detail in Reference 20.

JOINTS

For the design and construction of joints in composite pavements, both in a CRC and jointed concrete base, the designer is referred to References 19 and 20. Joints in these composite pavements should not present a significant problem that reduce the zero-maintenance life if quality materials are used as discussed in Section 5 (Material Specifications) and 6 (Construction Specifications). Because the concrete is covered with an asphalt concrete surface, the problems associated with water and foreign material infiltraton into joints and cracks should be minimized if not eliminated.

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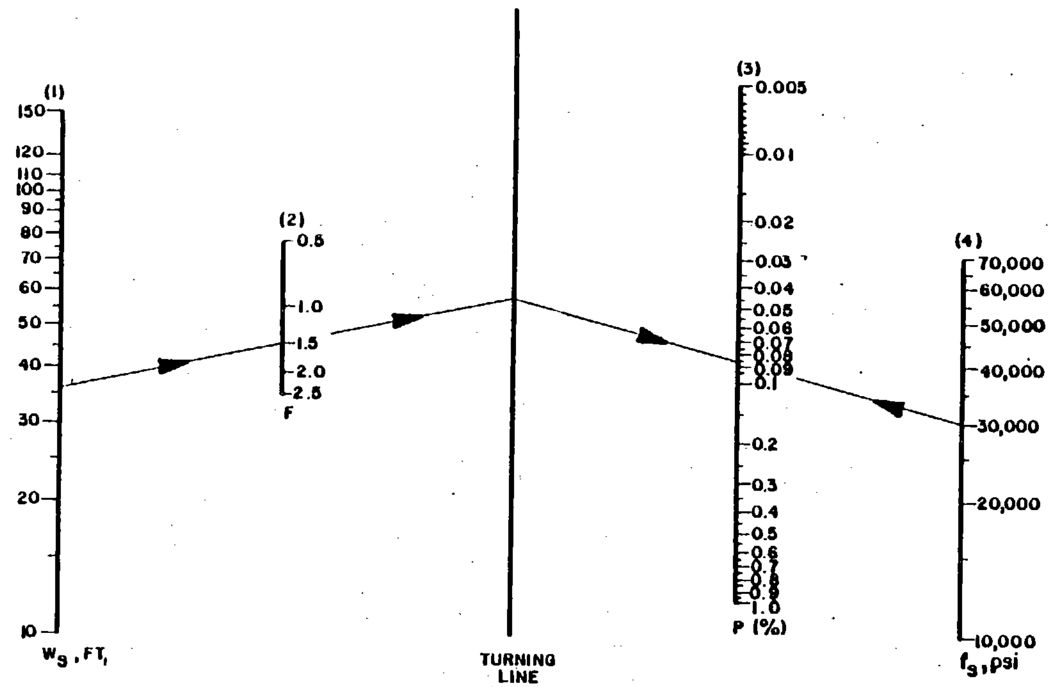
[1] "Continuously Reinforced Concrete Pavement", NCHRP Synthesis of Highway Practice No. 16, National Cooperative Highway Research Program, Highway Research Board, 1973.

[2] "Design, Construction, and Maintenance of PCC Pavement Joints", NCHRP Synthesis of Highway Practice No. 19, National Cooperative Highway Research Program, Highway Research Board, 1973.



Example Problem:

W_s = 36 ft
F = 1.5
f_s = 30,000 psi

Solution:

P_t = .085%

1 ft = 0.3948 m
1 psi = 6.89 kPa

Scale:

P_t = Transverse Steel, %
W_s = Slab Width, feet (should include the width of tied shoulders, if present)
F = Subbase Friction Factor
f_s = Allowable Working Stress in Steel, psi (.75 yield strength)

Figure 4.2 Transverse Steel Reinforcement Design Chart

DRAINAGE

Experience has shown that inadequate drainage is possibly responsible for more pavement distress than inadequate structural or material design. Consequently, effective drainage is essential to good pavement performance, and is a requirement that must be met for the structural design procedure to be valid. For drainage consideration, the discharge of surface runoff and the control of sub-surface water must both be considered. Surface runoff is readily controlled by the pavements crown or slope. However, where a relative permeable base overlies a relatively impermeable subbase, provision should be made for either horizontal drainage of the base through the shoulders, i.e. a daylighted base layer, or edge drains should be constructed in order to avoid a boxed or bathtub construction.

Subsurface drainage must not be neglected if zero-maintenance performance is desired. Certain natural materials are free draining and probably require very little subsurface drainage. Less permeable materials may trap moisture and cause other pavement layers to become wetter or perhaps saturated with the associated strength loss. To eliminate these problems subsurface drains must be designed. Drainage design has been extensively discussed and a detailed presentation is beyond the scope of this report. The basic object of this discussion is to impress the designer with the need for effective drainage so that saturation of the pavement structure is prevented. Whether this drainage is provided with naturally free draining soils, with permeable subgrades or with construction of subsurface drainage layers is not the real concern: the selected drainage system must be effective and remain effective during the 20 to 30 year design period. Detailed discussions on the design and construction of drainage layers is contained in References 21[1], 22[2], and 23[3]. If it is determined that a free draining material exists in the subgrade then the drainage layer and filter layer could be eliminated.

For the structural cross-sections listed in Appendix A, a drainage blanket (Ref. 23) has been recommended for use. This drainage system consists of a layer extending full width between shoulder edges. In

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[1]Cedergren, H.R., J.A. Arman, K.H. O'Brien, "Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections", Report No. FHWA-RD-73-14, Federal Highway Administration, February 1973.

[2]Cedergren, H.R., K.H. O'Brien, and J.A. Arman, "Guidelines for the Design of Subsurface Drainage Systems for Highway Structural Section", Report No. FHWA-RD-72-30, Federal Highway Administration, June 1972.

[3]"Implementation Package for a Drainage Blanket in Highway Pavement Systems", Federal Highway Administration, U.S. Department of Transportation, May 1972.

addition, a perforated collector pipe should be placed longitudinally along the edge of the pavement. The pipe should be placed in a trench section cut in the subgrade. Outlet pipes are connected to the collector pipes at various points along the pavement. To avoid damage from maintenance equipment, the exit points of the outlet pipes should be identified with a permanent marker such as a stake or post. Construction fabrics or other barriers are suggested between the subgrade and the drainage blanket to prevent clogging of the drainage layer.

The drainage layer should consist of an open graded aggregate material. Sand or sand-gravel blends should be avoided because of the poor drainage characteristics and long term water retention capacity. These materials are normally suitable for the filter layer depending on the gradations of these materials and of the subgrade. Open graded bases provide superior drainage characteristics, contribute to the structural capacity of the pavement, and have provided good performance (Ref. 21). An asphalt coated open graded aggregate drainage layer is preferred over an unbound aggregate course. Bituminous open grade mixtures offer stability, and erosion resistance, and exhibit excellent drainage characteristics.

Occasionally ground water tables at or near grade will be encountered. In such situations all free water must be eliminated to avoid the problems described above and to minimize potential frost heave and weakening of the subgrade soil. The free water internal drainage system will play a major role in the efficiency and long term performance of the pavement. To serve efficiently these drainage materials must be physically and chemically stable within their environment, must be structurally adequate for the anticipated stress-strain levels, and must have a gradation that will accomodate the anticipated volumes and/or serve as an effective filter layer.

TERMINAL ANCHORAGE OF CRC BASE

For information on the design and construction of terminal anchorages for CRC bases of composite pavements, please refer to NCHRP Synthesis of Highway Practice No. 16 (Ref. 19).

SECTION 5. MATERIAL SPECIFICATIONS

After thorough examination of available theory and pavement performance data, six primary materials were selected for use in premium pavements. These include: 1) asphalt concrete (including asphalt stabilized materials), 2) portland cement concrete, 3) cement stabilized materials, 4) granular or crushed aggregate, 5) lime and 6) pozzolanic materials. To evaluate the zero-maintenance potential of a material the properties of the material that effect performance must be identified. After identification, the factors which affect these properties must also be established. Therefore, each of the materials listed above is discussed in reference to each of the selected design criteria used to develop the structural cross-sections. Guidelines for these materials are also presented to try to ensure that a material will perform as anticipated.

The discussions included in this section are general comments only and are not intended to provide detailed specifications. More complete materials specifications are available and should be used in preparing final design plans.

ASPHALT CONCRETE

Asphalt concrete is a high quality mixture of asphalt cement and well graded, high quality aggregate that has been thoroughly compacted into a uniform mass. Asphalt concrete mixes can be designed to serve as either surface or base courses. In either position the asphalt concrete must exhibit adequate load distribution properties and, as a surface course, it must also resist weathering and the polishing effects of heavy traffic. In addition, the material must resist the adverse effects of aging and other environment influences.

Moisture interacts with some aggregates to produce adverse effects on material properties which result in significant damage to the asphalt concrete. These moisture interactions affect the adhesion between the asphalt cement and the aggregate. Alkaline rocks provide superior adhesion to asphalt in the presence of water than do acid or silicious rocks. When acid rocks are used in asphalt concrete, addition of an anti-stripping agent such as hydrated lime may be required. When lime is added the effect of moisture can be greatly reduced therefore lime-modified asphalt concretes are advised in regions where the average yearly rainfall is greater than 12 inches in an attempt to minimize the stripping potential. In determining the moisture-induced damage of the asphalt concrete mixture, the test procedure developed by Lottman (Ref. 24[1]) is recommended. A strength reduction from Lottman's procedure should not be greater than 80 percent.

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[1]Lottman, R.P., "Predicting Moisture-Induced Damage to Asphaltic Concrete", NCHRP Report No. 192, National Cooperative Highway Research Program, Transportation Research Board, 1978.

The coarse and fine aggregates used in the surface courses should be crushed to assure high stability and performance. Asphalt stabilized base courses, however, may include natural materials in the fine fractions.

Since the type and quality of mineral filler affects the mixture stability, the mineral filler used in surface courses should be limestone dust, portland cement, or other inert materials.

The dynamic modulus can be used as a surrogate for the modulus of elasticity of the bituminous concrete provided appropriate conditions of loading time and temperature are met. Therefore the modulus is determined for each different seasonal temperature value that is expected under field conditions. Since the stiffness for the asphalt concrete used in this design manual is based on mixtures reported in Reference 15, it is recommended that the Asphalt Institute mix design procedure be used (Ref. 25[1]).

A method for estimating the modulus of elasticity of asphalt concrete for situations when laboratory tests cannot be performed is included in Appendix D. This equation represents an indirect method for estimating the modulus of the asphalt concrete at the desired seasonal temperatures.

One factor that can severely limit the maintenance free life of an asphalt concrete pavement is the effect of the environment on asphalt cement properties. The Thin Film Oven Test gives an indication of how the asphalt will harden with time. In developing the design curves used in this manual, asphalt cements exhibiting more than 60 percent of the original penetration as measured by the Thin Film Oven Test were used. A penetration index of -1.0 for the asphalt cement was also used.

The aggregate used in the asphalt concrete mixture should be durable and resistant to freeze/thaw cycles. The engineer should recognize that if an insulating material is placed in the pavement structure, the pavement layers above the insulating layer will be subjected to a larger number of freeze/thaw cycles than if the insulation layer were not present. Therefore, special care must be exercised to ensure that all aggregates used in such pavement structures resist degradation under freeze/thaw action.

Materials

The material and specification used in the asphalt concrete should be the same as those normally used for the highest quality riding surface. The coarse aggregate may consist of crushed stone, crushed slag,

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[1]The Asphalt Institute, "Mix Design Methods for Asphalt Concrete and Other Hot Mixtures", Manual Series No. 2 (MS-2), College Park, Maryland, March 1979.

crushed gravel, or lightweight aggregate. The fine aggregate may consist of natural sand, stone screenings, or slag screenings, or combinations of these. Both coarse and fine aggregates, as well as mineral filler, if used, must meet the standard materials quality specifications, such as soundness, abrasion, cleanliness, etc. In addition, skid resistance requirements should be carefully considered to select aggregates that will maintain adequate or a minimum skid number over the design period (Ref. 26[1]).

The asphalt cement shall meet all of the standard specification requirements such as viscosity, penetration, ductility, etc. The selected asphalt cement grade should be of the proper viscosity grade to satisfy the environmental and traffic loads applied.

Asphalt hardening produces raveling and the occurrence of a brittle mixture. When the penetration of the in-service asphalt is 30 or less, or when the viscosity at 140°F (60°C) exceeds 35 kilopoise, the pavement becomes extremely susceptible to cracking. In such situations the rate of asphalt hardening can be reduced by reducing the voids content to approximately 2 percent. Since bleeding becomes a problem at these low void contents, some compromise is necessary; hence, most mix design criteria limit the in-service voids to 3 to 5 percent. We recommend that compaction requirements for construction range from 6 to 8 percent. Even though this may not be ideal it is an acceptable compromise and should be a cost effective recommendation. To require a lower void content would be impractical realizing the difficulty of achieving such while still satisfying all other requirements for the mix. For example, to attain a lower void content it would be necessary to increase the asphalt content but the consequences of that decision could be a less stable mix and perhaps bleeding at the pavement surface.

Proportions

The asphaltic concrete mix should be designed according to standard accepted mix design procedures. The mix must meet the required gradation, stability, flow, air voids, etc. It is recommended that the mix consist of minimum of 85 percent crushed aggregate, based on the total coarse and fine aggregate.

In order for the mixture to have an adequate asphalt cement content without bleeding, there must be sufficient air voids in the compacted mixture. This requirements can be satisfied if voids in the mineral aggregate (VMA) meet the following criteria:

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[1]"Skid Resistance", NCHRP Synthesis of Highway Practice No. 14, National Cooperative Highway Research Program, Highway Research Board, 1972.

Maximum size of aggregate, in (mm)	Voids in the Mineral Aggregate, Minimum percent
1 1/2 (38.1)	12
1 (25.4)	13
3/4 (19.0)	14
1/2 (12.7)	15
3/8 (9.5)	16

Changes in the VMA are made by adjusting the aggregate gradation. Specifications used by most state highway agencies usually produce adequate VMA but should be checked for each mix used.

LOW MODULUS CONCRETE

Low modulus concrete is suggested for use as a rigid base for composite pavements; either as continuously reinforced concrete or as plain jointed concrete slabs. This material must be designed to provide adequate load distribution properties and to resist any adverse environmental effects.

Current mixture designs for conventional concrete pavements require minimum cement factors of from 5.0 to 6.7 sacks per cubic yard, and maximum water cement ratios of 0.44 to 0.58. For low modulus concrete these cement factors can be reduced depending on the materials and climates under consideration. Since the concrete is not the surface layer, durability problems from wear of studded tires and scaling should not be a significant problem. However D-cracking is a factor that can severely reduce the serviceable life of a pavement structure. In northern areas some aggregates are known, or suspected, to cause D-cracking, such aggregates must be avoided. Air entrained concrete should be used in all regions to resist freeze/thaw deterioration and to improve workability of the mix.

The material types and specifications for the low modulus concrete should generally be the same as for normal PCC pavement. The coarse aggregates may be crushed or uncrushed gravel or slag. The fine aggregate may be that naturally contained in the coarse aggregate material or may be sand from a separate source. The aggregate durability, hardness, cleanliness, etc. should meet normal PCC concrete specifications. The gradation should be in a normal range also, with allowance for use of local materials, provided suitable mixtures can be produced.

The portland cement should be a standard brand that conforms to ASTM requirements. The water should be clean and free of substances that will adversely affect the mix. The curing material should be an asphalt emulsion. The admixtures should meet the normal ASTM specifications for air-entraining, water-reducing and set-retarding agents. Low modulus concrete with 28-day compressive strengths of 3,000 to 4,500 psi (20.78 to 31.0 MPa) can generally be produced in the laboratory with cement contents of 425 to 800 lb per cubic yard (252 to 475 kg per cubic meter) depending on the lightweight aggregate selected. Certain aggregates can be used to make concretes with strengths of 7,000 to 9,000 psi (48.3 to 62.1 MPa) with corresponding cement contents of 565 to 940 lb per cubic yard (336 to 558 kg per cubic meter). The rate of strength development for low modulus concrete is approximately the same as that for normal-weight concrete. Moist-cured specimens of low modulus and normal concretes of equal compressive strength have approximately equal flexural and tensile strengths. It is recommended that the flexural strength of low modulus concrete be 550 psi (3.79 MPa) at 28-days.

Normal concrete has a modulus of elasticity of 2,000,000 to 6,000,000 psi (13,789 to 41,369 MPa) depending on the compressive strength. The modulus of elasticity of low modulus concrete is generally 20 to 50 percent less than that for normal concrete of equal strength. However, at higher strengths greater differences occur. The following relationship can be used to estimate the modulus of elasticity, E_c, for low modulus concrete:

$$E_c = 33(w)^{3/2} \left(f'_c\right)^{1/2}$$

in which w is the unit weight of the concrete in pounds per cubic foot and f'_c is the compressive strength in psi, as determined from 6x12-in (15.24 x 30.48 cm) cylinders. This empirical formula is reasonably reliable for concretes with compressive strengths ranging from 3,000 to 5,000 psi (20.7 to 34.5 MPa). The modulus of elasticity for most low modulus concretes range from 1,500,000 to 2,500,000 psi (10,342 to 17,237 MPa). The modulus of elasticity should be determined by tests of concrete specimens. It is recommended that the mix be designed for a modulus of elasticity of 2,000,000 psi (13,790 MPa).

The materials should be proportioned to produce a mix with a minimum 28 day compressive strength of 3,000 psi (20.7 MPa) and air entrainment of 3 to 9 percent, depending on environmental conditions. The amount of cement should normally range from 225 to 250 lb per cubic yard (134 to 148 kg per cubic meter), of mix, but vary with the aggregate selected. The slump should not exceed 3 inches (7.62 cm). Set-retarding and water-reducing agents may be used if needed. All mix proportions and properties must be well defined in the mix designs completed prior to beginning of construction.

STRESS AND STRAIN ABSORBING MEMBRANE INTERLAYERS

Stress absorbing membrane interlayer or strain relieving interlayer and cushion courses (crack relief layer) are used to reduce the effect of horizontal or vertical movements at underlying joints or cracks in the concrete base. Basically, the stress absorbing membranes and cushion courses are used to minimize the occurrence of reflection cracking and should therefore be placed between the asphalt concrete surface and the concrete base.

The stress absorbing membrane layer is a mixture of paving grade asphalt, rubber extender oil, and ground rubber. These components are blended in a conventional distributor truck at a temperature ranging from 175 to 200°F (79 to 93°C). The significant ingredient that produces the membrane properties is the ground rubber which consists of a dry, free flowing blend of powdered reclaimed rubber and ground vulcanized scrap with high natural rubber content. Different rubber formations are being developed and should be evaluated by the designer.

The crack-relief layer is a layer of coarse, open-graded hot mix, containing 25 to 35 percent interconnecting voids and made up of 100 percent crushed material. It is the first course of asphalt concrete and is designed to reduce reflection cracking. Because of the large amount of interconnecting voids, this crack-relief layer provides a medium that resists the transmission of differential movements of the underlying slabs.

The selection of an open-graded mix depends initially on the availability of the size of aggregate in a given area. The use of a particular mix should also depend upon the characteristics of the material in the existing pavement. Highly expansive or new portland cement concrete pavements, such as those constructed with washed silica gravel, require crack-relief layers with the larger maximum size aggregates (Mix A or B of Table 5.1). Less expansive PCC pavements can be overlaid with Mix C of Table 5.1.

UNBOUND GRANULAR MATERIALS

The unbound granular base and subbase materials are materials that meet the grading and other requirements described in the U.S. Army Corp of Engineers specifications (Ref. 7). It is recommended that for this particular usage that the 1.5 inch (3.81 cm) top size aggregate be used if possible.

The modulus of these materials is dependent not only on moisture content and density, but also on the state of stress to which the material is subjected. For most granular materials the resilient modulus increases as the bulk-stress increases. Hence, procedures for estimating the moisture content, density, and stress state in the granular layers have been used to develop a test procedure for estimation of the modulus of elasticity.

The granular base consists of aggregates such as crushed stone, crushed slag, crushed or uncrushed gravel and sand or of combinations of these materials. Specifications for base course materials are generally considerably more stringent than for subbase materials in requirements for strength, plasticity, and gradation.

TABLE 5.1 GRADATION RECOMMENDATIONS FOR THE CRACK-RELIEF LAYER

Sieve	Percent Passing		
	A	B	C
3 in (75 mm)	100	-	-
2-1/2 in (63 mm)	95-100	100	-
2 in (50 mm)	-	-	100
1-1/2 in (38.1 mm)	30-70	35-70	75-90
3/4 in (19.0 mm)	3-20	5-20	50-70
3/8 in (9.52 mm)	0-5	-	-
No. 4 (4.75 mm)	-	-	8-20
No. 8 (2.36 mm)	-	0-5	-
No. 100 (150 μm)	-	-	0-5
No. 200 (75 μm)	-	0-3	-

The specifications presented in AASHTO designations M-147 and M-75 are typical of the gradation and quality of untreated base aggregates. Additional requirements for quality of base materials, based on test procedures used by the constructing agency, may also be included in materials or construction specifications.

For environments where frost is expected to penetrate the pavement structure, a maximum of 3 percent passing the No. 200 sieve is recommended to insure that the material will not be susceptible to frost action.

DRAINAGE LAYER

The draining and filtering function of a drainage blanket creates two unique construction problems because of the cohesionless nature of the material used in the drainage blanket. A material with no fines tends toward natural segregation and consequently wide variations in permeability occur. In addition, rutting and dislodgement of the drainage layer may occur as the asphalt concrete surface layer is placed on the drainage layer. One remedy to this second problem is to include sufficient fines or add asphalt-cement to provide cohesion so that compaction can occur. However, the percent fines required to achieve compaction may reduce the permeability too severely. Therefore, the amount of fines should be limited to about 3 percent passing the Number 200 sieve as shown below.

Sieve Size	% Passing
1" (25.4 mm)	100
3/4" (19.0 mm)	90-100
3/8" (9.5 mm)	40-100
No. 4 (4.75 mm)	25-40
No. 8 (2.36 mm)	18-33
No. 30 (600 μm)	51-5
No. 50 (300 μm)	0-7
No. 200 (75 μm)	0-3

Membrane filters or filter fabrics can also be used for this purpose and are generally manufactured of synthetic fibers; they may be woven, spun bonded, needled, or otherwise fabricated to provide a porous cloth-like material (Ref. 27[1]). Their use in drainage systems involves serving as one element in a multi-layered filter system and as such they replace one layer of granular material. The opening size of the fabric should be compatible with both the protected layer and the element into which the free water shall drain. Aggregate used as filters and permeable media should consist of sound, clean granular materials with zero

[1]"Sample Specifications for Engineering Fabrics", Report No. FHWA-TS-78-211, Federal Highway Administration, U.S. Department of Transportation, 1978.

plasticity. The gradation should be designed to prevent the loss of soil fines by hydraulic piping and still provide adequate flow capacity. Collector pipes should be of a material that will be stable in the physical and chemical environment in which they are to serve for the design life of the improvement or pavement. The filter layer need be only as permeable as the material on which it rests, but the grading of the two material should be compared to ensure that the filtering capacity is adequate. The filter must meet the dual requirements of preventing migration of the native soil toward the surface and at the same time not itself migrate into the drainage layer.

The asphalt treated drainage layer consists of an open graded aggregate, in which particles are restricted to the range between No. 4 to 3/4" sieves. These particles are mixed with enough asphalt to bind the open graded aggregate into a stable mass. The asphalt content should range between 1 1/2 and 2 percent of 85 to 100 penetration grade asphalt cement. The grading of this layer should generally follow the grading below:

Sieve Size	% Passing
1" (25.4 mm)	100
3/4" (19.0 mm)	90-100
3/8" (9.5 mm)	30-50
No. 4 (4.75 mm)	0-5
No. 8 (2.36 mm)	0-2

The asphalt content functions only as a binder for the open graded aggregate and in no way hinders the flow of water through the drainage layers.

Two drainage systems are recommended for consideration in the design of zero-maintenance pavements. The first system is designed to lower a high water table and consists of perforated pipes. The second system is designed to rapidly remove surface moisture infiltration from the pavement structure and consists of a 2 layer drainage system. References 20, 22, 28[1], and 29[2] adequately explain the construction procedures and purposes of these drainage systems. Underdrains or interceptor drains are the most widely employed technique for lowering a high water table. The interceptor drains should be designed to provide sufficient capacity to keep the water table below the final grade a minimum height of 7 feet (2.1 m) for cohesionless soils and 10 feet (3.0 m) for cohesive soils.

SOIL STABILIZATION SUBGRADE

Subgrade as used herein refers to the natural, processed, or fill soil foundation on which a pavement structure is placed. The method

[1]"Drainage of Asphalt Pavement Structures", MS-15, The Asphalt Institute, May 1966.

[2]Cedergren, H.R., Drainage of Highway and Airfield Pavements, John Wiley and Sons, 1974.

for subgrade soils is affected by changes in moisture content, density, and variations in the stress state. Therefore the test procedure described in Appendix B contain provisions for considering these factors when setting up the test.

For expansive or compressible soils proper densification or stabilization is recommended to minimize the potential for volume change. Discussion of techniques for identifying potentially expansive soils are given in References 30[1] and 31[2]. Lime, cement, or asphalt stabilization is the accepted method for controlling the swelling of soils and improving the strength characteristics of marginal materials. Stabilization as used here refers to treatment of a soil with such agents as bitumen, portland cement, slaked or hydrated lime, fly ash, etc. to obtain a substantial increase in the strength of the treated material over its natural strength. Figure 5.1 developed by McKeen (Ref. 32[3]), illustrates a selection process used by the Federal Aviation Administration for identification of expansive soils. The logic pattern contained in Figure 5.2 can then be used to select a suitable soil stabilizer. Stabilized soils that transfer loads by beam action should be characterized using the flexural beam test. Flexural modulus values determined directly for laboratory test can be used when cracking in the stabilized layer produces no significant effect on other layers and when the strain, determined using the laboratory flexural modulus, does not exceed an allowable strain for the material being used.

Lime Stabilization

Lime and/or pozzolans are added to the soil for strength improvement. Only fine grain soils can be effectively stabilized with lime. Lime has been found most effective with clay soils containing montmorillonite, illite, and kaolinite. Lime-fly ash stabilization is applicable to a broader range of soil types because its cementing action is less dependent on fines contained within the soil.

Lime treatment of clay soils can convert the material from one that shows negligible to moderate frost heave to one that is highly susceptible to frost heave. The treated material acts more like a silt than a clay. This adverse effect can be caused by insufficient curing time

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[1]Snethen, D.R., L.D. Johnson, and D.M. Patrick, "An Evaluation of Expedient Methodology for Identification of Potentially Expansive Soils", Report No. FHWA-RD-77-94, Federal Highway Administration, June 1977.

[2]Snethen, O.R., L.D. Johnson, and D.M. Patrick, "An Investigation of the Natural Microscale Mechanism that Cause Volume Change in Expansive Clays", Report No. FHWA-RD-77-75, Federal Highway Administration, January 1977.

[3]McKeen, R.G., "Design and Construction of Airport Pavements on Expansive Soils", Report No. FAA-RD-76-66, Federal Aviation Administration, U.S. Department of Transportation, June 1976.

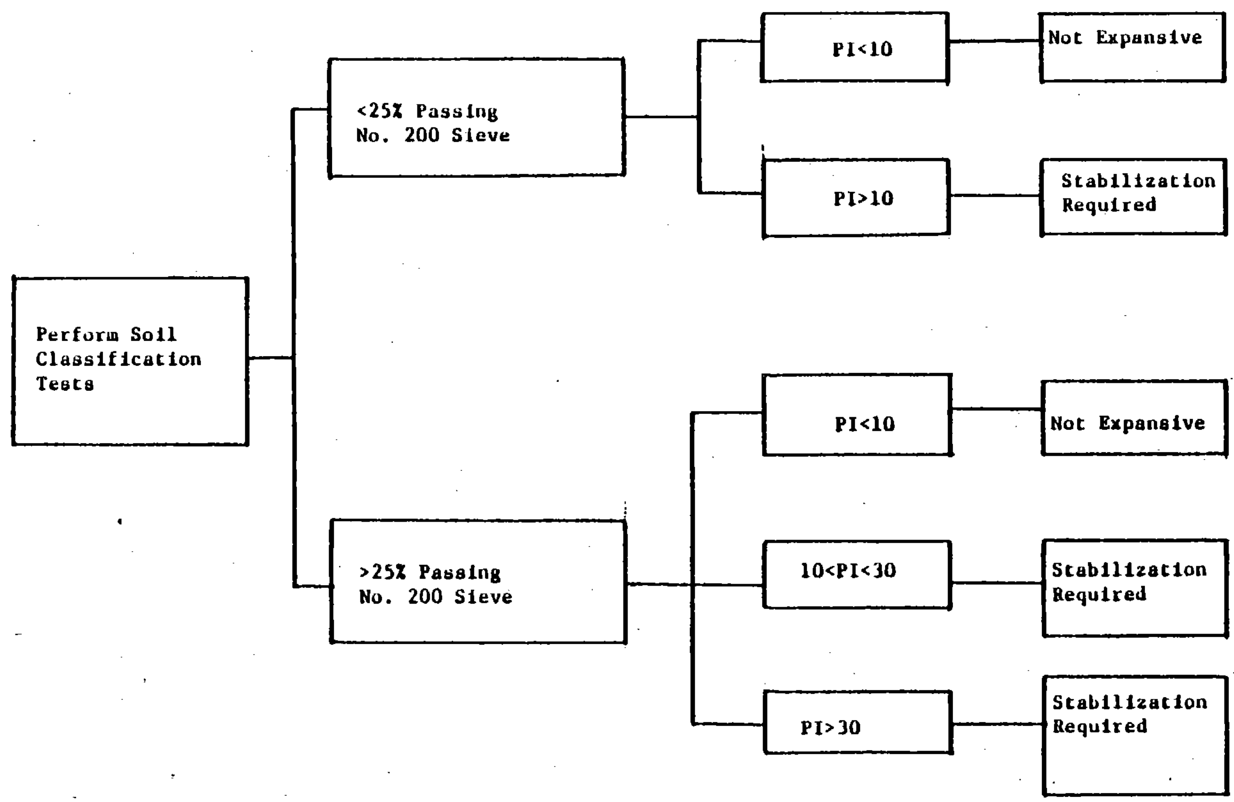

Figure 5.1 General Flow Diagram for Determining if a Soil can be Stabilized to Reduce the Swelling Potential.

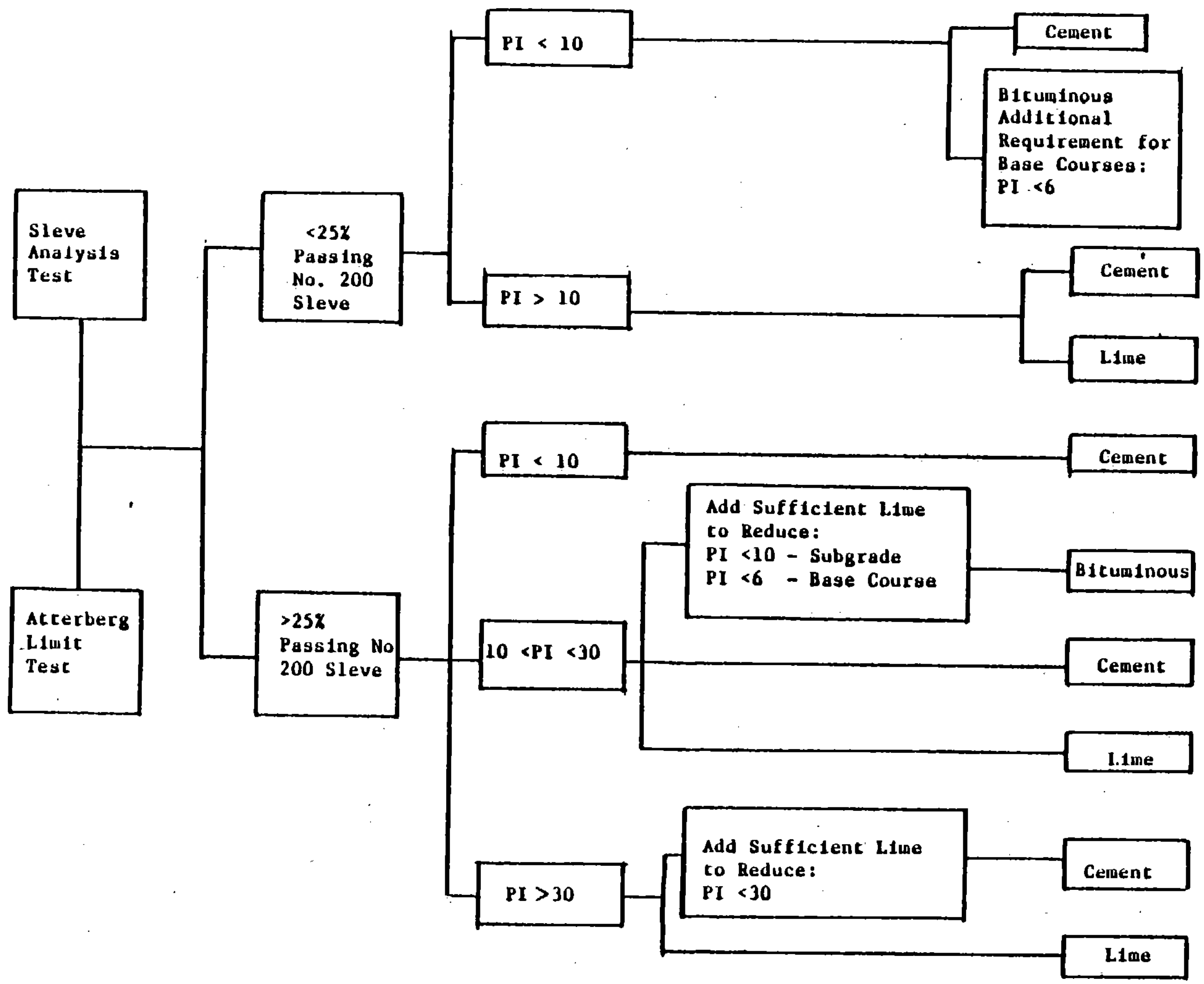

Figure 5.2 Flow Diagram to Determine the Type of Stabilizer for a Specific Soil Condition.

before freezing occurs. Hence it is emphasized that an adequate curing period is critical to the performance of these materials. The major durability problem associated with lime soil mixtures is resistance to cyclic freeze and thaw action. Soils classified as CH, CL, MH, ML, SC, and GC, with a plasticity index greater than 12, and with at least 10 percent passing the No. 40 Sieve are potentially suitable for stabilization with lime. Hydrated lime, in powder form or mixed with water as a slurry, is normally used in stabilization. The minimum strength specified for a lime stabilized base is 150 psi (1.03 MPa) in 28 days. To determine the design lime content for a subgrade soil, the following steps are suggested:

1) Determine the initial design lime content by mixing varying amounts of lime with the soil in water and measuring the pH levels in one hour intervals. Select the lowest lime mixture level for which a pH of 12.4 occurs as the initial design lime content.

2) Prepared specimens at the initial design lime content and at about 2 and 4 percent lime above that from step 1 and cure specimens for 28 days at 73°F (23°C).

3) Determine the unconfined compressive strength for all cured specimens. Select as the construction design lime content the minimum percent required to achieve a compressive strength of 150 psi (1.03 MPa).

4) Add one half to one percent additional lime in the lower percentage ranges to compensate for problems associated with non-uniform mixing during construction.

Portland Cement Stabilization

Portland cement is widely used for stabilizing low plasticity clays, sandy, and granular materials to improve their strength and stiffness characteristics. At low cement contents the product is generally termed cement-modified soil. These modified soils exhibit improvements in such properties as plasticity, expansive characteristics, and frost susceptibility. Relatively small amounts of portland cement can be used to reduce the plasticity index and swell characteristics of many soils. For soils to be stabilized with cement, proper mixing requires that the soil have a plasticity index of less than 20 and a minimum of 45 percent passing the No. 40 sieve. However, heavier clays that have been treated with lime or fly ash are sometimes suitable for subsequent treatment with portland cement.

Asphalt Stabilization

Asphalt stabilized materials are generally used as bases and subbases. Use of asphalt as a stabilizing agent produces different effects depending on the soil and may be divided into three principal groups:

1) sand-asphalt - asphalt produces additional strength and water proofing in cohesionless soils, such as clean sand by acting as binder or cementing agent, 2) soil-asphalt - the asphalt helps water proof and stabilize the moisture content of cohesive fine grain soils, 3) sand-gravel asphalt - asphalt provides cohesive strength and waterproofs pit-run gravelly soils with inherent tensile strength.

The durability of asphalt stabilized mixtures generally can be assessed by measurement of their water absorption characteristics.

SECTION 6. CONSTRUCTION SPECIFICATIONS

The basic objective of the construction specifications is to define those requirements which are necessary in order to achieve an in-situ structure which is compatible with the design assumptions. Two major considerations must be incorporated in the construction specifications; 1) to achieve an appropriate in-place state or condition and 2) to achieve uniformity throughout the total pavement structure.

In developing the material and thickness requirements for premium pavements it was necessary to determine reasonable expectations for in-place material properties. Such properties as tensile strength, modulus of elasticity, permeability and fatigue characteristics of various elements of the pavement are indicative of the properties used in the development of design recommendations. Unfortunately, it is not convenient to measure thse properties for construction control. It is therefore necessary to substitute proxy tests in lieu of direct measurements. For example, density is used as a proxy for shear strength and modulus of elasticity; air voids for permeability; and compressive strength and cement content for tensile strength. Thus, construction specifications generally depend on proxy tests such as density, water content, aggregate gradation, asphalt content, cement content and lime content as a measure of construction adequacy.

The second consideration is uniformity of in-place conditions; i.e. density, admixture content, etc. It must be recognized that all in-situ material conditions will exhibit some degree of inherent variability which is beyond the control of the contractor and the engineer. However, it is necessary to minimize any additional variability by adequate quality control and quality assurance procedures. It must be remembered that pavements are not judged on their average condition; they are judged by what is observed to happen to 10 or 15 percent of the paved area which in turn is influenced by the magnitude of the variability in material properties.

To ensure that design assumptions and requirements are met, construction of the facility is extremely crucial and highly dependent on existing environmental conditions. Some of these effects and consequences of environment are discussed in Reference 33[1]. The failure to achieve specified quality construction may have serious consequences by reducing the maintenance free life of the pavement structure. Continuous inspection of the pavement should be made during construction to determine if deficiencies exist and if they do, to adopt corrective measures.

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[1]"Effect of Weather on Highway Construction", NCHRP Synthesis of Highway Practice 47, National Cooperative Highway Research Program, Transportation Research Board, 1978.

Each agency should have good specifications which can be adapted for premium pavements. This Section is not intended to provide complete specifications or to replace agency specifications. Rather it is intended to highlight several major construction factors that significantly affect pavement life and performance.

In selecting the materials suitable for use in premium or zero-maintenance pavements, careful consideration was given to the construction process because construction is a dominant factor in determining whether the life of pavement will be maintenance free. Some of the construction variables to be discussed include factors such as, 1) temperature and length of curing, 2) water content during compaction, 3) degree of compaction, 4) variability of the in-place properties of materials, etc.

GRADATION

Gradation requirements for stabilized and unstabilized materials are referenced in Section 5. Job-mix-formulas should be required for all processed materials; i.e. asphalt concrete, portland cement concrete and unbound base. The job-mix-formula should specify the gradation and quantity of asphalt or cement as appropriate for the material specified.

Allowable tolerance from the job-mix-formula should be based on laboratory test information which indicates the materials will meet design requirements with the full range of the established tolerances. For example, when mixes are fabricated with aggregate gradations at the extreme limits of tolerances, the resulting mixes should meet design requirements; i.e. stability, tensile strength, etc. as appropriate for the material being tested.

ASPHALT AND CEMENT CONTENT

Strict control of asphalt content, lime content, cement content and water cement ratios is important to those materials designed with these additives. The allowable tolerance on asphalt should not exceed ±0.3 percent for 75 percent of the test results and should be within ±0.4 percent for 100 percent of the test results.

At final compaction the lime content for lime treated subgrade should be within ±0.5 percent.

COMPACTION

This design method is based on the premise that the material properties selected for design are actually achieved in the field. Thus, it is important that the materials be properly compacted in order to achieve the specified conditions. Proper compaction must be achieved without regard to the material selected for use in the particular layer. Compaction requirements for each layer are set out in Table 6.1.

Although compaction usually increases soil strength, some adverse effects can occur as a result of the compaction process. Some soils lose strength after being scarified and recompacted, while other soils shrink or expand excessively when the in situ moisture content changes. When these soils are encountered, special treatment is required. Also, if settlement of a deep fill over a compressible layer is expected, the fill material should be placed early so that it acts as a surcharge weight and remains in place long enough for the majority of the initial settlement to occur before the structural layers are placed. Suggested treatments are included in Reference 34[1].

Each pavement layer should be compacted to the specified density. Fill sections generally should be built in layers not exceeding 6 inches (15 cm) after compaction. Some sheepsfoot rollers, heavy pneumatic-tired rollers, and vibratory compaction rollers may provide satisfactory compaction for lifts up to 12 inches (30 cm), but these thicker lifts should be used only if control compaction sections indicate that the specified density can be obtained.

SUBGRADE PREPARATION

Both the natural soil and the compacted embankments used as subgrades for structural sections should be well consolidated and thoroughly compacted prior to the placement of the structural section. Otherwise, differential settlement or swell can produce sags in the grade line that may trap and hold water. To minimize such problems, the subgrades and embankments should be compacted to a specified percentage of the maximum density by controlling water content at or near the optimum moisture content. To minimize post-construction settlement or consolidation, unsatisfactory foundation materials should be removed or stabilized before placement of the structural cross-section.

SUBGRADE STABILIZATION

The decision to specify soil stabilization should be based on review of the soil conditions and engineering judgment. The subgrade is stabilized to improve the engineering properties by reducing plasticity and controlling expansion. This section contains information for in-place stabilization of subgrade soil to improve the engineering properties of the soil, to make the soil more workable and/or to expedite

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[1]"Treatment of Soft Foundations for Highway Embankments", NCHRP Synthesis of Highway Practice No. 29, National Cooperative Highway Research Program, Highway Research Board, 1975.

TABLE 6.1 COMPACTION REQUIREMENTS FOR CONSTRUCTION OF VARIOUS PAVEMENT LAYERS

Pavement Layer	Minimum Density Requirements	Reference Test Method ASTM	AASHTO
Surfacing (asphalt concrete)	98%	D 1559 (75 blows per face)	T245 (75 blows per face)
Base			
Untreated aggregate	100%	D 1557 (Method D)	T180 Method D)
Cement treated Note - Do not include if not part of recommended pavement designs.	100%	D 1557 (Method D) for compaction and D 558 for sample preparation	T180 (Method D) for compaction and T134 for sample preparation
Asphalt treated	98%	D 1559 (75 blows per face)	T245 (75 blows per face)
Subbase			
Untreated aggregate	100%	D 1557 (Method D)	T180 (Method)
Subgrade			
Cohesionless material	100%	D 1557 (Method D)	T180 (Method D)
Cohesive material	95%	D 1557 (Method D)	T180 (Method D)
Stabilized subgrade (a)			
Cement	95%	D 1557 (Method A) and D 558	T180 (Method D)
Lime	95%	D 1557 (Method A)	T180 (Method D)
Fill			
Cohesionless	95%	D 1557 (Method D)	T180 (Method D)
Cohesive	90%	D 1557 (Method D)	T180 (Method D)

(a) subject to allowable variations as stipulated herein construction. The soils normally considered for stabilization are silts, clays, and fine grained sands. In-place mixing of the soils and stabilizing agent is permissible, however, plant mixing will produce a more uniform product. Although the soils strength is upgraded through stabilization, no reduction in the pavement thickness was made in the design cross-sections presented in this manual.

Lime Stabilization

After the soil is brought up to the required grade, it should be scarified to the required depth, reducing the material to a clod size of less than 2 inches (5.08 cm). Modern rotary mixers can normally achieve this degree of pulverization, in one pass, except for heavy clays which may require additional passes. All debris such as stumps, roots, and aggregations larger than 3 inches (7.62 cm) should be removed.

Lime can be spread either dry or in slurry form that is typically 1 ton of lime to 500 gallons of water (0.9 tonnes per 1893 liter). In dry form the engineer should insure that uniform distribution is achieved and that dry lime is not lost through wind erosion or other disturbances. Lime slurry can be prepared in a central mix plant and transported to the site if agitation is provided to prevent lime solids from settling out of the solution. Provisions also must be made to prevent the runoff of slurry when placed on slopes. Standard water or asphalt distributors are commonly used to distribute lime slurry.

Lime and soil may be mixed in a central plant and transported to the construction site. In this case, the material must be excavated, transported, treated, and distributed at the site. The material should be spread using a mechanical spreader to minimize density variations. Lime stabilization requires thorough mixing to distribute the lime throughout the soil layer. Curing time varies typically from 2 days for silts to 7 days for very heavy clays. Ideally, the soil should be pulverized enough for 100 percent to pass the 1-in (2.54 cm) sieve and 60 percent to pass the No. 4 sieve. After placement the lime/soil mixture is lightly compacted to prevent carbonation and to protect it from rain. For heavy clays a second mixing stage is usually required after initial curing.

Compaction is normally accomplished in one lift. A sheepsfoot roller is first used, then a 10-ton (9-tonne) pneumatic tire roller, and finish rolling is accomplished with a light pneumatic roller. The compaction requirement is usually 95 percent of the maximum AASHTO T99 (ASTM D698) test.

After compaction the surface is maintained in a moist condition either by sprinkling or by sealing the surface with a membrane. Strength increases as the length of the curing period increases. Construction cutoff dates must be established to allow completion of curing before freezing temperatures occur. In addition provisions must be made to prevent erosion due to heavy rainfall during curing.

Cement Stabilization

Mixing and pulverization of soils suited to stabilization is usually more easily accomplished than for soils stabilized with lime. Soils suitable for cement stabilization are usually not heavy clays (PI < 30). Before application of the cement the soil is generally scarified and placed in a windrow. The final mixture should meet the criteria of 100 percent passing the 1-in (2.54 cm) sieve and 60 percent passing the No. 4 sieve.

The cement may be spread from a bulk transport truck or closed dump truck with an attached mechanical spreader. Spreading should not occur until the soil moisture content is below optimum because experience has shown that cement will not mix adequately with wet soil. The cement and soil shall be mixed with the appropriate amount of water to bring the moisture content to that specified in the mixture design. When a central plant is used to mix the soil, cement, and water a more uniform mixture is produced. The soil/cement mixture should then be distributed with spreader boxes in order to reduce density variations.

A variety of compaction equipment can provide satisfactory compaction for soil/cement mixtures. Sheepsfoot rollers can be used with contact pressures of 75 to 125 psi (0.52 to 0.86 MPa) for friable silty and clayey sandy soils; 100 to 200 psi (0.69 to 1.38 MPa) for clayey sands, lean clays, and silts; and 150 to 200 psi (1.03 to 1.38 MPa) for medium to heavy clays. The minimum field density required is 95 percent of the maximum density as determined by AASHTO T134 or ASTM D558.

Lime/Cement Stabilization Procedures

The procedures for the construction of lime/cement stabilized soil are identifical to those previously described. The expense and time involved in use of both stabilizers is justified only if the material is a heavy clay soil (PI > 30) that is not lime reactive and will not mix with cement. In this situation, the lime is used to improve the workability and reduce the plasticity index while the cement increases the strength. Lime is added to produce a friable material that is better suited to cement stabilization.

ASPHALT SPRAY COATS

Prime coats are often used: 1) to seal surface or base courses in areas where rain may be expected prior to placement of other pavement layers, 2) to bind together dusty surfaces, 3) to resist surface tractive forces of construction traffic on a base course, and 4) to provide adhesion between overlaying bituminous courses and the base.

Prime coats materials are generally liquid asphalts of grade MC-70, MC-250, RC-70, RC-250 or RT-2 and RT-3 tars. Application rates of the liquid asphalts and tars are between 0.15 and 0.4 gallons per square yard (0.68 to 1.81 l/m^2). Sufficient bitumen should be used to fill the voids but not more than can be readily absorbed. Asphalt emulsions have been used experimentally with varying success for prime coats. Emulsions do not penetrate as well as liquid cutback asphalts. In addition, a sand fill is required to prevent cracking. Emulsions used for priming are SS-1 and SS-1h diluted with 50 percent water and applied at approximately 0.1 gallons per square yard (0.45 l/m^2).

Tack coats are required to ensure good bond between two asphalt concrete layers. Tack coats may not be required between new layers of pavement where the upper layer is immediately constructed as the lower layer is completed. However, tack coats should be used between layers when construction is delayed. Tack coat should also be placed on surfaces which have become coated with fine sand or dust or have been soiled by construction traffic.

DRAINAGE LAYER

In the construction of a subbase, base, or special "filter" layer under an open-graded drainage layer, care must be taken to avoid any disturbance or contamination of the layer. Dirt and other foreign matter must be kept off the tires and tracks of earth-moving or other construction equipment to avoid contamination of the drainage layer with harmful amounts of foreign materials. While exposed, these drainage layers should be protected from mud and dirt fines transported by rainfall or other surface water.

The filter layer may be placed in a single lift by end dumping and spreading to a uniform thickness. Spreading should be followed by wetting and compacting with a single pass of an empty 3 to 5 ton (2.7 to 4.5 tonne) steel wheel roller. Optimum benefit from the wetting and compaction of the filter layer will result when completed immediately prior to placement of the asphalt treated drainage layer. Use of an asphalt paving machine with the widest possible track is recommended for placement of the asphalt treated drainage layer. Some displacement of the filter layer is to be expected due to the action of wheels of trucks delivering the asphalt treated material. The asphalt treated drainage layer may be placed in one or two lifts with no compaction other than that occurring due to the tamping action of the paver itself.

After the drainage layer has been placed, no subsequent construction activity that will impair the integrity of the drainage layer should be permitted. Excessive amounts of tack coats or prime materials should not be permitted to penetrate the open-graded drainage layer.

When a concrete base is placed over an open-graded base, procedures should be developed to prevent significant amounts of cement mortar from flowing into the open-graded base. A thin layer of stone chips could be used as a leveling course and as a "choker" to aid in keeping mortar out of the drainage layer. The size of the choker course should be approximately one-fourth the D_{15} size of the open graded base. Any such course should be rolled with a three-wheel steel roller before the concrete is poured. To confirm that mortar will not penetrate into the open-graded base drainage layer, a small test slab could be poured and vibrated to simulate actual construction procedures as closely as possible. After the concrete in the test slab has set sufficiently, the slab should be lifted and the base inspected for mortar penetration. Modification of construction procedures can then be made to prevent penetration of mortar into the drainage layer.

Collector Pipes

The material used for filling the trench around collector pipes should be placed so that no significant segregation occurs. During the placement of the pipes and cover materials, care must be exercised to prevent the pipes from breaking or collapsing and to prevent the intrusion of foreign matter that could impede the flow of water. As the pipes are laid, the longitudinal grade should be checked to ensure that the proper grade is maintained. After the pipes have been installed, the continuity of the passageway should be verified either by drawing an object through the pipe or by inserting a light and performing a visual inspection.

In all areas where collector pipes are used the perforations or slots in the pipe should be at the bottom. Pipes that are transporting water but are not drainage pipes should have solid walls.

Drain Trench Backfill

After the pipes have been placed in a trench, the backfill material should be placed promptly to minimize the potential for entry of foreign matter into the trench. Drainage materials around pipes should be placed with equipment designed to provide a uniform placement of the material without segregation and without dislodging or damaging any filter cloths placed on the sides and bottom of the trench. Compaction of the trench backfill material should be sufficient to prevent settlement of overlying pavement or shoulder material under traffic. Drainage materials should not be overcompacted because the permeability may be reduced below the required level.

Outlets and Outlet Markers

To keep rodents, other animals, and birds from building nests or depositing debris in the pipes, a suitable screen should be installed at outlet locations. The screen retention mechanism should be designed so that it will move outward under low water pressure if grass or other matter collects on the inner side of the screen and begins to block flow.

Outlet ends of pipes should be protected and marked with a suitable post as soon as the installation is completed.

LOW MODULUS CONCRETE

Low modulus concrete is similar to normal portland cement concrete in many ways. Therefore the same construction practices as outlined in ACI Manual of Concrete Practice (Ref. 35[1]) can also be used for low modulus concrete. However, for low modulus concrete the surface smoothness, the finish, and the joints (if a jointed pavement) do not require as much attention to detail as is required for the standard surface mix. Low modulus concrete is generally easier to handle and place than normal concrete. A slump of 3 inches (7.62 cm) or less produces excellent results in finishing low modulus concrete. Larger slumps may result in segregation, and a rough, uneven surface.

On flat surfaces a high-frequency vibrating screed is effective for finishing. Finishing operations should be started earlier than for normal concrete, but finishing too early may be harmful. A minimum amount of floating and troweling should be done. The same curing practices used for normal concrete should be followed for low modulus concrete.

The PCC base should be mixed in standard approved mixing equipment. No construction traffic should be permitted on the concrete base for 14 days.

The curing compound should be an asphalt emulsion that is applied at a rate of 0.20 gallons per square yard (0.91 l/m^2). The surface should be placed to the proper cross section and should vary no more than 3/8 inch in 16 feet (0.95 cm in 4.88 m). No special surface texture is required.

If the base is placed as a jointed pavement, the joints should be sawed so that the panel lengths do not exceed 20 feet (6.10 m). It is not necessary to seal the joints since no intrusion of foreign matter is expected.

STRESS ABSORBING MEMBRANE INTERLAYER

The stress absorbing membrane layer is approximately 3/8 inch (0.95 cm) thick and must be carefully constructed to serve properly. The purpose of this interlayer is to absorb stress transmitted upward from the concrete base toward the asphalt concrete surface, thus reducing the tendency for reflection cracking to occur. It is recommended that an engineer who has experience in this type construction be on site during placement of this pavement layer.

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[1]"ACI Manual of Concrete Practice", Parts 1 and 2, American Concrete Institute, Detroit, Michigan, 1979.

ASPHALT CRACK RELIEF MIX

The crack relief layer in the pavement system consists of a 3 to 4 inch (7.62 to 10.16 cm) layer of 100 percent crushed coarse, open graded hot mix asphalt concrete containing 25 to 35 percent interconnecting voids. This layer is placed above the concrete base to reduce reflection cracking. Because of the large amount of interconnecting voids, this crack relief layer provides a medium which does not readily transmit differential movements of the underlying slab. The crack relief layer is placed first and then a leveling course provides a smooth foundation for the surface course. A critical element in the long term performance of this system is drainage of the crack relief layer. Because of the large void content, water will readily enter the open graded layer. A convenient method of insuring adequate drainage is to daylight the crack relief layer to the shoulder. Alternately longitudinal subsurface drains can be used at the edge of the pavement to collect water from the crack relief layer and to transfer that water to a sub-surface outlet.

Preparation of the concrete slab to receive the crack relief layer is similar to that for a conventional pavement. No special methods or equipment are required. The pavement surface should be prepared so that it is as clean as practicable and then a tack coat is applied. To insure a thin and uniform coverage, emulsified asphalt SS-1, SS-1h, CSS-1 or CSS-1h diluted with equal parts water is recommended at a rate of 0.10 gallons per square yard (0.45 l/m^2).

Compaction of the crack relief layer should be made using 4 to 10 tons (3.6 to 9 tonnes) static rollers. Heavier rollers may crush some softer aggregates. One complete coverage of the crack relief layer should be sufficient. Overcompaction can minimize the effectiveness of the crack relief layer by reducing the voids content to the extent that joint or crack action is not adequately absorbed and water transmission to the longitudinal edge drains is affected.

DENSE-GRADED ASPHALTIC CONCRETE SURFACE

The top layer of a composite or flexible pavement consists of a high quality dense-graded asphaltic concrete made from crushed aggregates exhibiting good skid resistance properties.

The asphaltic concrete surface layer should be mixed and placed according to standard, proven procedures and specifications. The proper mixing and placing temperatures as well as the required density and stability must be met. The very smooth surface should also be attained.

One of the most common deficiencies associated with the placement of asphalt concrete is improperly constructed longitudinal construction joints. Premature raveling and potholes normally first occur in this area. In order to prevent this occurrence, a construction procedure which provides a semi-hot joint should be adopted. A semi+ bt joint is secured by scheduling for the paver to drop back and place the second lane before the temperature of the material in the first lane drops below 140°F (60°C), which typically occur between 2 and 4 hours after placement. A hot joint is recommended i.e., paving in echelon, however such procedures are not always possible. Adequate density can be achieved in the longitudinal joint if good construction practices are followed; primarily to be sure that an adequate amount of material is crowded into the joint and that the mix is properly compacted.

It is likely that the density of material adjacent to longitudinal construction joints will be lower than that in the rest of the lane, particularly if the joint is a cold joint. Therefore the surface layer should be constructed so that the longitudinal joint is never located in the wheelpath area. The next least desirable location for a longitudinal joint is in the center of a traffic lane where accumulated oil drippings affect the properties of the asphalt concrete.

The recommended acceptance criteria for density of asphalt concrete is summarized as follows:

Each lot of compacted pavement will be accepted, with respect to density, when the average field density is equal to or greater than 98 percent of the laboratory prepared specimens and when no individual determination deviates more than 2 percent from the average field density. Four field density determinations will be made from each lot. Each lot shall not exceed 500 tons (450 tonnes) of asphalt concrete.

SECTION 7. EXAMPLE PROBLEM

The following subsections describe an example problem illustrating the use of this design manual. The example problem includes a design for a full-depth asphalt concrete pavement structure and the summary discusses the additional considerations required for the design of a composite pavement structure. For simplicity, only 3 design sections (based on soil exploration data) will be considered in the example; however, a design for each boring or significant change in the subsurface soils should be prepared. To facilitate the use of this example problem, all of the text has been included at the front, followed by the appropriate figures and worksheets required to demonstrate the procedure.

ASPHALT CONCRETE PAVEMENT EXAMPLE PROBLEM

For this example problem assume that a section of pavement is to be constructed near San Antonio, Texas, for a truck and bus express lane that is to be part of IH-35. For simplicity, only a full-depth asphalt concrete pavement structure will be considered for this premium pavement design.

Input - Worksheet A

Temperature data for Worksheet A can be obtained from meteorological data (Ref. 12). This data for San Antonio, Texas, is shown in Figure 7.1 with the pertinent data circled.

Item 1. Obtain Mean Annual Air Temperature from historical records and enter on Worksheet A, value is 68.3.

Item 2. Obtain Warmest Mean Monthly Air Temperature from historical records and enter on Worksheet A, value is 84.9.

Item 3. Obtain Coldest Mean Monthly Air Temperature from historical records and enter on Worksheet A, value is 44.1.

Item 4. Compute Mean Monthly Air Temperature change and enter on Worksheet A, value is 84.9-44.1 = 40.8.

Item 5. Obtain Design Air Freezing Index from historical records and enter on Worksheet A. Figure 2.2 can be used as an estimate in the absence of other information, value is 50.

Item 6. Secure subsurface soil information from a soil survey.

Item 7. List section or boring number and location. A design can be prepared for each boring or a design prepared for each significant change in the materials encountered during subsurface explorations. In this problem, three separate soil types are included as Soil I, Soil II, and Soil III.

Item 8. Based on classification tests, determine each soil type using the Unified Soil Classification and record along with the plasticity index (PI). From the gradations, determine the percent finer than 0.02 mm for each soil strata and list the larger. Use Figure 2.3 and Table 2.2 to determine the frost soil classification for each of the three soil types.

Item 9. Using the test procedure outlined in Appendix B, determine the subgrade stiffness value. In this example three widely different values have been assumed. Normally the variation in stiffness modulus will not be this large, unless the soils are extremely variable.

Item 10. Using the subsurface investigation information, record the depth to the water table, values are 5, 5, and 2.

Item 11. The number of 18-kip (80 kN) design lane wheel load applications is obtained from line 10 of the Traffic Worksheet B (Figure 2.4).

Traffic - Worksheet B

Based on projected traffic values for each axle load type, use Traffic Worksheet B (Figure 2.4) to estimate the number of 18-kip (80 kN) design wheel load applications for the design period. In this example the traffic is taken to be 20 x 10^6 18-kip (80 kN) applications for 20 years.

Effective Modulus - Worksheet D

Item 1. From Worksheet A (Figure 7.2) record the Mean Annual Air Temperature on line 1 of Worksheet D (Figure 7.3), value is 68.3.

Item 2. From Worksheet A record the Mean Yearly Temperature Change, value is 40.8.

Item 3. Obtain Environmental Region Number for area in question by entering Figure 7.4 with the Mean Annual Air Temperature from Item 1 and projecting vertically and with the Mean Yearly Temperature Change from Item 2 and projecting horizontally. The line nearest the point of intersection of these 2 lines determines the environmental region number, value is Region #1.

Item 4. Determine the minimum pavement temperature for the asphalt concrete associated with these environmental conditions by entering Figure 7.5 with the Mean Annual Air Temperature from Item 1 and projecting vertically to the environmental region number from Item 3 and then projecting horizontally to obtain the minimum pavement temperature, value is 35.

Item 5. Determine the allowable minimum original penetration to prevent or control low-temperature cracking using Figure 7.6. Enter Figure 7.6 with the minimum pavement temperature from Item 4, project vertically to the diagonal in Figure 7.6 and then horizontally to determine the asphalt cement penetration. In this case use the minimum of 30.

Item 6. Using the allowable asphalt cement penetration, select an asphalt cement grade to meet the above low temperature cracking requirement, value is AC40.

Item 7. The effective asphalt concrete modulus is based on the accumulated fatigue damage resulting from loads applied during each season for the fatigue equation adopted for use in this design method. The calculation procedure for this effective modulus is described in Items 8 through 13 and is used along with pavement type and traffic to select the appropriate figures in Appendix A that contain the required pavement cross-section.

Item 8. For each season the mean pavement temperature is determined by using one of Figures 3.8 through 3.12 (here Figure 7.7 is selected) that is selected using the Region number and annual rainfall. For region 1 enter Figure 7.7 (the same as Figure 3.8) with the mean annual air temperature (Worksheet A, line 1) of 68.3°F (20°C) and 29.64 inches (75.3 cm) of rainfall and project vertically to each seasonal line and then horizontally to estimate the seasonal mean pavement temperatures (values shown on Figure 7.7).

Item 9. Determine the asphalt concrete modulus for each season from Figure 3.13. Enter Figure 7.8 (the same as Figure 3.13) with the seasonal mean pavement temperature and project vertically to the selected asphalt cement grade determined in Worksheet D, line 6, and then horizontally to estimate the asphalt concrete dynamic modulus for each season.

Item 10. The fatigue factor associated with the asphalt concrete modulus for each season is determined using Figure 3.14. Enter Figure 7.9 (the same as Figure 3.14) with each asphalt cement modulus and project horizontally to the established line and then vertically and estimate the fatigue factor for each season (values shown on Figure 7.9).

Item 11. Multiply column 9 and 10.

Item 12. Obtain the summation for columns 10 and 11.

Item 13. The asphalt concrete effective modulus is computed by dividing the summation of column 11 by the summation of column 10. Enter this effective modulus rounded to the nearest thousand on line 4 of Worksheet C, value is 695,100.

Cross Section - Worksheet C

Items 1-5. Enter information required from Worksheets A and D on line 1-5 of Worksheet C, Figure 7.10.

Item 6. To select the pavement cross section turn to Table A.1 of Appendix A. Using the pavement type and traffic level, select the set of design cross sections that are appropriate for the conditions.

a. For this problem (full depth flexible pavement serving 20 x 10^6 18-kip (80 kN) equivalent wheel loads), Figures A.1 through A.4 should be used.

b. Using the effective asphalt concrete modulus from line 4, select the figures from Item 6(a) that bound that effective modulus. For this problem Figure A.1 and A.2 with effective moduli of 1,000,000 and 600,000 will be used.

c. For each of the subgrade types and their respective resilient moduli, a design cross section should be selected. For example, for Soil I with a resilient modulus of 20,000 (Worksheet A, line 9) the appropriate cross-sections are shown below:

Layer	Effective Modulus	
	1,000,000 (Figure A.1)	600,000 (Figure A.2)
Surface	9 in. (22.9 cm)	10.8 in. (27.4 cm)
Drainage Layer	4 in. (10.2 cm)	4 in. (10.2 cm)

By interpolation the design cross section entered into Worksheet C line 6 for Soil I is: 10.4 in. (26.4 cm) of surface and a 4 in. drainage layer. Similarly the layer thicknesses for Soil II (resilient modulus of 6,000) and Soil III (resilient modulus of 2,000) were determined and drawn on the sketch of this worksheet.

It should be noted that the engineer may interpolate on a particular figure between subgrade moduli values. Of course, all such interpolations are assumed to be linear. Even though interpolations on effective asphalt concrete modulus and subgrade moduli are allowable, the engineer should not interpolate between the two traffic levels of 20×10^6 and 40×10^6 18-kip (80 kN) ESAL. Such linear interpolations on traffic are not recommended but rather the engineer should use the design charts included in Volume I (Ref. 1) when traffic volumes are significantly different from those included in Appendix A.

Item 7. The frost penetration below the pavement surface for the particular area can be estimated using the relationships contained in Figures 3.15 - 3.17. For Region 1, enter Figure 7.11 (the same as Figure 3.15) with the design air freezing index value from line 5 of Worksheet A (50) and project vertically to the particular subgrade material (line 3 for example problem) and then horizontally to estimate the frost penetration. For this problem no frost penetration is predicted, therefore a "0" is entered in line 7 of this worksheet.

Item 8. Using Tables 3.1 or 3.2 determine whether partial or full protection is recommended to protect subgrade or pavement structure from damage due to frost action. If full protection is required, determine the additional thickness required to prevent the frost from penetrating the frost susceptible material (Figures 3.15-3.18). If partial protection is recommended or desired as an alternative to full protection, the additional surface thickness required to resist additional fatigue when the subgrade thaws and weakens should be determined using Figure 3.20 for flexible pavements and Figure 3.19 for composite pavements. For this example problem, using Figure 7.11 (the same as Figure 3.20), there is no frost penetration, therefore, no additional protection is required.

Item 9. Adjust initial cross-sections to account for additional thicknesses and sketch in line 9 graph of Figure 7.10.

Item 10. In addition to the adjustment in the pavement layers for strength loss due to freeze-thaw, the subgrade soil must be checked to determine if chemical stabilization is needed to minimize the effect of potential volume changes. The percent passing the No. 200 sieve and plasticity index should be obtained from Worksheet A line 8 (Figure 7.2) and used along with the logic in Figure 5.1 to determine if improvement is required. If stabilization is indicated then the logic in Figure 5.2 is used to determine the type of stabilization suggested to minimize the effect of volume change. Once the type of stabilizer agent is selected, a laboratory study should be performed to determine the optimum percent stabilizer required for each soil.

For all pavement cross-sections which require a stabilized base layer, an improved subgrade layer thickness of 24 inches (61 cm) is required. The minimum thickness of the stabilized base layer is recommended to be 6 inches (15.2 cm). For conditions when the base thickness is less than 6 inches (15.2 cm), a reduction in the improved subgrade layer can be made using a layer equivalency value for the following materials:

Cement Treated Base - 5
Asphalt Treated Base - 2

Since stabilization is required for each of the three soil types in this example, the only question is to what depth. For soil type I with a PI of 5 and a stiffness modulus of 20,000, no stabilized base is shown in Figures A.1 and A.2, therefore, a lime-treated subgrade of 6 inches (15.2 cm) is required. For soil type II with a PI of 35 and a stiffness modulus of 6,000, no stabilized base is shown in Figures A.1 and A.2, but a 10 inch (25.4 cm) improved subgrade is shown. Therefore, that 10 inches (25.4 cm) should be improved using lime as a stabilizing agent. For soil type III with a PI of 10 and a stiffness modulus of 2,000 an asphalt stabilized base is required as shown in Figures A.1 and A.2 with a 24 inch (61.0 cm) improved subgrade. That subgrade should be improved using cement as the stabilizing agent. Each of these final design thicknesses is incorporated into the final cross-section shown on the graph at line 9 of Figure 7.10.

SUMMARY

In summary, this example problem has demonstrated the individual steps required to develop a design using this flexible pavement design procedure for premium pavements. The cross-sections developed are thicker than those occuring on most pavement projects. However, the engineer must remember that very stringent performance requirements have been built into the procedure and in order to obtain higher reliabilities the cross-sections are thicker than those developed using current design procedures.

In order to design a composite pavement, the same basic steps outlined above are followed. However, the individual figures and tables used in the design steps may be different. In addition, the catalogue of designs for composite pavements are contained in Appendix A in Figures A.17 through A.28. For the design of the joints and other steel reinforcement for both jointed and CRC composite pavements, the user is referred to Section 4 of this report. Nomographs and references are included for completion of the concrete base design.

Meteorological Data For The Current Year

Station: SAN ANTONIO, TEXAS # 12921 INTERNATIONAL AIRPORT Standard time used: CENTRAL Latitude: 29° 32' N Longitude: 98° 28' W Elevation (ground): 788 feet Year: 1977

Month	Temperature °F Averages Daily maximum	Daily minimum	Monthly	Extremes Highest	Date	Lowest	Date	Degree days Base 65 °F Heating	Cooling	Precipitation in inches Water equivalent Total	Greatest in 24 hrs.	Date	Snow, Ice pellets Total	Greatest in 24 hrs.	Date
JAN	53.4	34.[illegible]	44.1	80	27	20	10	643	0	3.10	1.14	22-23	0.0	0.0	
FEB	66.0	38.8	52.8	83	24	28	27	326	3	0.91	0.42	10-11	0.0	0.0	
MAR†	74.2	49.4	61.8	85	15	30	7	144	52	0.88	0.27	26-27	0.0	0.0	
APR	77.0	56.0	66.9	88	3	41	6	32	98	8.80	4.88	19-20	0.0	0.0	
MAY	81.6	68.0	74.8	89	31	59	12	0	311	1.62	1.01	21-22	0.0	0.0	
JUN	90.2	72.7	81.5	93	7	61	5	0	802	2.26	1.46	22-23	0.0	0.0	
JUL	93.6	76.[illegible]	84.9	98	31	71	17	0	620	0.10	0.06	18-19	0.0	0.0	
AUG	93.9	75.5	84.7	97	23	70	4	0	618	0.06	0.03	2	0.0	0.0	
SEP	92.1	72.3	82.3	99	5	65	20	0	525	2.11	1.10	12-13	0.0	0.0	
OCT	82.2	60.1	71.2	94	1	38	13	19	218	3.47	2.10	21-22	0.0	0.0	
NOV	73.3	49.4	61.4	87	16	28	10	138	38	6.01	4.87	1	0.0	0.0	
DEC	66.5	40.2	53.4	85	3	20	22	360	5	0.32	0.22	11-12	0.0	0.0	
YEAR	78.8	57.8	68.3	99	SEP 5	20	DEC 22	1672	2990	29.64	4.88	APR 19-20	0.0	0.0	

Month	Relative humidity, pct. Hour 00	Hour 06	Hour 12	Hour 18 (Local time)	Wind Resultant Direction	Resultant Speed m.p.h.	Average speed m.p.h.	Fastest mile Speed m.p.h.	Direction	Date	Percent of possible sunshine	Average sky cover, tenths, sunrise to sunset	Number of days Sunrise to sunset Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperature °F Maximum (b) 90° and above	Maximum 32° and below	Minimum 32° and below	Minimum 0° and below	Average station pressure mb. Elev. 794 feet m.s.l.
JAN	76	80	59	61	02	4.4	10.1	30	01	28	45	6.9	5	11	15	13	0	0	4	0	0	13	0	991.5
FEB	71	78	50	44	36	1.2	10.4	32	32	26	71	4.8	11	7	10	5	0	0	2	0	0	5	0	990.5
MAR†	71	76	47	43	10	2.6	10.5	26	30	27	68	6.7	6	9	16	5	0	2	4	0	0	3	0	985.1
APR	83	89	56	51	12	3.9	10.0	27	35	4	55	5.6	8	9	13	12	0	8	5	0	0	0	0	988.4
MAY	91	95	73	69	14	9.1	10.8	29	04	31	30	8.6	0	8	23	7	0	4	1	0	0	0	0	985.1
JUN	82	87	59	56	19	7.6	11.0	29	17	22	57	6.0	6	14	10	8	0	7	1	21	0	0	0	986.5
JUL	74	83	53	43	15	9.4	10.9	20	10	30	73	4.9	8	19	4	3	0	2	0	31	0	0	0	988.2
AUG	75	87	54	47	14	7.6	9.7	23	12	27	68	5.6	3	23	5	3	0	2	0	30	0	0	0	986.1
SEP	78	88	57	49	16	5.9	10.3	42	18	13	45	4.9	11	15	4	5	0	4	0	26	0	0	0	985.1
OCT	75	82	55	52	11	2.3	9.1	31	02	11	35	5.4	10	13	8	6	0	4	1	2	0	0	0	989.2
NOV	78	86	57	56	35	1.6	9.4	30	08	1	50	4.9	13	4	11	5	0	4	4	0	0	2	0	987.8
DEC	71	76	52	49	36	2.6	9.2	29	02	9	47	5.8	10	8	13	5	0	0	6	0	0	4	0	989.2
YEAR	77	84	56	52	13	3.4	10.1	42	18	SEP 13	57	5.8	91	142	132	77	0	37	30	110	0	27	0	987.8

† DATA CORRECTED AFTER PUBLICATION OF THE MONTHLY ISSUE.

Normals, Means, And Extremes

Month	Temperatures °F Normal Daily maximum	Daily minimum	Monthly	Extremes Record highest	Year	Record lowest	Year	Normal Degree days Base 65 °F Heating	Cooling	Precipitation in inches Water equivalent Normal	Maximum monthly	Year	Minimum monthly	Year	Maximum in 24 hrs.	Year	Snow, Ice pellets Maximum monthly	Year	Maximum in 24 hrs.	Year
(a)				36		36					35		35		35		35		35	
J	61.6	39.8	50.7	89	1971	0	1949	481	8	1.66	8.52	1968	0.04	1971	3.18	1968	4.7	1949	4.7	1949
F	65.6	43.4	54.5	92	1959	6	1951	310	16	2.06	6.43	1965	0.03	1954	2.34	1965	3.5	1966	3.5	1956
M	72.5	49.1	60.8	100	1971	21	1948	194	64	1.34	4.19	1957	0.03	1961	2.36	1945	T	1965	T	1968
A	80.3	58.8	69.6	99	1963	33	1975	31	169	2.84	9.32	1957	0.14	1953	4.88	1977	0.0		0.0	
M	86.2	65.7	76.0	101	1967	44	1954	0	341	3.07	11.24	1972	0.17	1961	6.53	1972	0.0		0.0	
J	92.4	72.0	82.2	103	1960	53	1964	0	516	2.79	10.44	1973	0.01	1967	6.18	1951	0.0		0.0	
J	95.6	73.8	84.7	106	1954	62	1967	0	611	1.89	8.19	1942	T	1944	6.97	1958	0.0		0.0	
A	95.9	73.4	84.7	106	1962	61	1946	0	611	2.41	11.14	1974	0.00	1952	5.57	1950	0.0		0.0	
S	89.8	68.8	79.3	102	1951	41	1942	0	439	3.71	15.78	1946	0.06	1947	7.28	1973	0.0		0.0	
O	81.8	59.8	70.5	95	1963	33	1970	32	202	2.84	9.56	1942	T	1952	5.28	1942	0.0		0.0	
N	71.1	48.2	59.7	91	1962	21	1976	179	20	1.77	6.01	1977	T	1966	4.87	1977	0.3	1957	0.3	1957
D	64.6	41.8	53.2	90	1955	14	1950	373	7	1.56	4.51	1965	0.02	1950	2.89	1944	0.2	1964	0.2	1964
YR	79.8	57.8	68.8	106	AUG 1962	0	JAN 1949	1570	2994	27.54	15.78	SEP 1946	0.00	AUG 1952	7.28	SEP 1973	4.7	JAN 1949	4.7	JAN 1949

Month	Relative humidity pct. Hour 00	Hour 06	Hour 12	Hour 18 (Local time)	Wind Mean speed m.p.h.	Prevailing direction	Fastest mile Speed m.p.h.	Direction	Year	Pct. of possible sunshine	Mean sky cover, tenths, sunrise to sunset	Mean number of days Sunrise to sunset Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, Ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility ¼ mile or less	Temperatures °F Max. (b) 90° and above	Max. 32° and below	Min. 32° and below	Min. 0° and below	Average station pressure mb. Elev. 794 feet m.s.l.
(a)	35	35	35	35	35	15	34	34		35	35	35	35	35	35	35	35	35	35	35	35	35	5
J	75	80	60	57	9.1	N	86	NW	1955	49	6.2	9	6	16	8	*	1	5	0	*	8	*	991.3
F	75	80	57	52	9.8	NE	86	N	1954	53	6.1	9	5	14	8	*	1	3	*	*	4	0	990.5
M	72	79	53	47	10.5	SE	87	NE	1955	58	6.2	8	8	15	7	0	2	3	1	0	2	0	985.1
A	77	83	56	52	10.6	SE	87	N	1953	55	6.4	7	8	15	8	0	4	1	2	0	0	0	986.6
M	81	88	58	55	10.1	SE	73	NW	1946	56	6.3	6	11	14	8	0	7	1	9	0	0	0	984.6
J	80	88	56	51	10.1	SE	99	E	1953	67	5.5	7	16	7	6	0	4	*	22	0	0	0	985.4
J	75	87	51	45	9.1	SSE	82	NE	1943	75	5.1	9	15	7	6	0	3	*	28	0	0	0	987.9
A	74	86	51	46	8.5	SE	74	NE	1942	74	4.9	11	14	6	5	0	4	*	28	0	0	0	987.6
S	78	86	55	52	8.5	SE	49	NE	1952	68	5.2	10	12	8	7	0	4	*	17	0	0	0	986.9
O	77	84	54	53	8.4	N	43	NW	1945	65	4.8	12	10	9	6	0	2	2	4	0	0	0	989.8
N	76	81	55	56	8.9	N	43	N	1950	56	5.4	11	7	12	6	0	2	3	*	0	2	0	990.2
D	76	80	57	57	8.6	N	48	NW	1947	52	5.9	10	6	15	7	0	1	5	*	0	6	0	990.5
YR	76	84	55	52	9.4	SE	74	NE	AUG 1942	61	5.7	109	118	138	81	*	36	23	111	*	22	*	988.1

Means and extremes above are from existing and comparable exposures. Annual extremes have been exceeded at other sites in the locality as follows: Highest temperature 107 in August 1909; maximum monthly snowfall 6.4 in January 1926; maximum snowfall in 24 hours 5.0 in January 1940.

Figure 7.1 Meterological Data for San Antonio, Texas (Ref. 12).

"ZERO-MAINTENANCE" DESIGN

INPUT-WORKSHEET A

Project: IH-35 Date: Nov. 15, 1980

Location: San Antonio, Texas

ENVIRONMENTAL DATA

(1) Mean Annual Air Temperature (MAAT), °F	68.3
(2) Warmest Mean Monthly Air Temperature (WMMAT), °F . .	84.9
(3) Coldest Mean Monthly Air Temperature (CMMAT), °F . .	44.1
(4) Mean Monthly Air Temperature Change, (MMATC), °F (MMATC = WMMAT - CMMAT)	40.8
(5) Design Air Freezing Index (Figure 2.2)	50

NATURAL SOIL DATA

	Soil I	Soil II	Soil III
(6) Boring Number	1	2	3
(7) Boring Location	Sta. 1+00	Sta. 110+00	Sta. 250+00
(8) Soil Type: Unified Soil Classification and P. I. ( ) . . .	CH (45)	CL (35)	CL (10)
Percent finer than 0.02 mm . . .	50	40	60
Frost Soil Classification (Table 2.2, Figure 2.3)	F-3	F-4	F-4
(9) Subgrade Stiffness (Appendix A) .	20,000	6,000	2,000
(10) Water Table Depth, ft.	5	5	2

TRAFFIC DATA

(11) Design Applications 18-kip (80 kN) Equivalent Axle Loads (EAL) in Design Lane (Worksheet B, Figure 2.4)	20×10^6

Figure 7.2 Example Problem #1 worksheet tabulating input information.

PREMIUM PAVEMENT DESIGN

EFFECTIVE MODULUS WORKSHEET D

Project: IH-35 Date: Nov. 15, 1980

Location: San Antonio, Texas

(1) Mean Annual Air Temperature Worksheet A, °F 68.3

(2) Mean Yearly Temperature Change, °F 40.8

(3) Environmental Region (Figure 3.3) . . . . #1

(4) Minimum Pavement Temperature, (Figure 3.4, 3.5), °F 34

(5) Allowable Minimum Original (Figure 3.6) Penetration 30

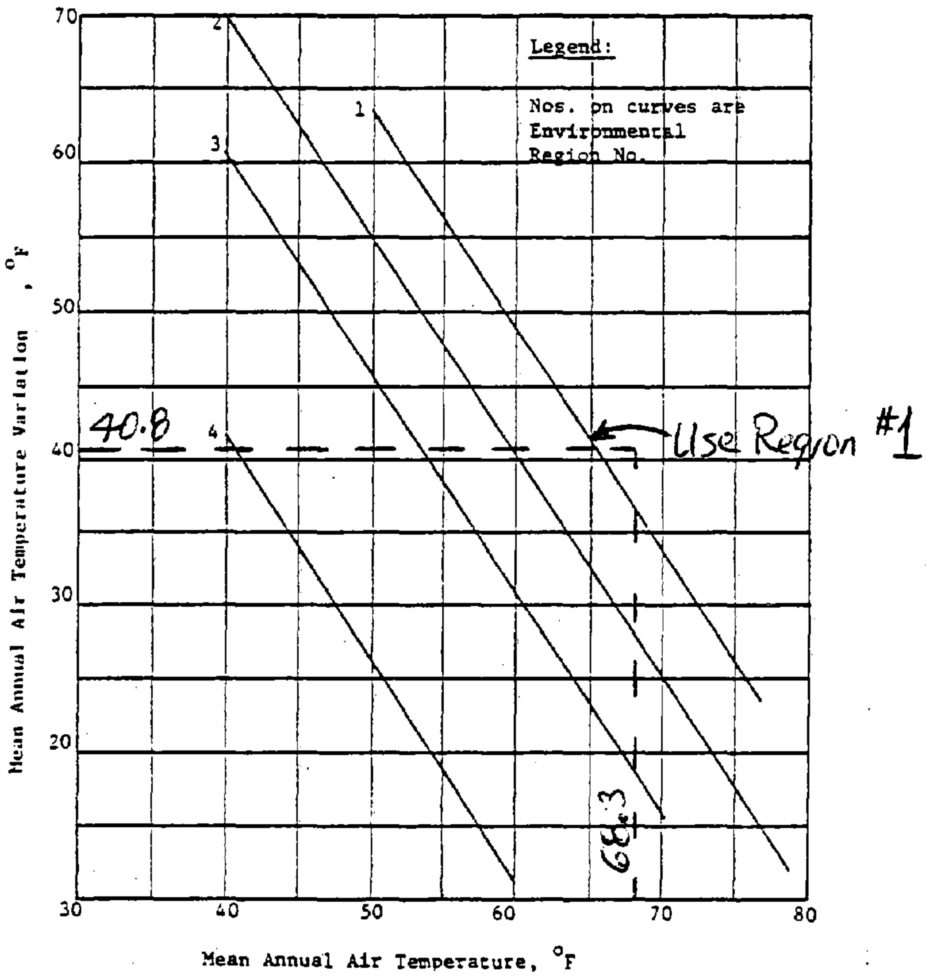
(6) Asphalt Cement Grade AC-40

(7) Season	(8) Mean Pavement Temperature (Figure 3.8 - 3.12) °F	(9) Asphalt Concrete Modulus (Figure 3.13) psi	(10) Fatigue Factor (Figure 3.14)	(11) (9) x (10)
Fall	81	1,600,000	.11	176,000
Winter	59	3,800,000	.019	72,200
Spring	87	1,100,000	.22	242,000
Summer	105	470,000	1.10	517,000
(12) Total			1.449	1,007,200
(13) Asphalt Concrete Effective Modulus, psi (Σ(11)÷Σ(10))				695,100

°C = (°F - 32)/1.8   1 psi = 6.89 kPa

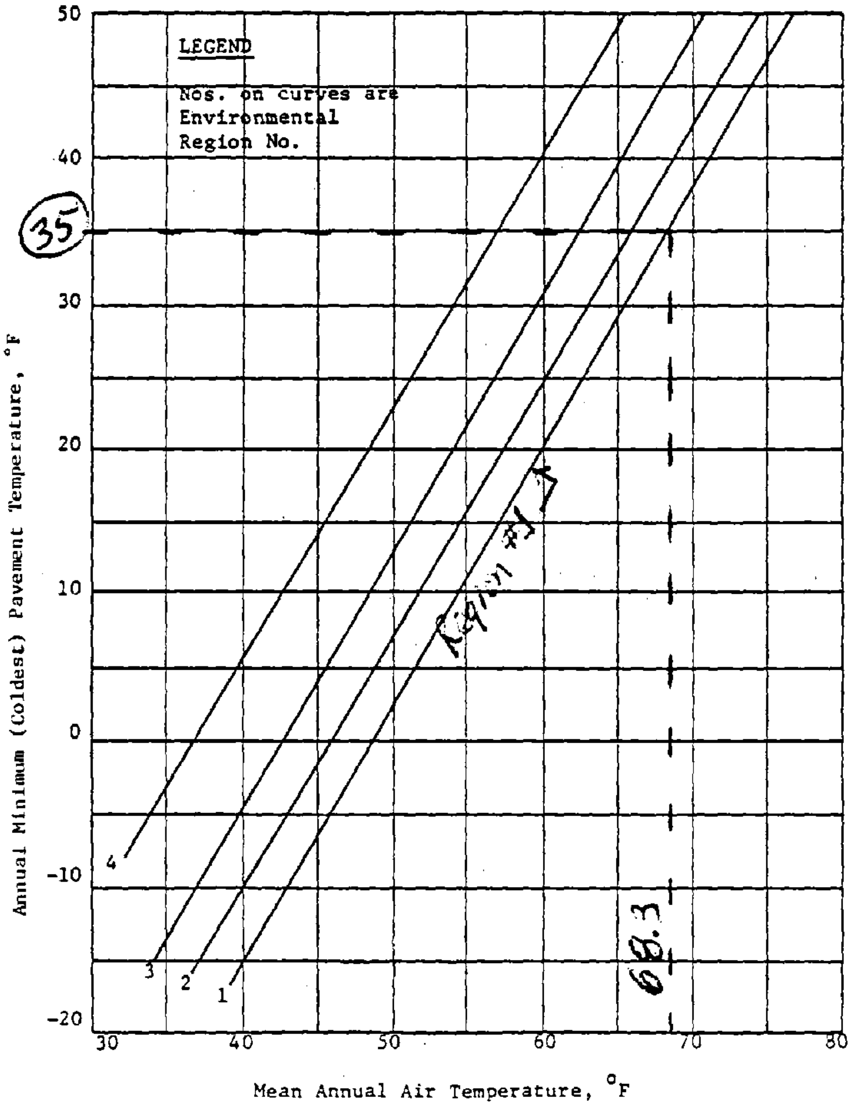
Figure 7.3 Worksheet for computing the asphalt concrete effective modulus.

Example:
Mean monthly maximum temperature - 81°F
Mean monthly minimum temperature - 53°F
Mean monthly variation - 28°F
Mean annual temperature - 72°F
Environmental Region 1



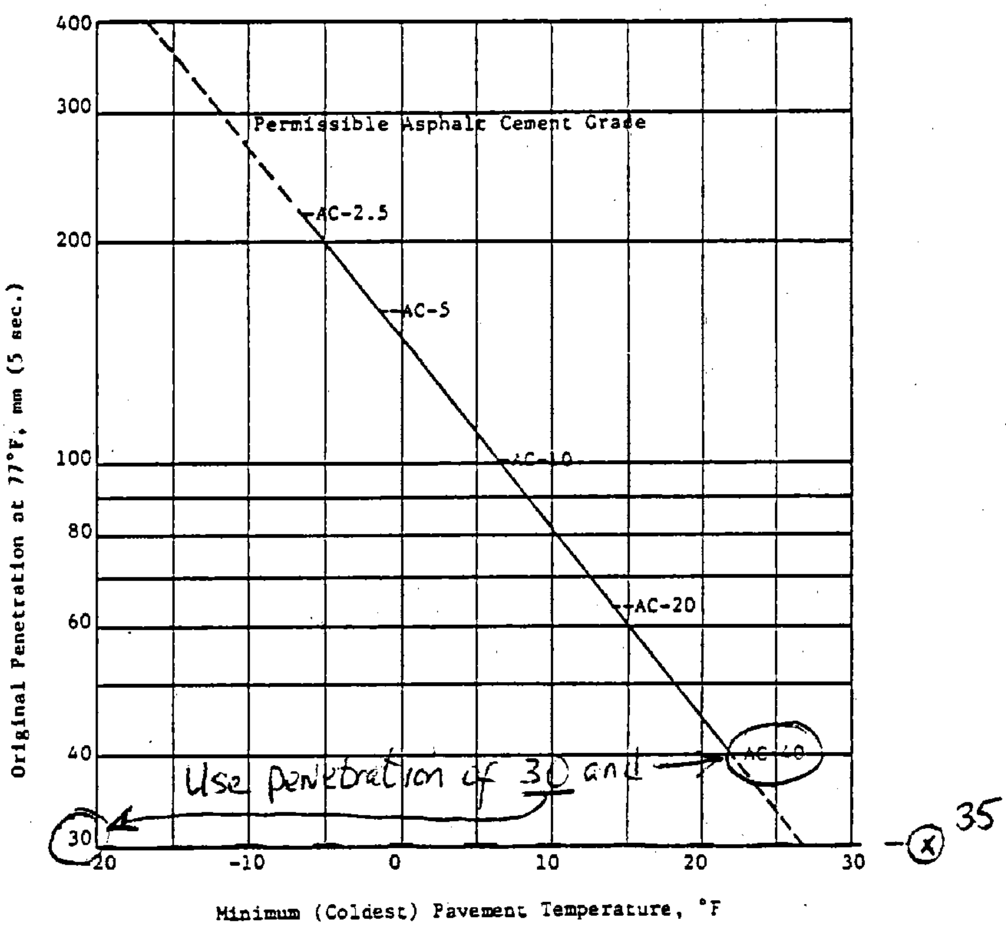
°C = (°F - 32)/1.8

Figure 7.4 Determination of the Environmental Region Number



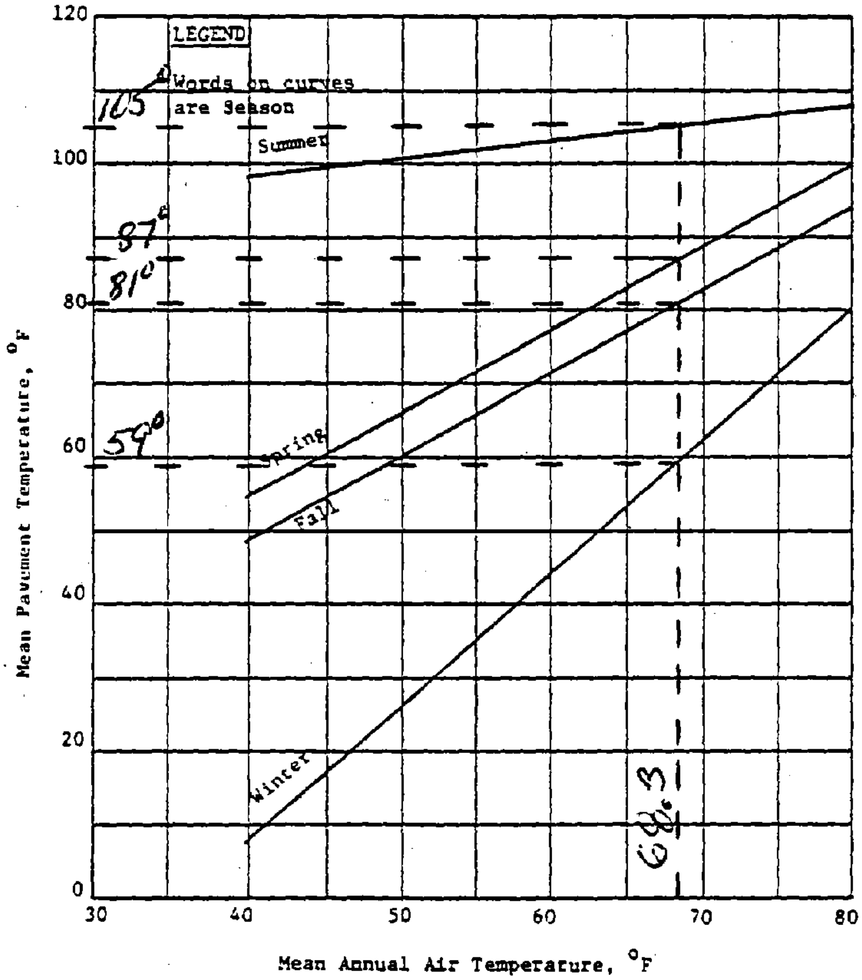
°C = (°F - 32)/1.8

Figure 7.5 Estimation of the Annual Minimum (Coldest) Pavement Temperature for Wet Environments (Average Rainfall > 12 in).



°C = (°F - 32)/1.8

Figure 7.6 Determination of the Asphalt Cement Grade or the Allowable Original Penetration for Asphalts with a Penetration Index of -1.0.



°C = (°F - 32)/1.8

Figure 7.7 Estimation of the Mean Pavement Temperature for Environmental Region No. 1.

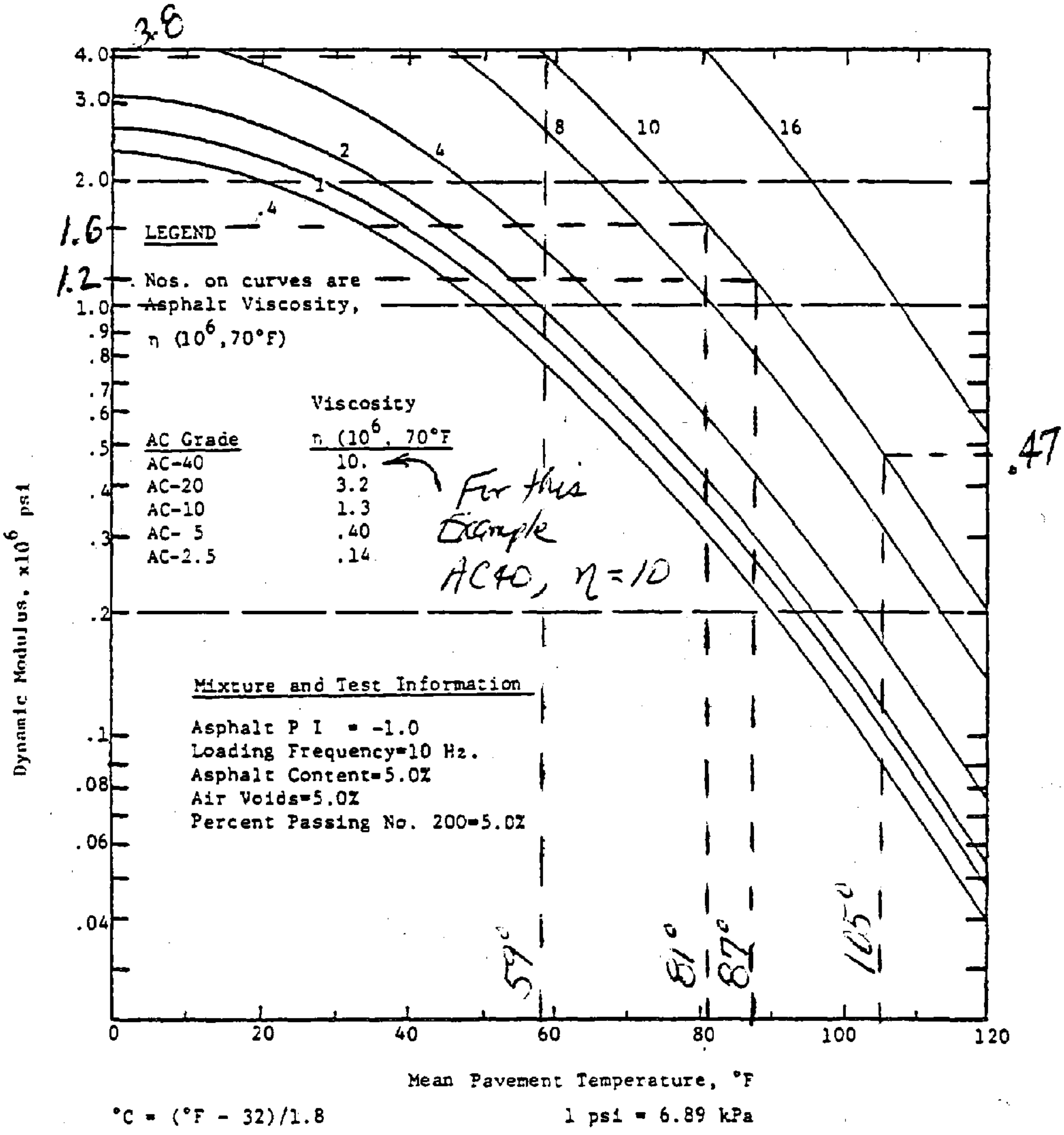


Figure 7.8 Estimation of the Asphalt Concrete Dynamic Modulus as a Function of Mean Pavement Temperature (Ref. 15).

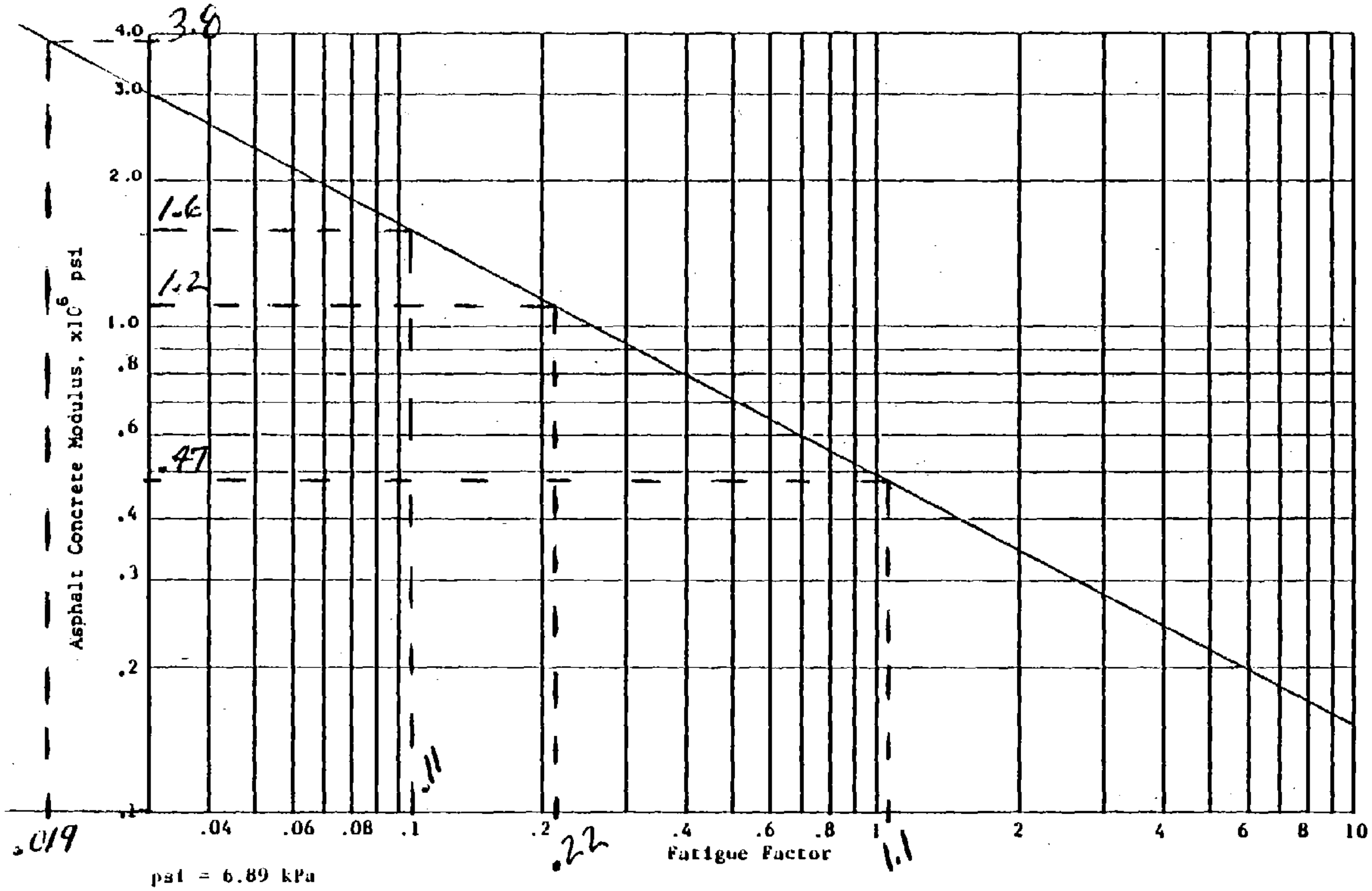


Figure 7.9 Estimation of the Fatigue Factor.

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C*

Project IH-35 Date Nov 15, 1980

Location San Antonio, Texas

(1) Pavement Type: Full Depth Asphalt Concrete

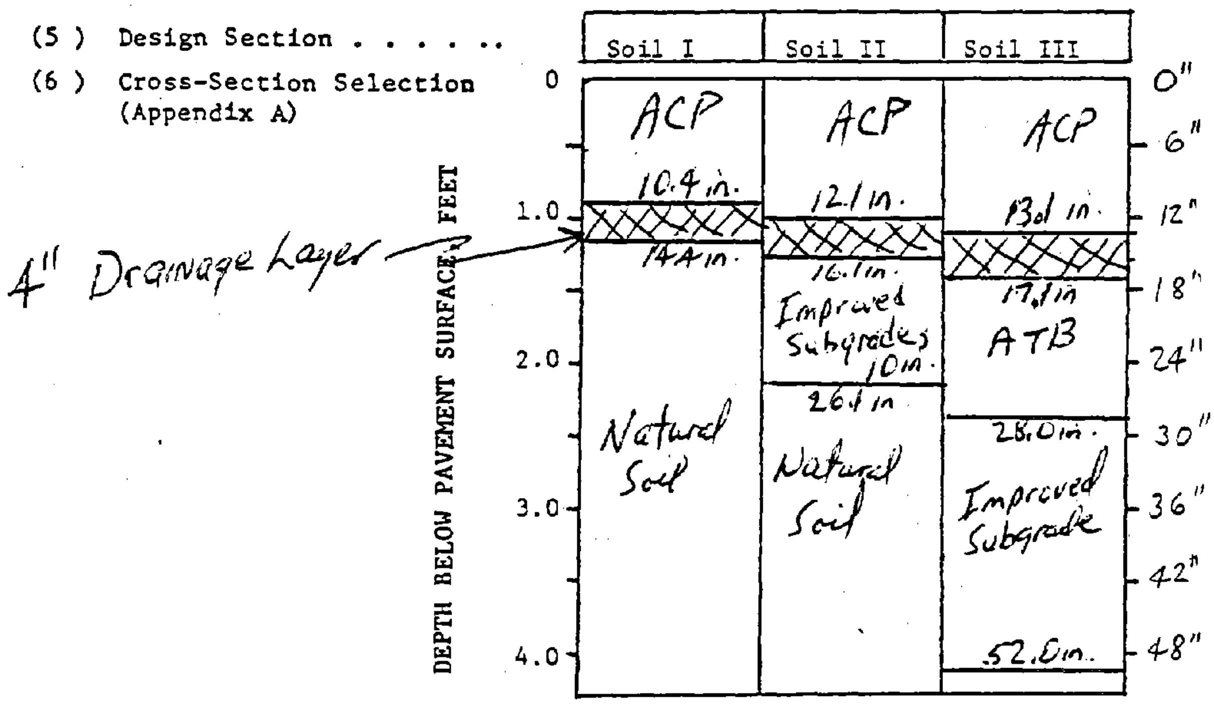
(2) Environmental Region No. (Figure 3.3)... #1

(3) Asphalt Cement Grade (Figure 3.6). . AC-40

(4) Effective Asphalt Concrete Modulus (Figure 3.7 line 13), psi 695,100

(5) Design Section . . . . . .

(6) Cross-Section Selection (Appendix A)



	Soil I	Soil II	Soil III
(7) Frost Penetration Below Pavement Surface (Figure 3.15 - 3.17) feet	0	0	0
(8) Increased Thickness of Non-Frost Susceptible Material (Figures 3.15 - 3.20).			

1 psi = 6.89 kPa
1 ft = 0.3048 m

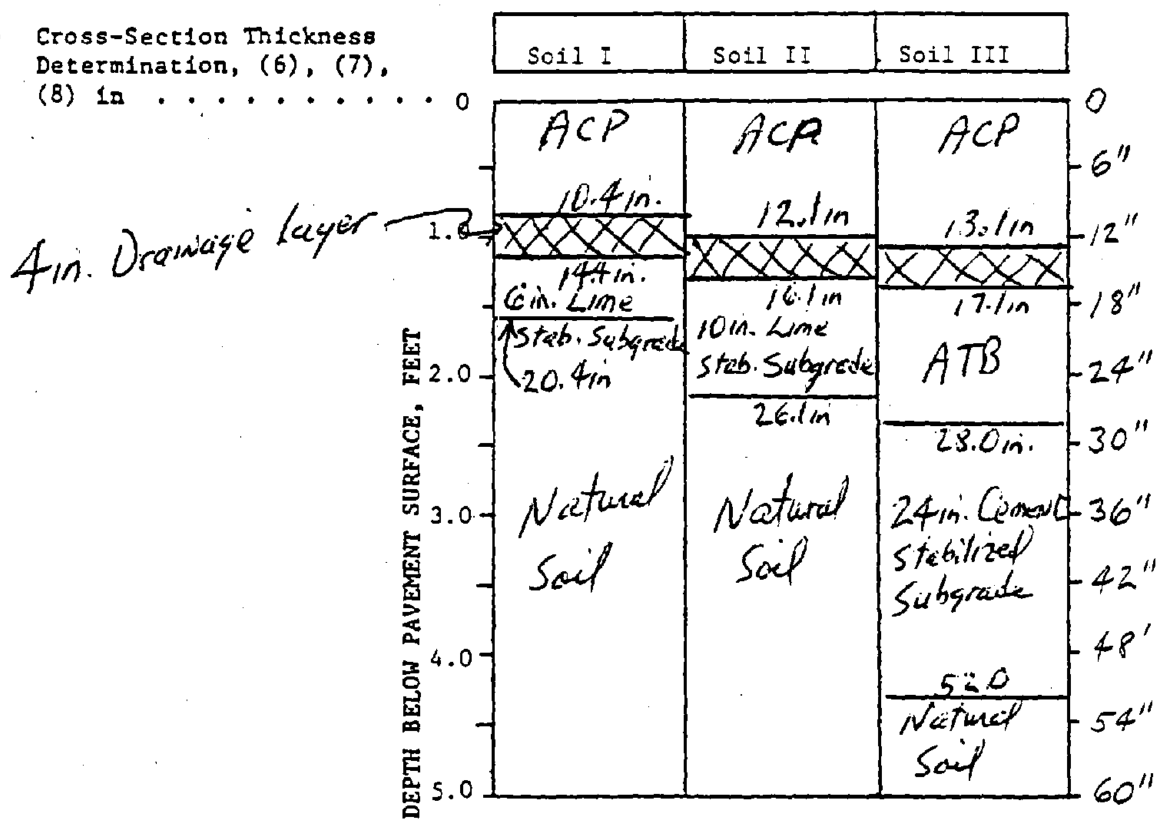
*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure 7.10 Worksheet for Determining the Initial Zero-Maintenance Structural Cross-Section

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C* (continued)

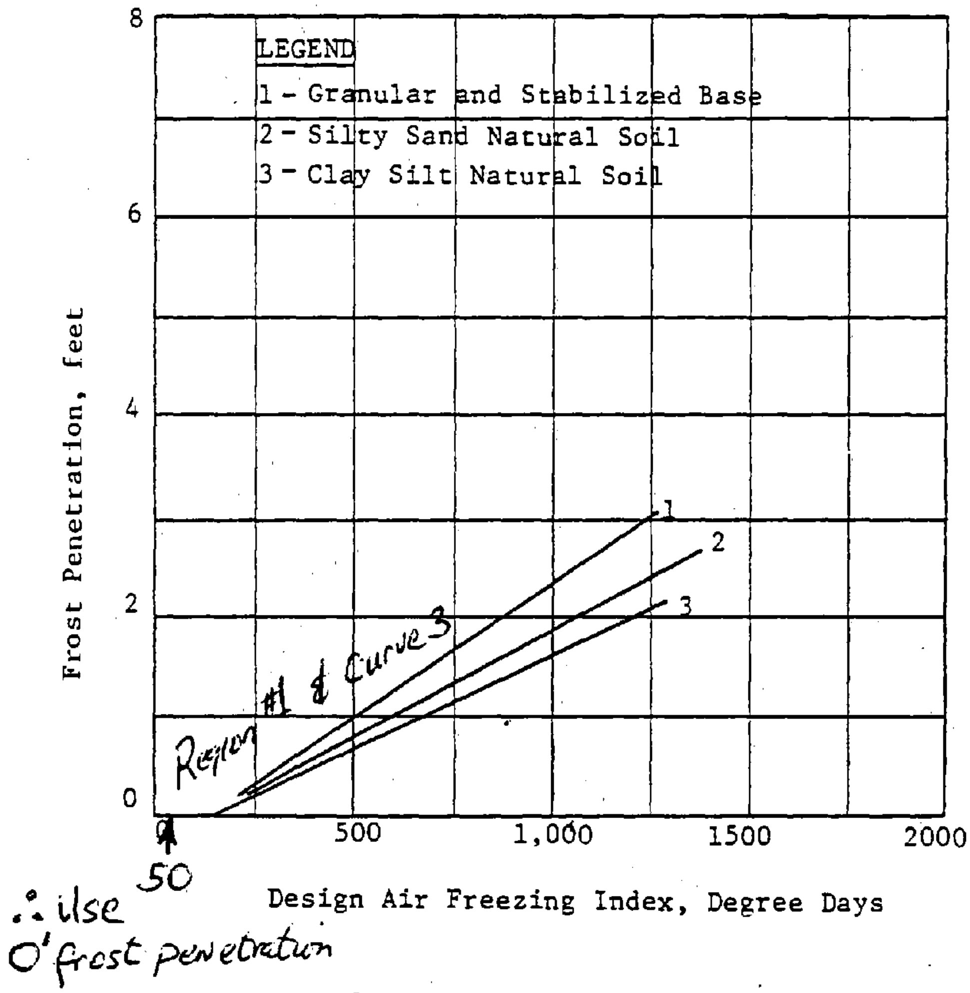
(9) Cross-Section Thickness Determination, (6), (7), (8) in . . . .



1 ft = 0.3048 m
1 in = 2.54 cm

*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure 7.10 Worksheet for Determining the Final Zero-Maintenance Structural Cross-Section (continued)



1 ft = 0.3048 m

Figure 7.11 Determination of the Frost Penetration into Different Materials Below the Pavements Surface for Environmental Region No. 1.

SECTION 8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

The design procedure presented in this manual identifies and specifies materials and structural configurations which will meet the performance requirement of premium or zero-maintenance pavements. These configurations were developed using mechanistic models as well as observed performance data. Both material and construction specifications have been presented to ensure that the performance required of these pavements will result in a high level of reliability. However, most of the performance criteria were developed from observations of existing pavements which themselves have not met the criteria of zero-maintenance. As a result extrapolation beyond the normal range of experience was required. Therefore the following aspects of the design procedure must be clearly identified as areas which are of more concern than others.

1. Quality Control - This is probably the most important item of concern in premium pavements, since any pavement not properly constructed will not provide the high level of performance required for the minimum 20 year design. The pavement structures and pavement materials must be properly inspected and controlled to correct construction deficiencies or replace materials which do not meet the specifications set forth.

2. Asphalt Concrete Durability - The deterioration of asphalt concrete can result in a reduction of the maintenance-free life of a pavement structure. Very little definitive information is available on aging effects and moisture related damage over long periods of time. Therefore, asphalt concrete material property changes were extrapolated for the minimum 20 year design period and performance was estimated from these extrapolations.

3. Low Modulus Portland Cement Concrete Durability - Limited information is available on the long-term performance of low modulus concrete as a base material in composite pavements. Of particular concern is the effect of environment on the interaction between the PCC and asphalt concrete layer.

4. Environmental Considerations - In developing the pavement cross-sections, the effects of both temperature and frost on material properties and distress have been considered. In order to simplify the design procedure, the assumptions made are defined and explained in the background work (Ref. 1).

5. Drainage - Inherent in this design manual is the assumption that adequate drainage will be provided in the pavement structure. Although drainage layers and edge drains may be successfully constructed, it is also imperative that the drains do

not become clogged thereby trapping water and detrimentally affecting long term performance. Therefore, adequate filter requirements must be met and drain inspections and maintenance must be periodically completed. This should have no detrimental effects on traffic flow on the pavement.

CONCLUSIONS

In conclusion every attempt has been made in this study to investigate available pavement performance data and to synthesize this data into a reasonably coherent and reliable design method. If the methods and concepts presented are conscientiously applied with care and engineering skill, premium pavements can be built to give good, long-term performance.

In any case the manual should not be used capriciously or by casual pavement designers, but by knowledgeable, practical, experienced professional engineers. In cases where local information and experience is documented and known to differ with recommendations presented herein, such information should be documented and used by the engineer in his design.

RECOMMENDATIONS

We recommend that this manual be carefully examined by practical and experienced design engineers from a variety of user agencies and environments, and that comments and comparisons of this manual with other experience be prepared and submitted in writing. This additional experience can then be collated for updating this manual.

It is also important that premium pavements of all kinds be observed and documented for actual pavement performance under a variety of field conditions. Although accelerated tests and other theoretical studies can be of assistance, in the final analysis realistic observations of in-service pavements are required to determine whether or not this design manual is valid and under what conditions; or conversely how it should or must be modified.

APPENDIX A

CATALOGUE OF PREMIUM PAVEMENT DESIGNS

This catalogue presents a total of 140 possible pavement designs which meet premium pavement requirements for a wide variety of conditions of traffic and environment and for two basic pavement types, flexible and composite. Charts A1 through A16 are for flexible and A17 through A28 are for composite pavements. Thickness for no frost problems and nonfrost susceptible materials are included. Corrections for frost protection are given after Chart A28. Criteria for premium pavements always involve heavy traffic, for this reason two levels of traffic; heavy ($20x10^6$ equivalent 18k (80 kN) axle loads) and very heavy ($40x10^6$ equivalent 18k (80 kN) axle loads), are provided in this manual.

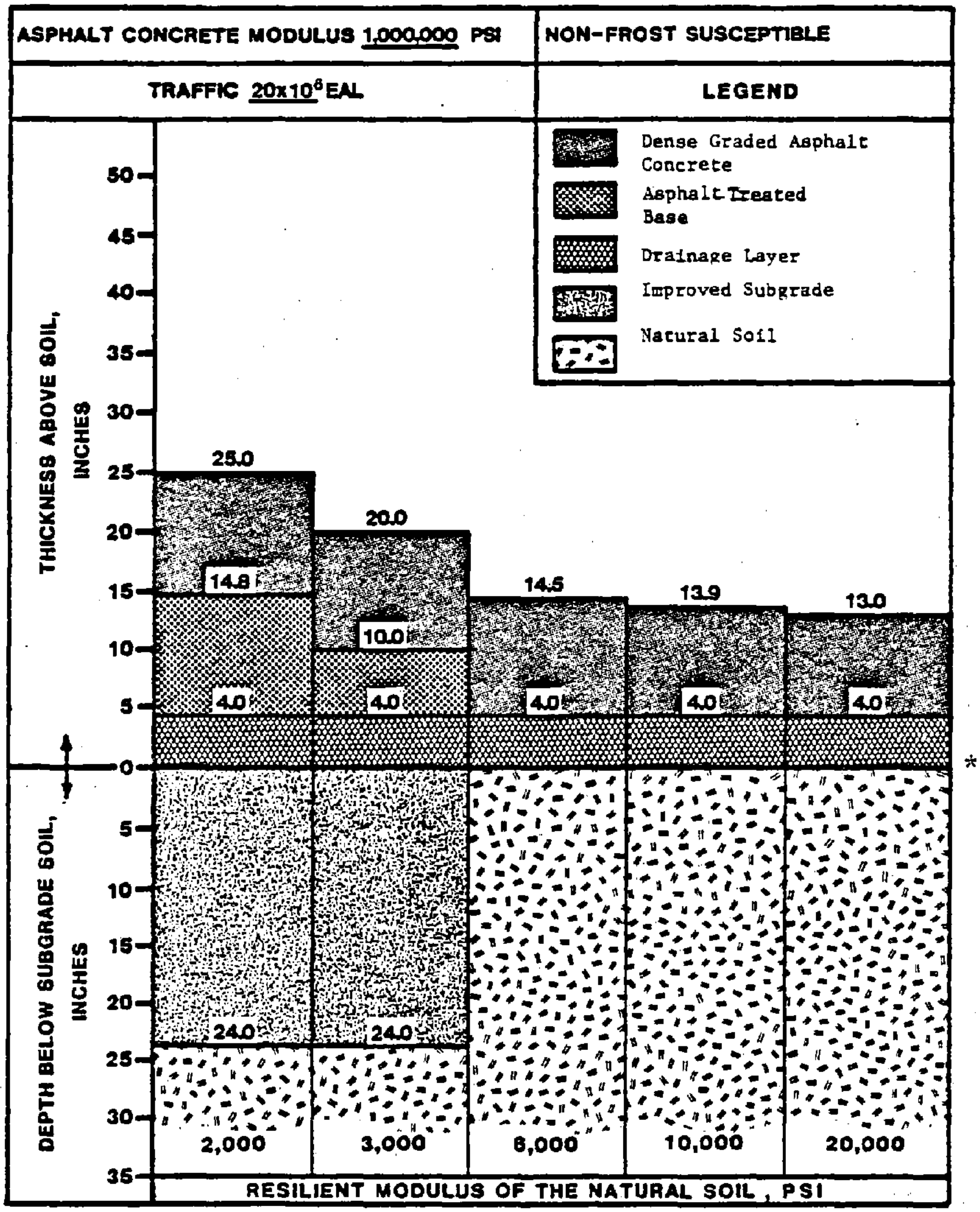
Table A.1 provides a summary road map to this appendix, review it and see where to find your needs. Work sheets to be used in your design are depicted in Figures A.29 through A.33 and can be reproduced and used for your own design needs.

Where the term "drainage layer" is used in the Figures in this Appendix, it is assumed that appropriate filter materials or fabrics are used where needed. The detailed design of such filter layers is beyond the scope of this report, see the section on drainage layers of Section 6.

When the permeability of the subgrade is equal to or greater than the permeability of the base material no drainage layers are required in any of the cross-sections and may thus be omitted.

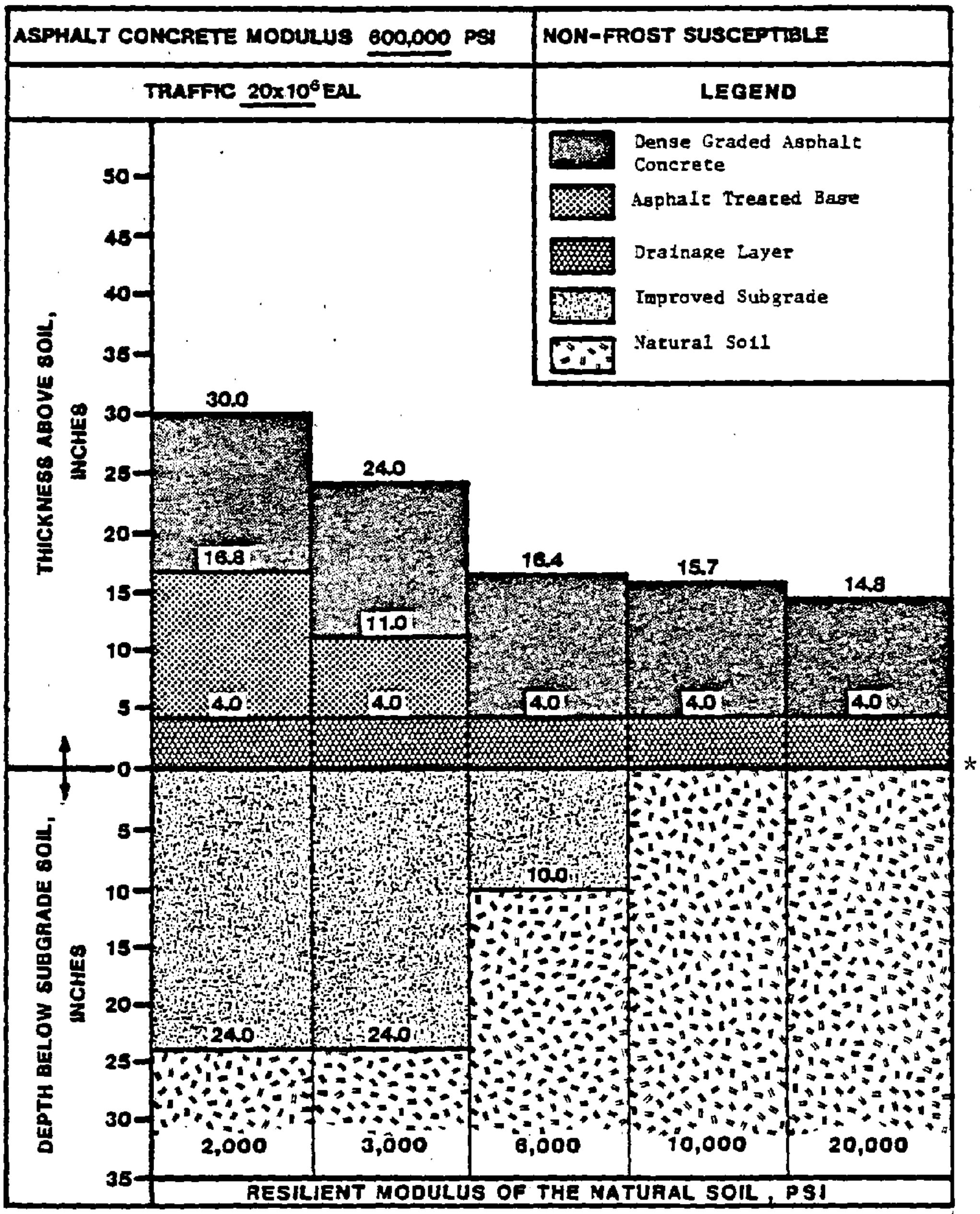
TABLE A.1 FIGURES CONTAINING PREMIUM PAVEMENT DESIGN CONFIGURATIONS FOR EACH PAVEMENT TYPE AND TRAFFIC LEVEL

Pavement Type	Materials Used in Crossection	Cumulative Traffic at 20 yrs., x 10^6	Figure Numbers with Design Crossections
Flexible	Full Depth	20	A.1 - A.4
		40	A.5 - A.8
	Unbound Granular Base or Cement Treated Base	20	A.9 - A.12
		40	A.13 - A.16
Composite	Low Modulus Continuously Reinforced Concrete Base	20	A.17 - A.19
		40	A.20 - A.22
	Low Modulus Jointed Concrete Base	20	A.23 - A.25
		40	A.26 - A.28



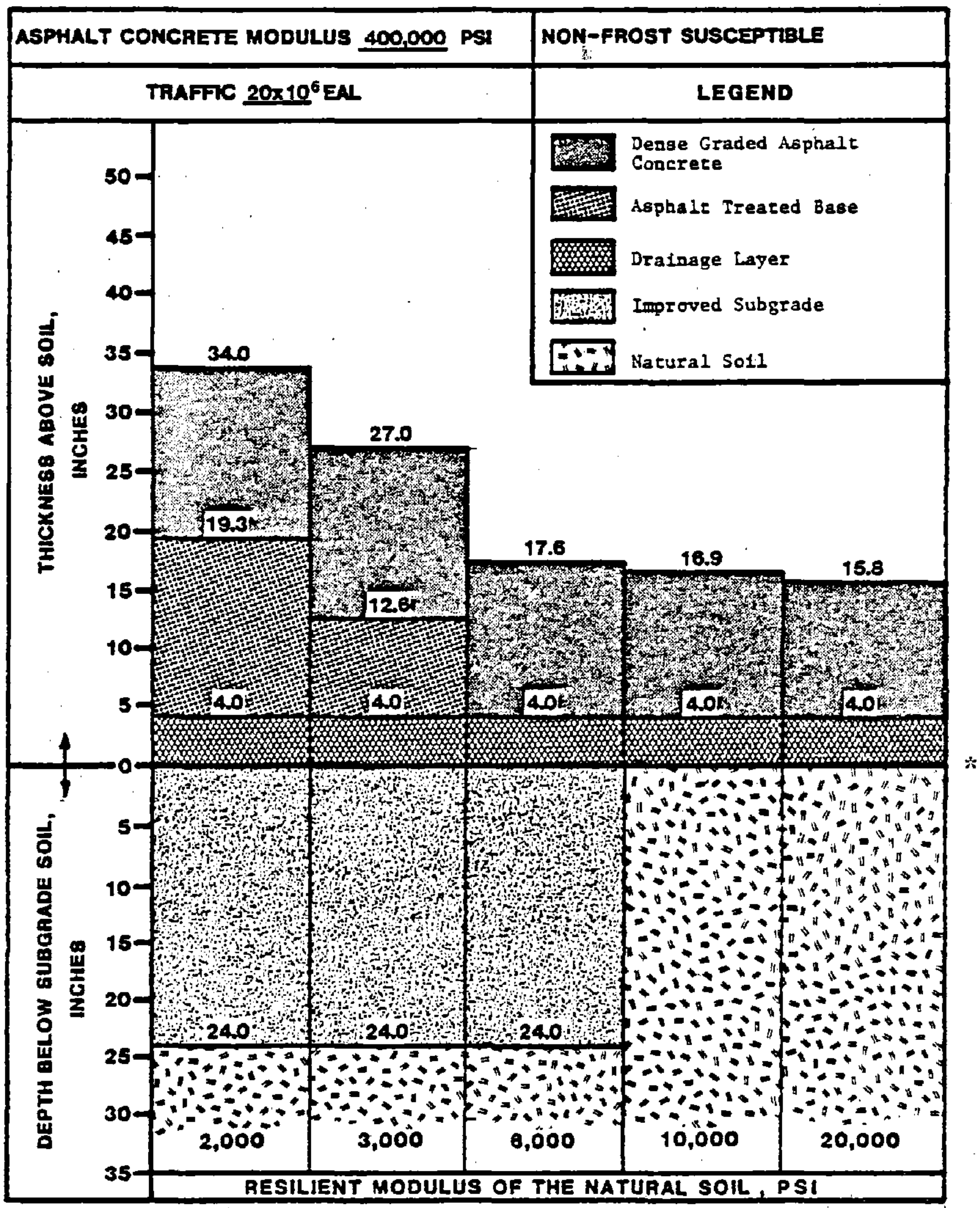
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.1 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



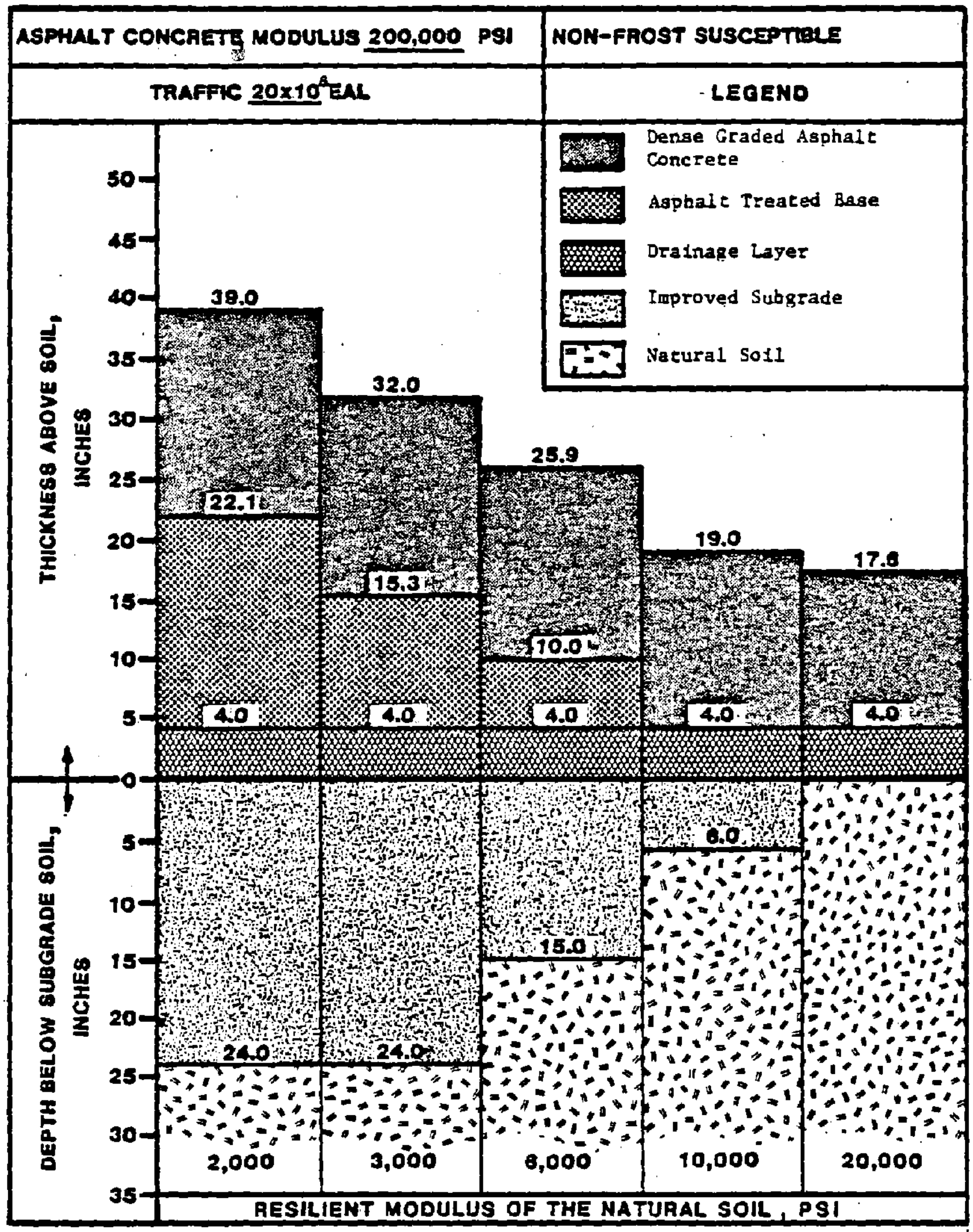
* Filter layer located between drainage layer and underlying layer, if required.

Figure A.2 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



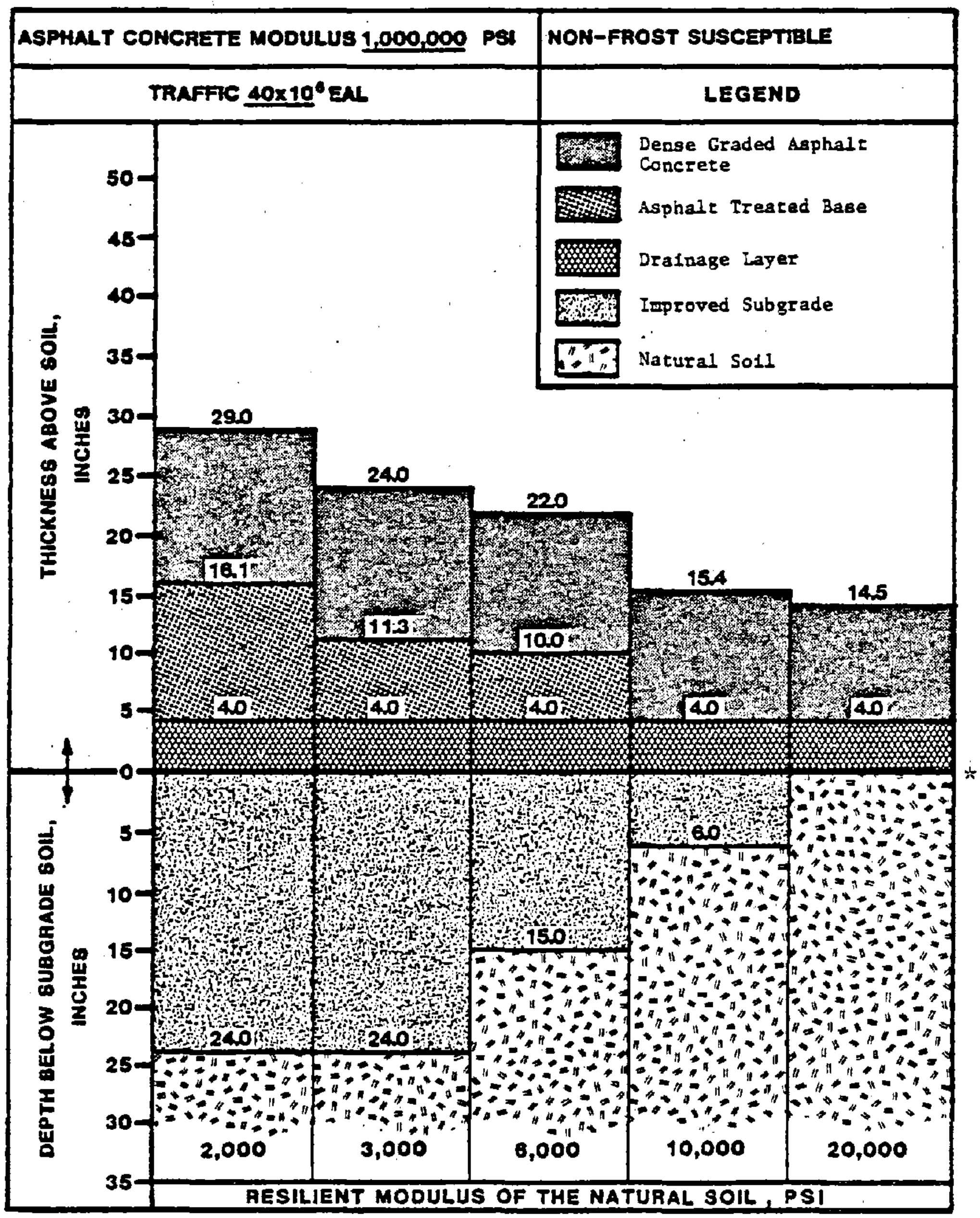
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.3 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



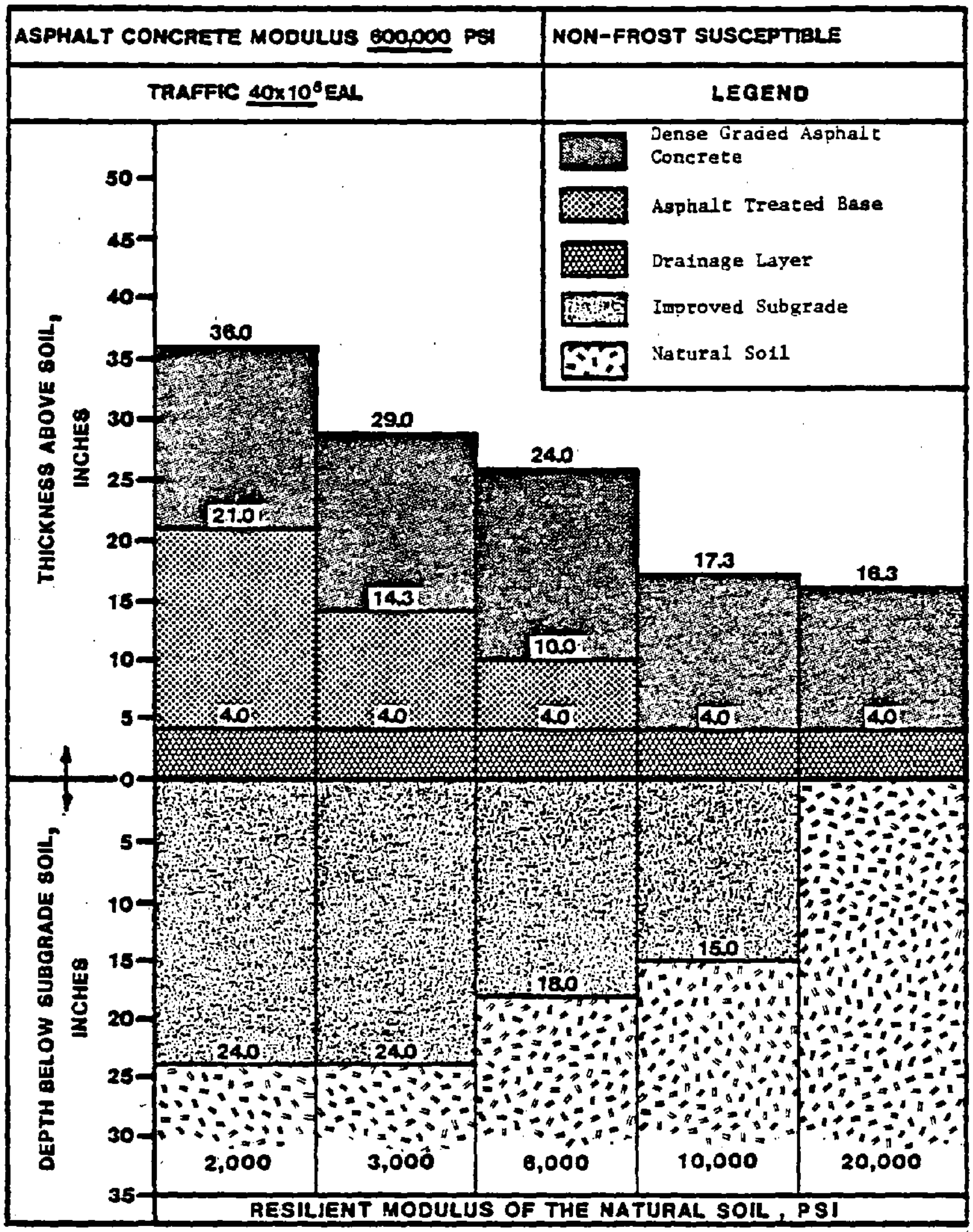
*Filter layer located between drainage layer and underlying layer, if required.

Figure A. 4 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



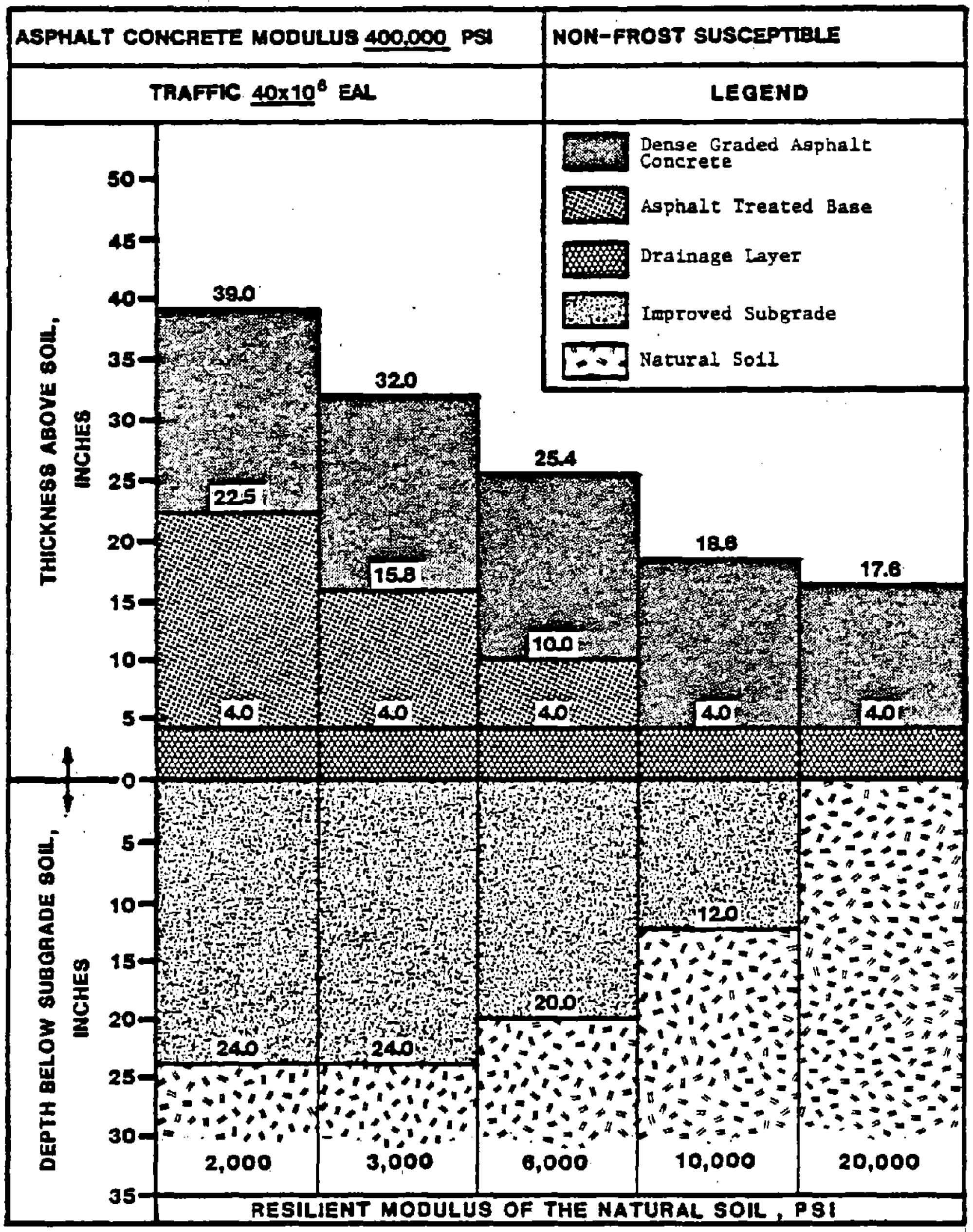
* Filter layer located between drainage layer and underlying layers, if required.

Figure A. 5 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



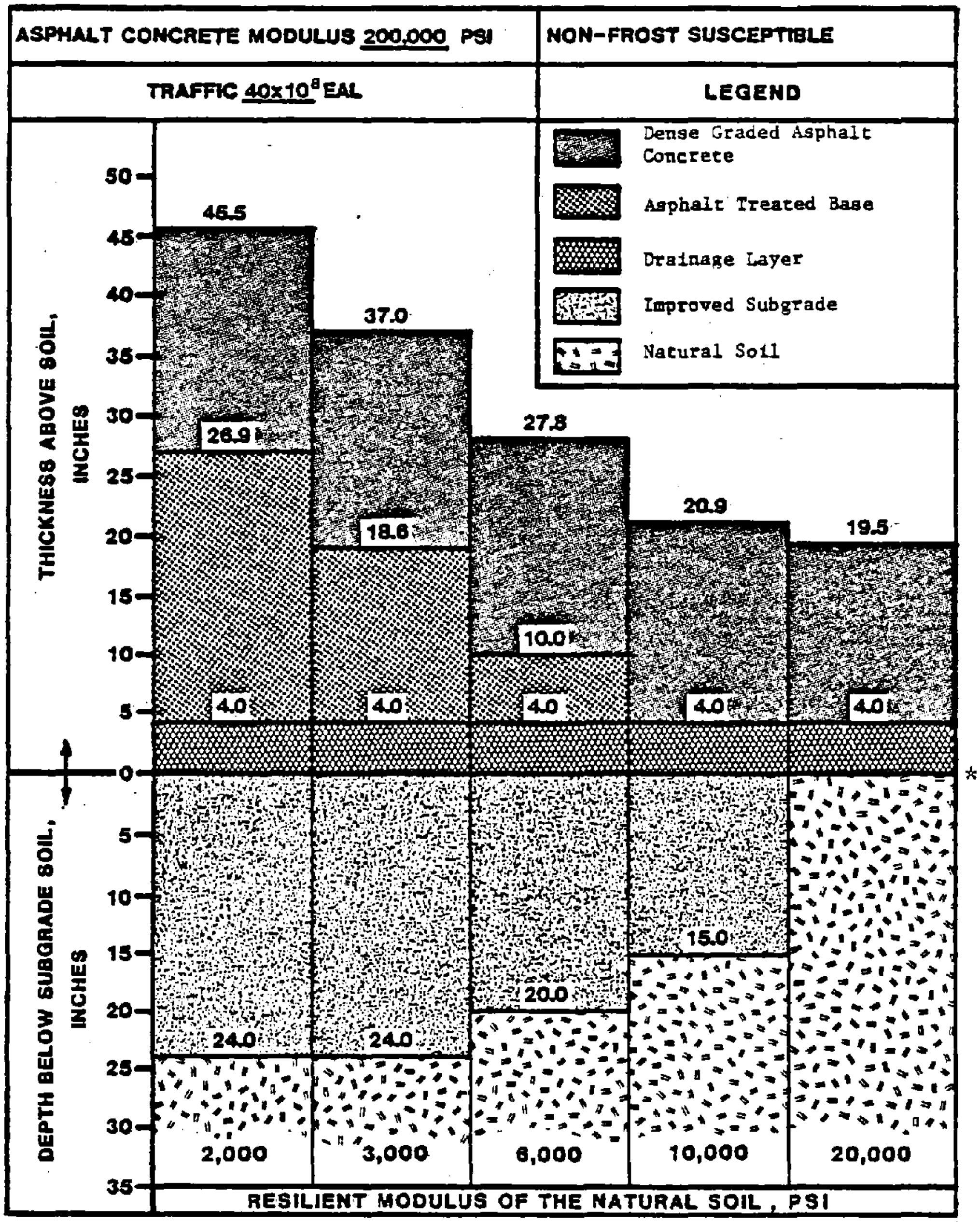
*Filter layer located between drainage layer and underlying layers, if required.

Figure A.6 Flexible Pavement Cross-Sections, Full Depth Asphalt Concrete.



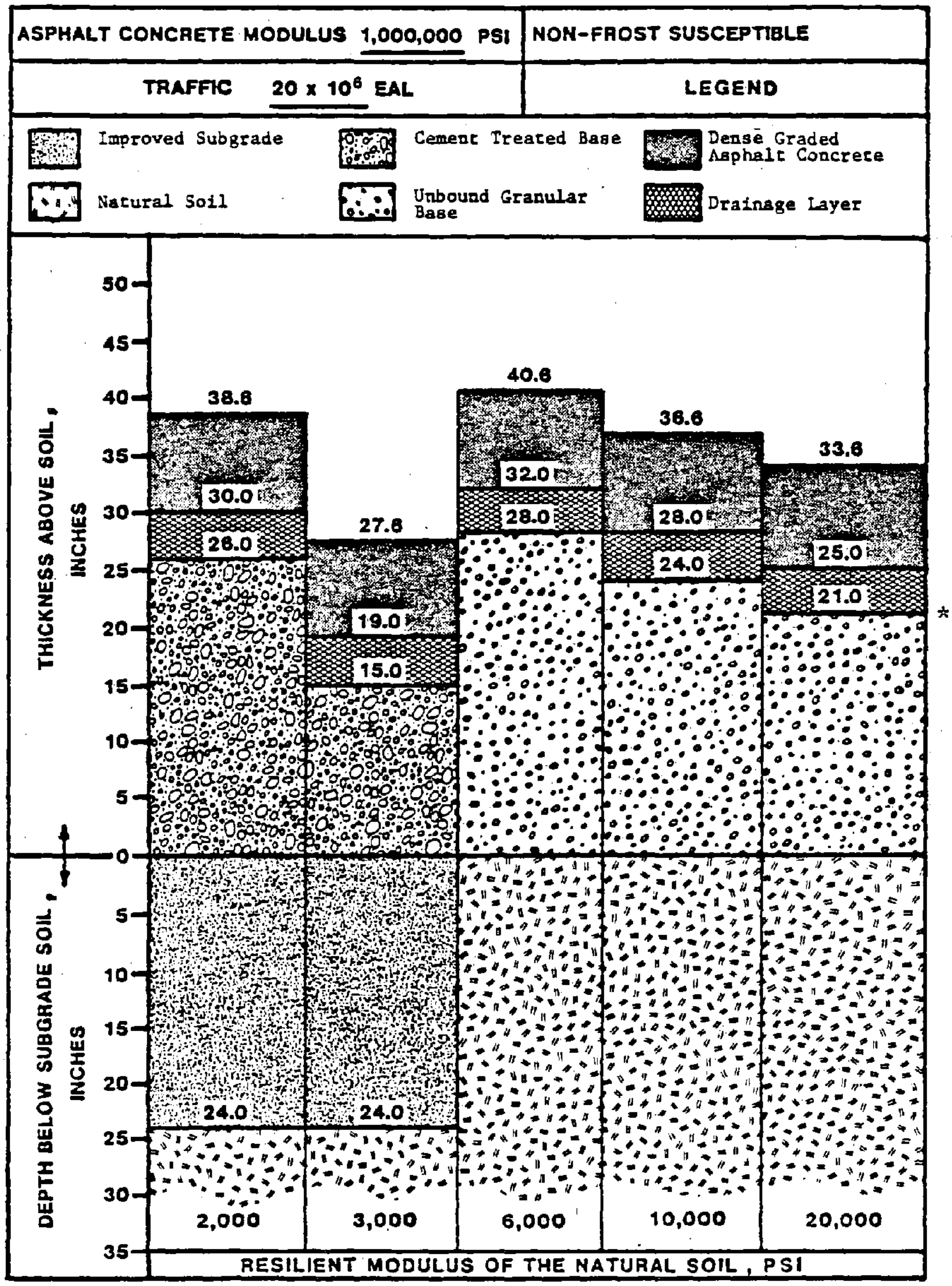
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.7 Flexible Pavement Cross-Section, Full Depth Asphalt Concrete.



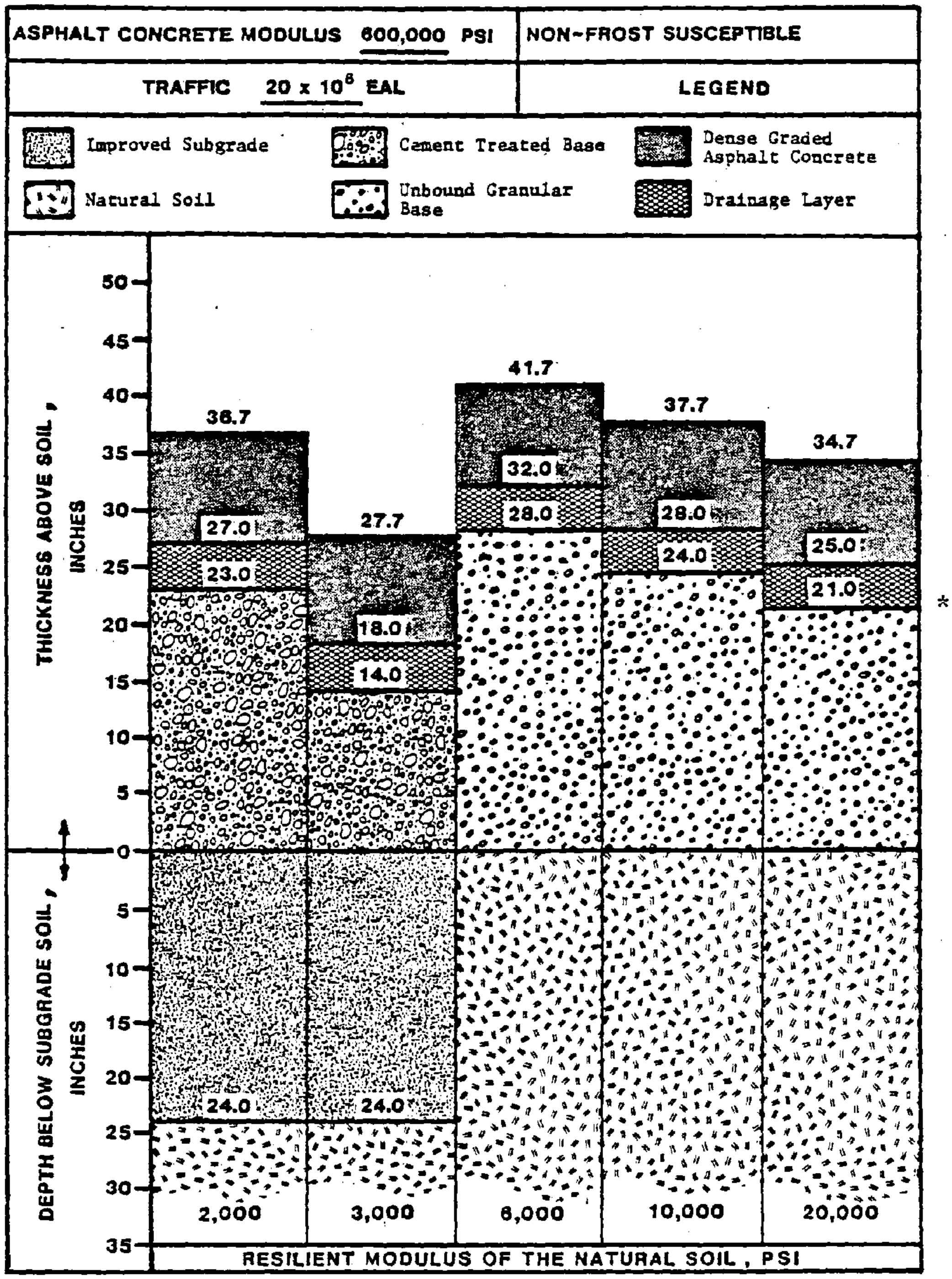
*Filter layer located between drainage layer and underlying layers, if required.

Figure A.8 Flexible Pavement Cross-Section, Full Depth Asphalt Concrete.



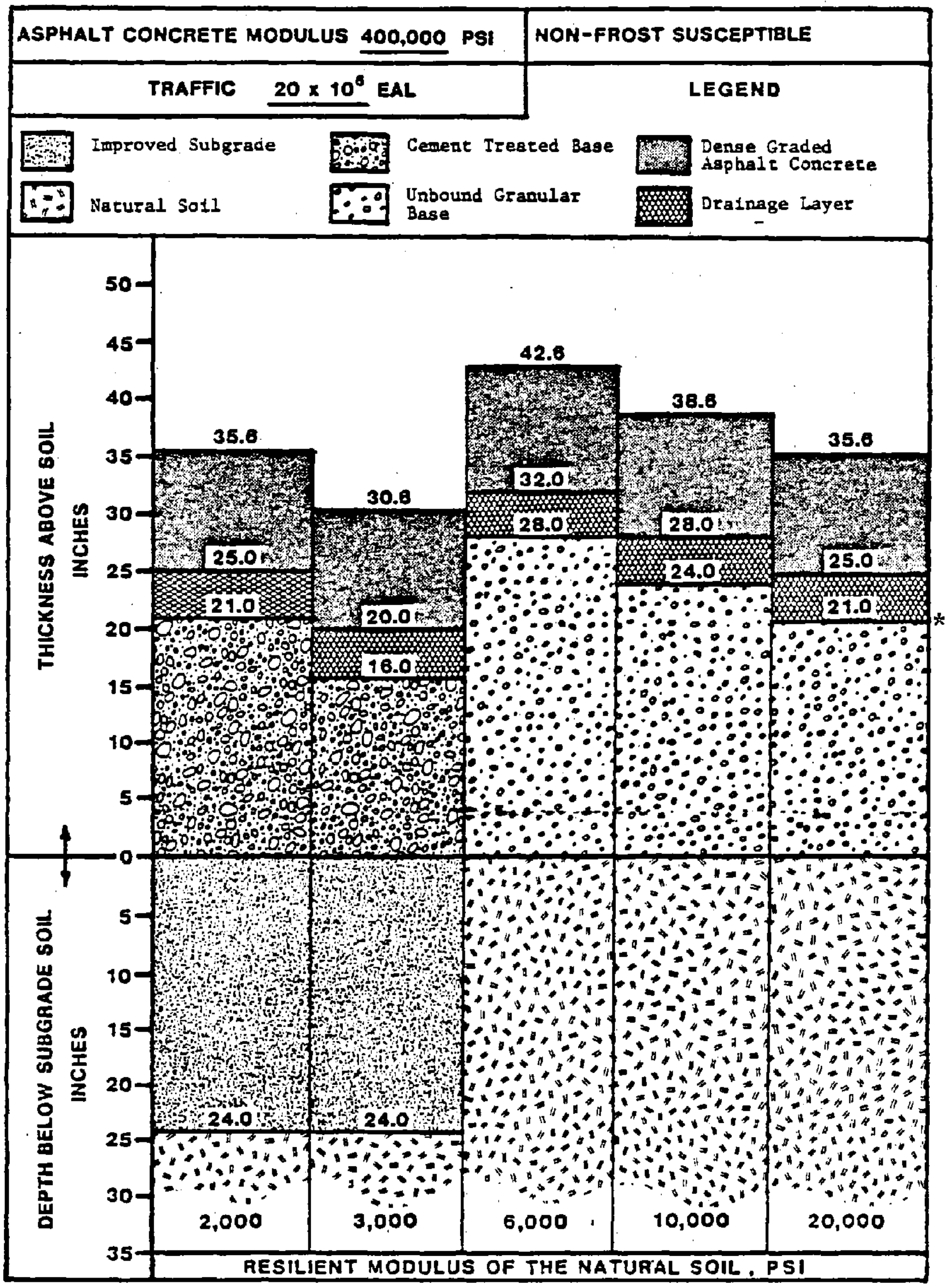
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.9 Flexible Pavement Cross-Section, Unbound Granular of Cement Treated Base



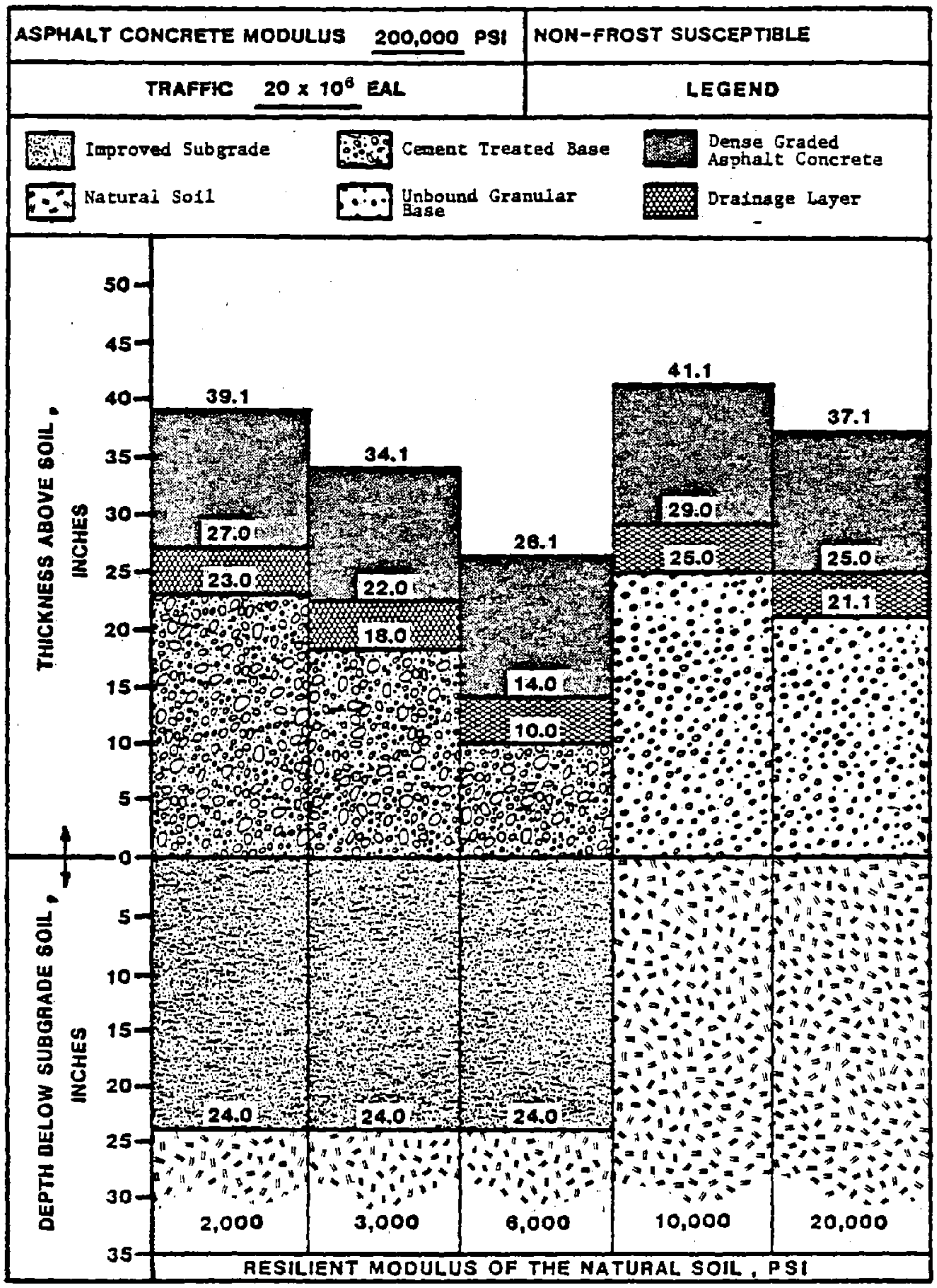
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.10 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



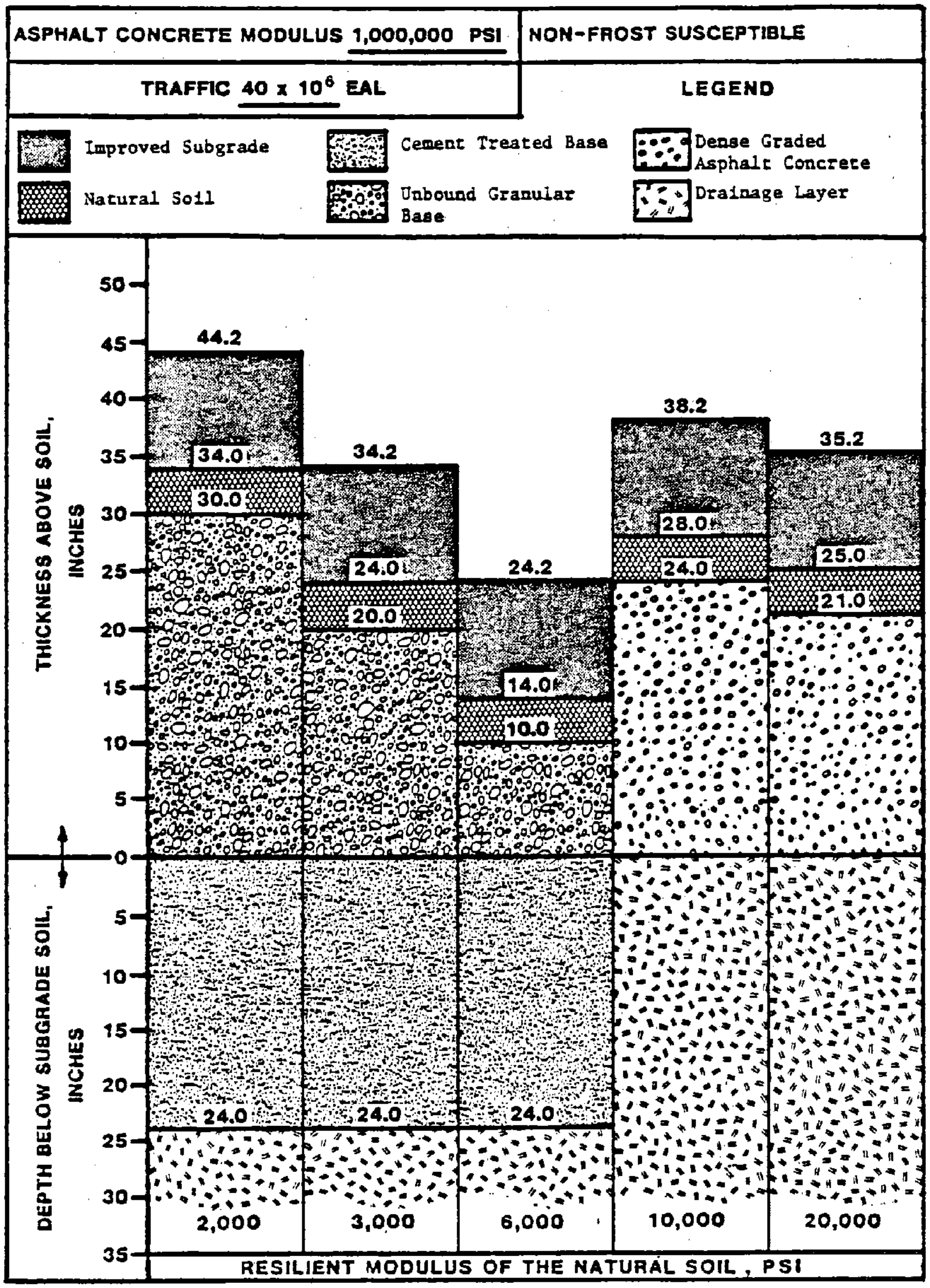
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.11 Flexible Pavement Cross-Section, Unbound Granular or Cement Treated Base.



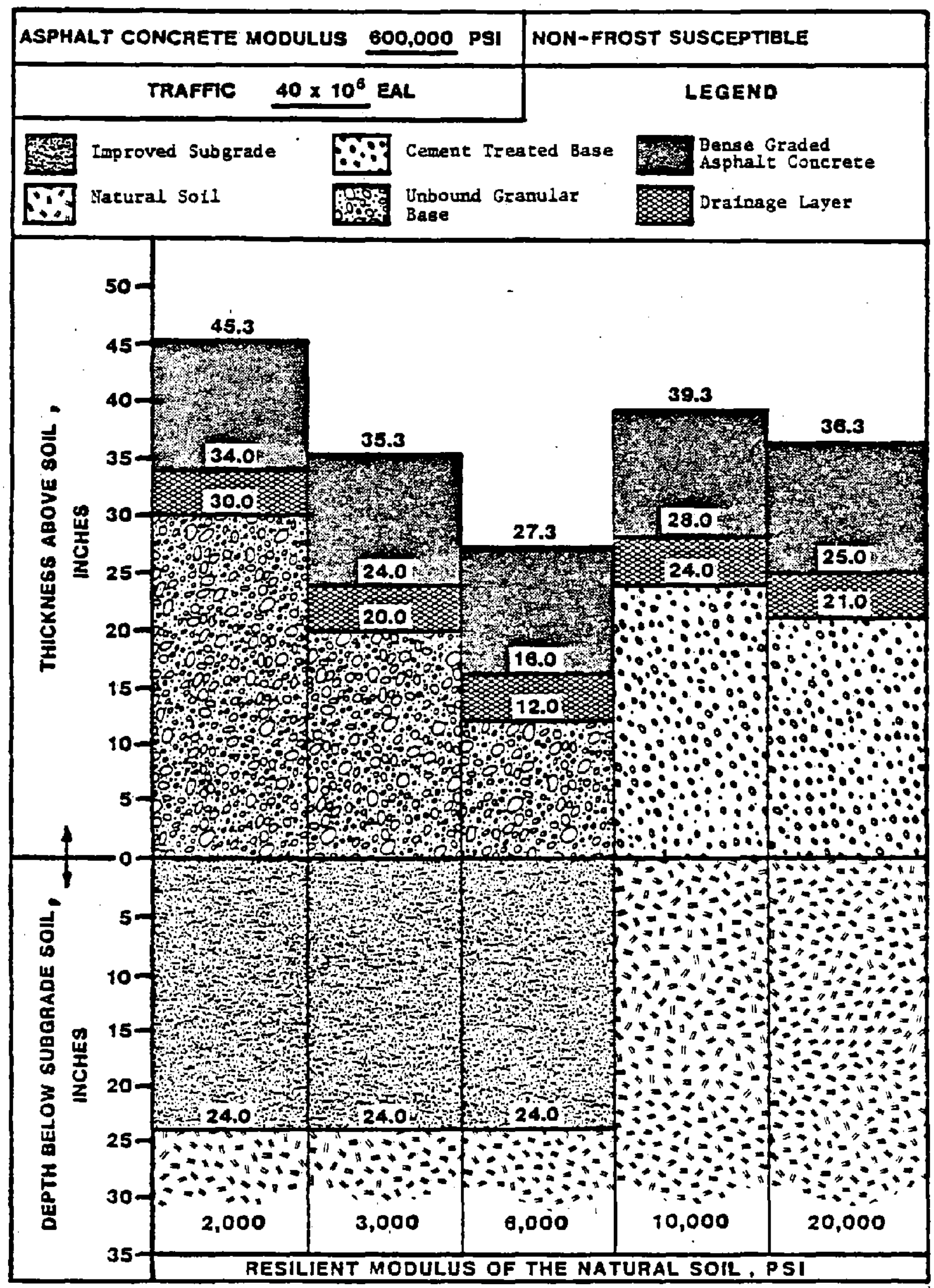
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.12 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



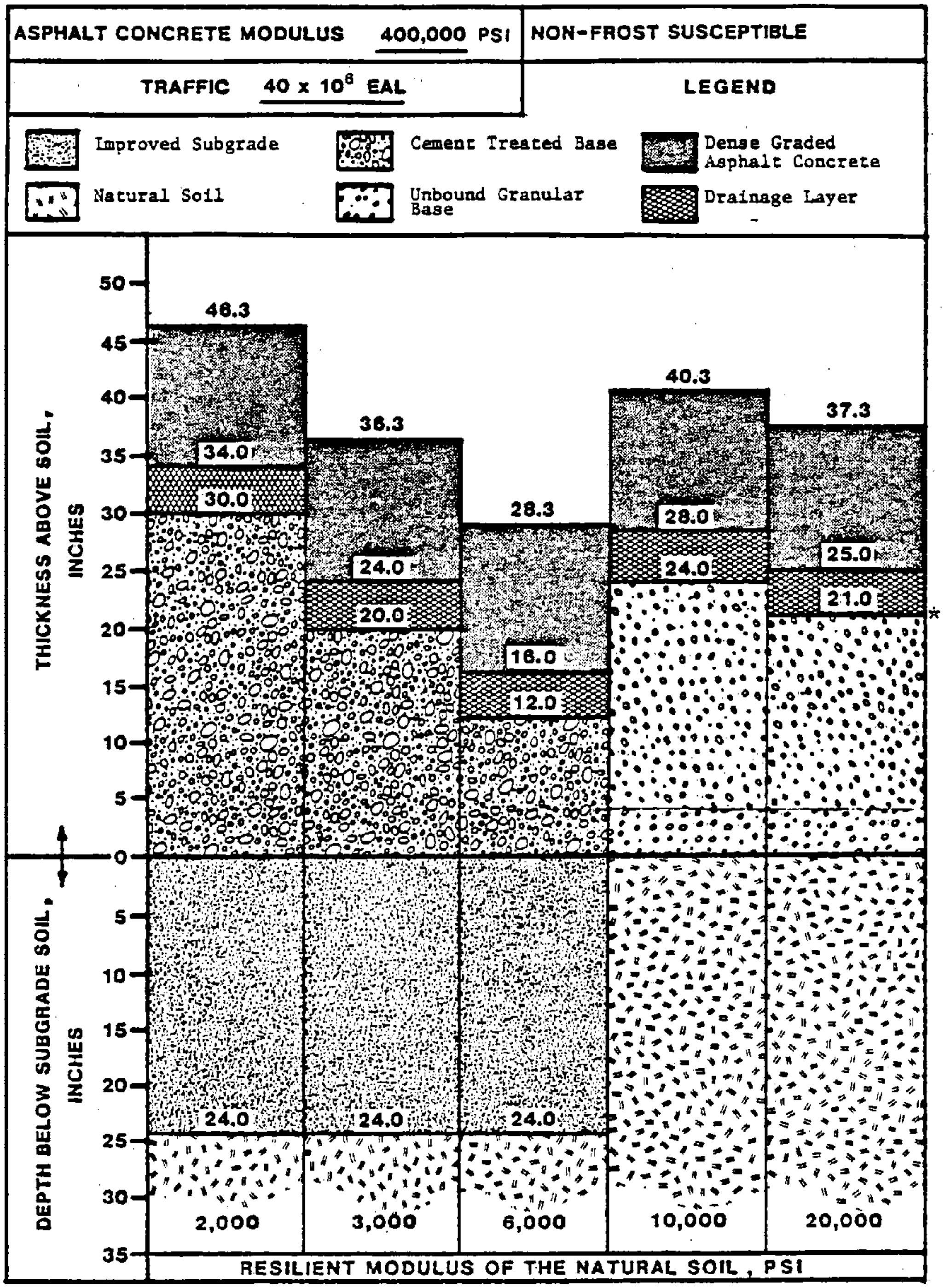
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.13 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



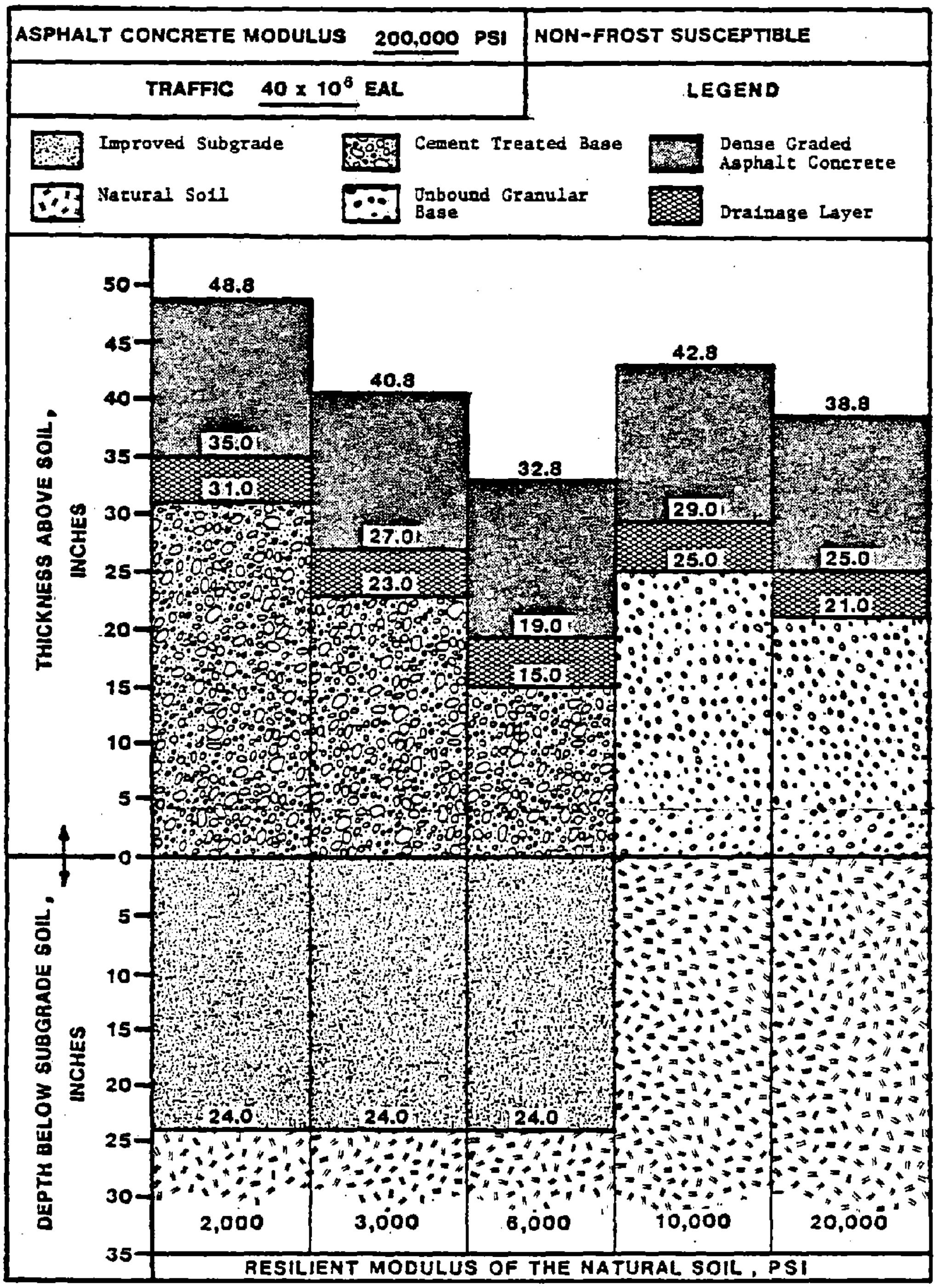
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.14 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



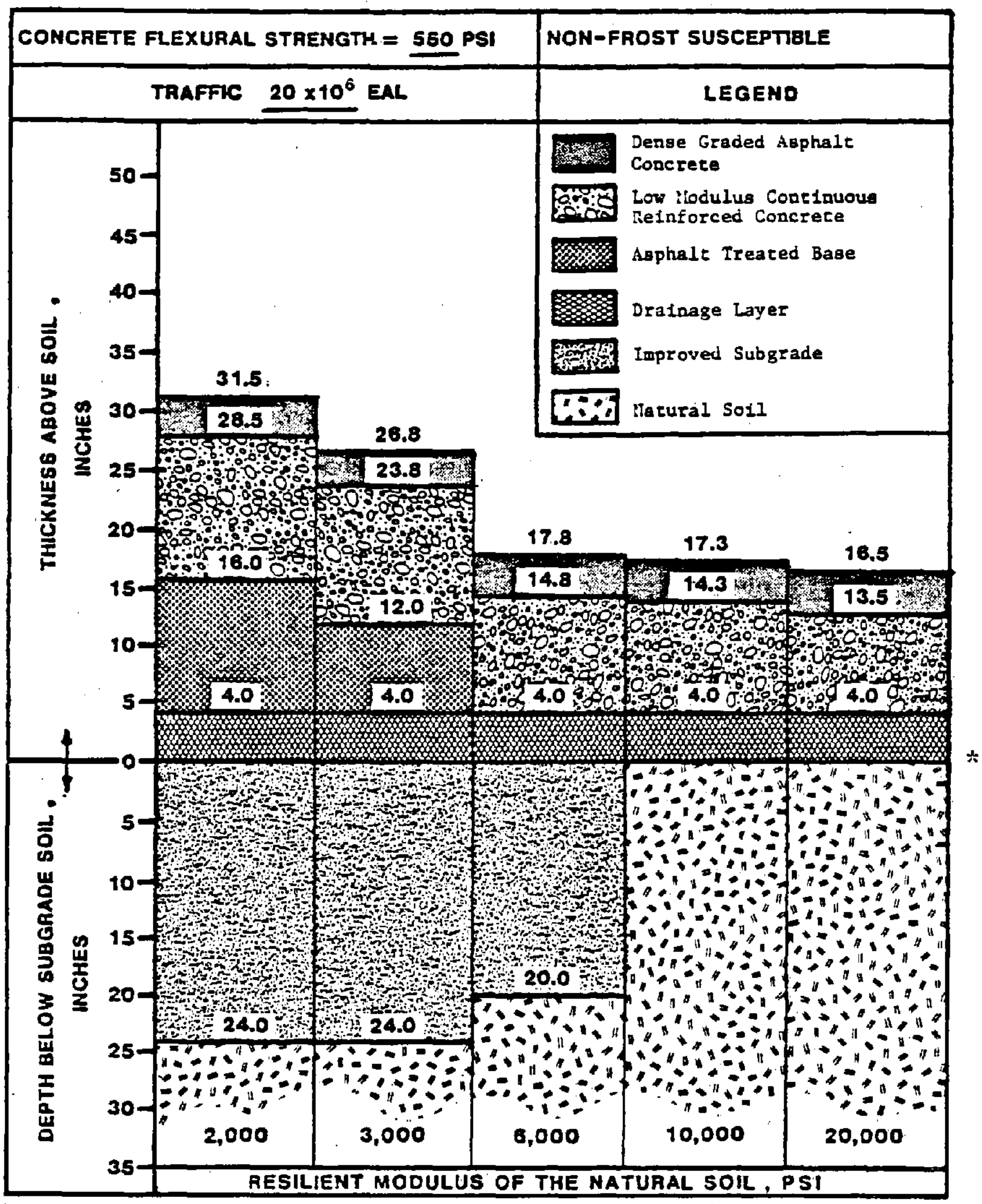
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.15 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



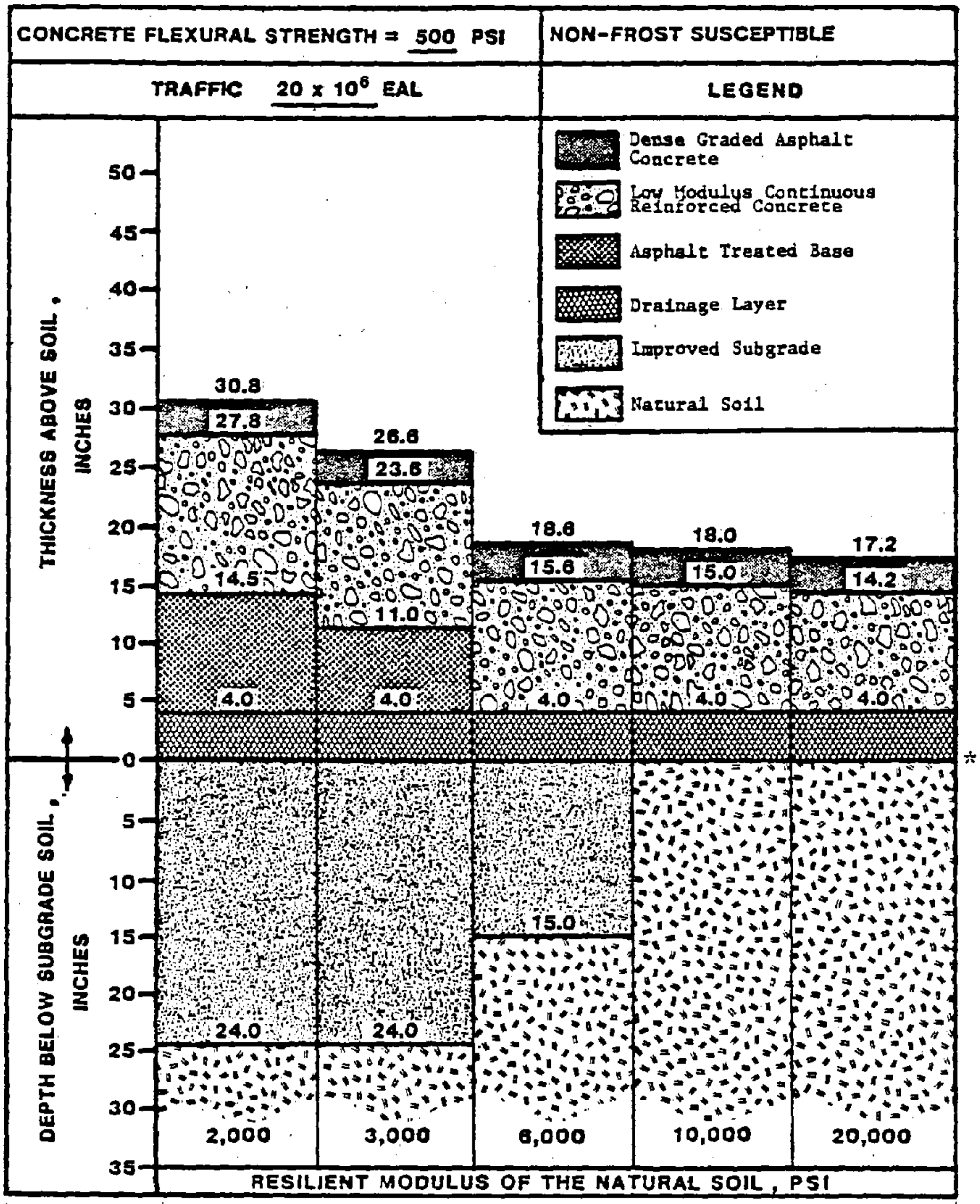
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.16 Flexible Pavement Cross-Sections, Unbound Granular or Cement Treated Base.



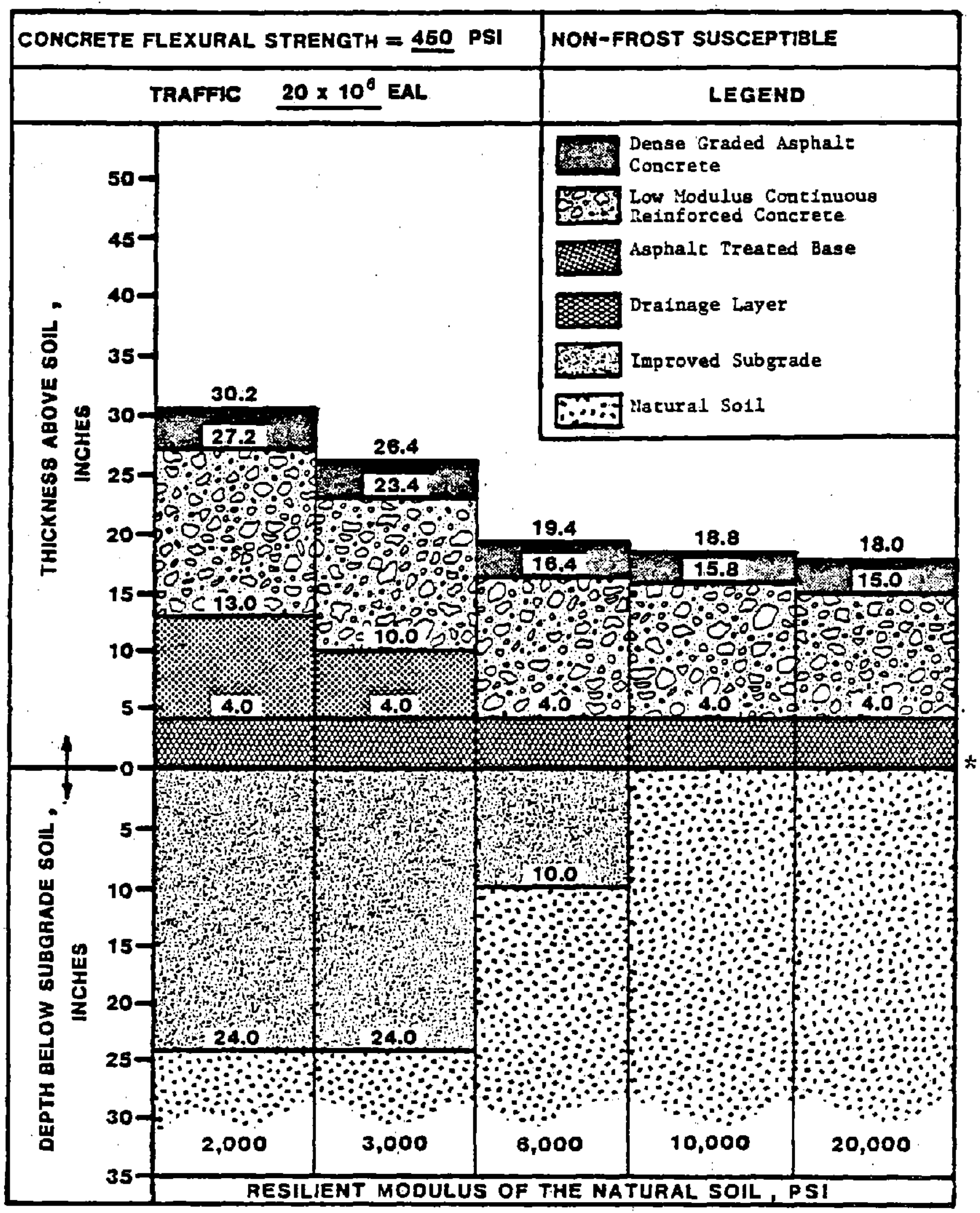
*Filter layer located between drainage layer and underlying layers, if required.

Figure A.17 Composite Pavement Cross-Sections, Low Modulus CRC Base.



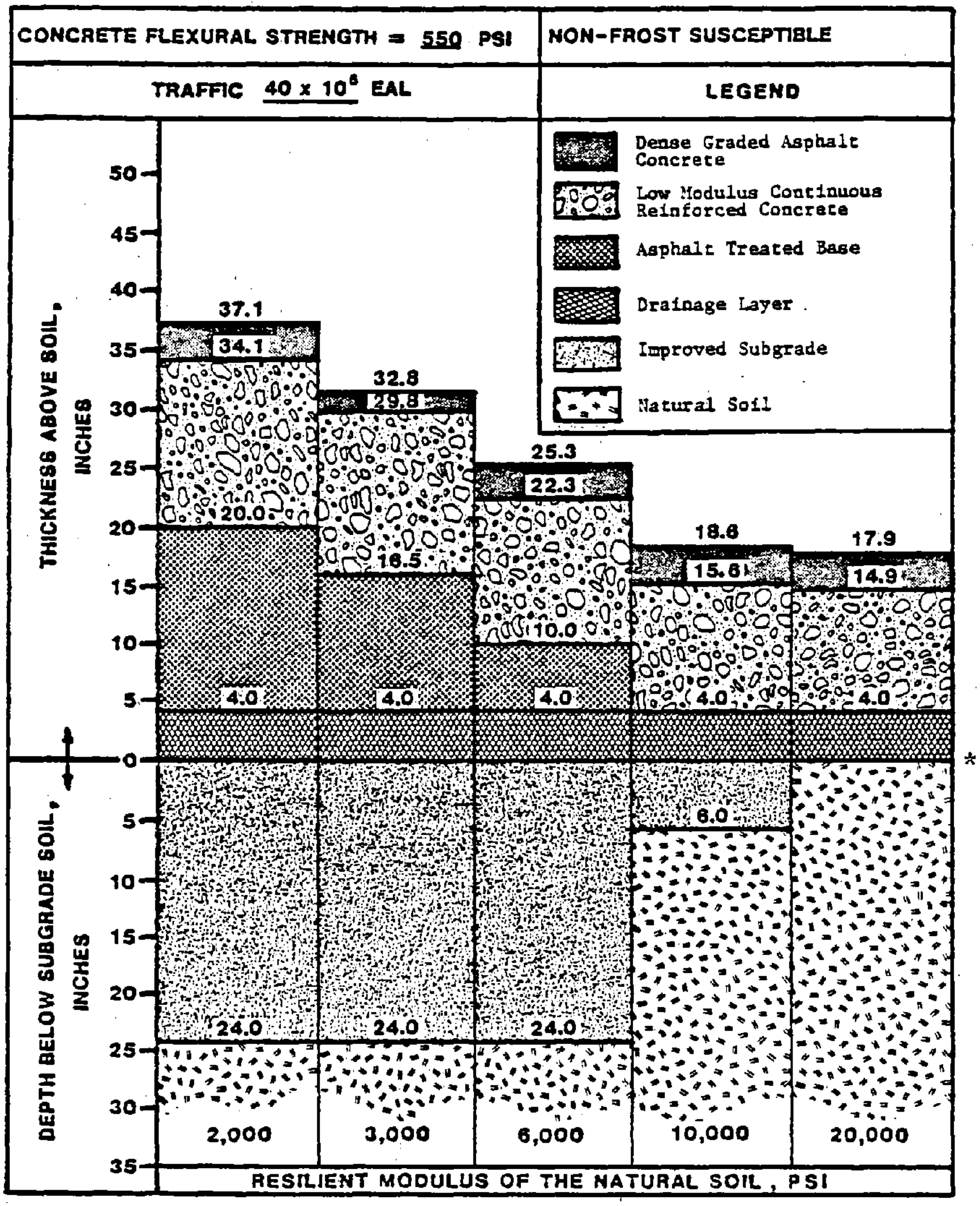
*Filter layer located between drainage layer and underlying layers, if required.

Figure A.18 Composite Pavement Cross-Sections, Low Modulus CRC Base.



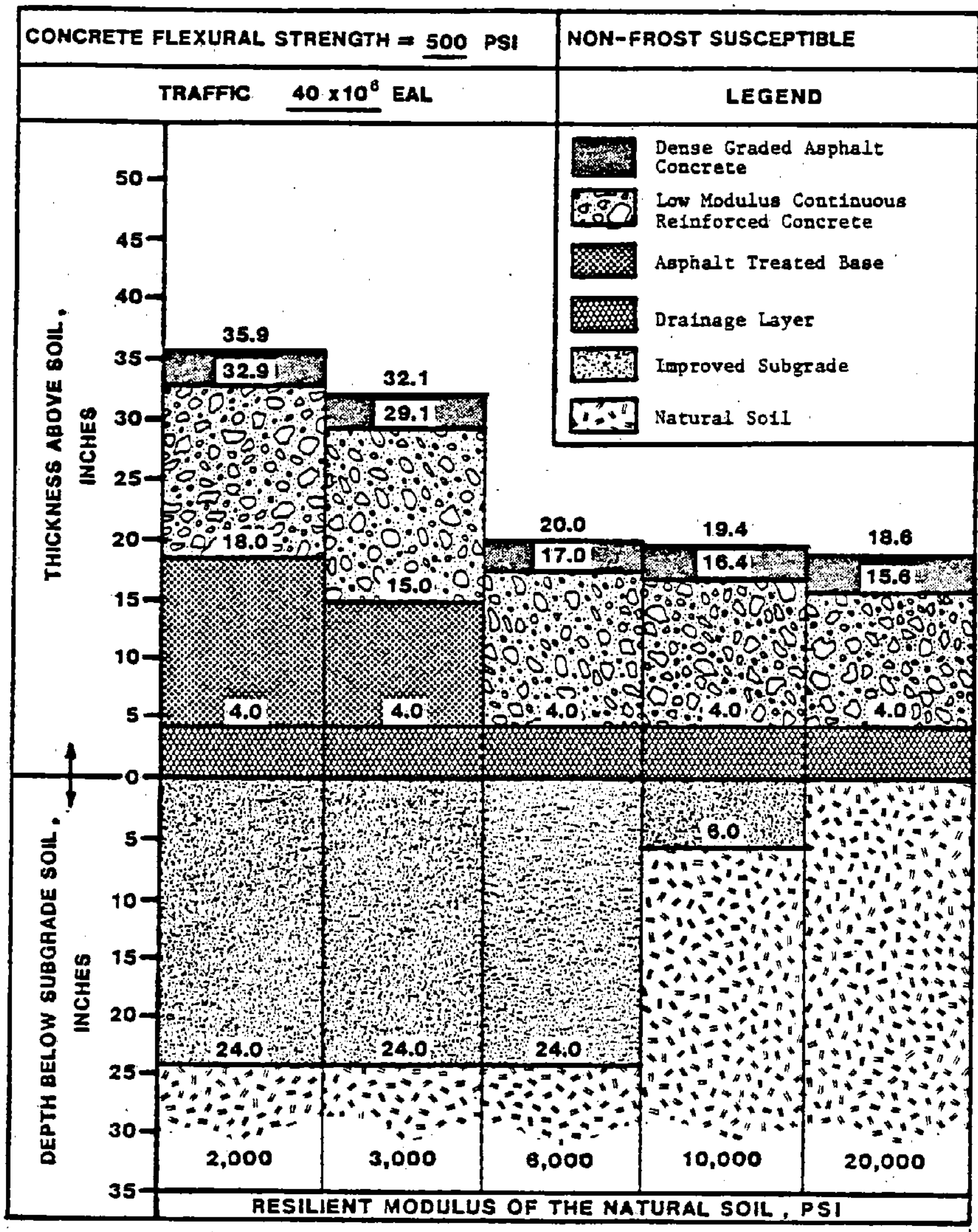
*Filter layer located between drainage and underlying layers, if required.

Figure A.19 Composite Pavement Cross-Sections, Low Modulus CRC Base.



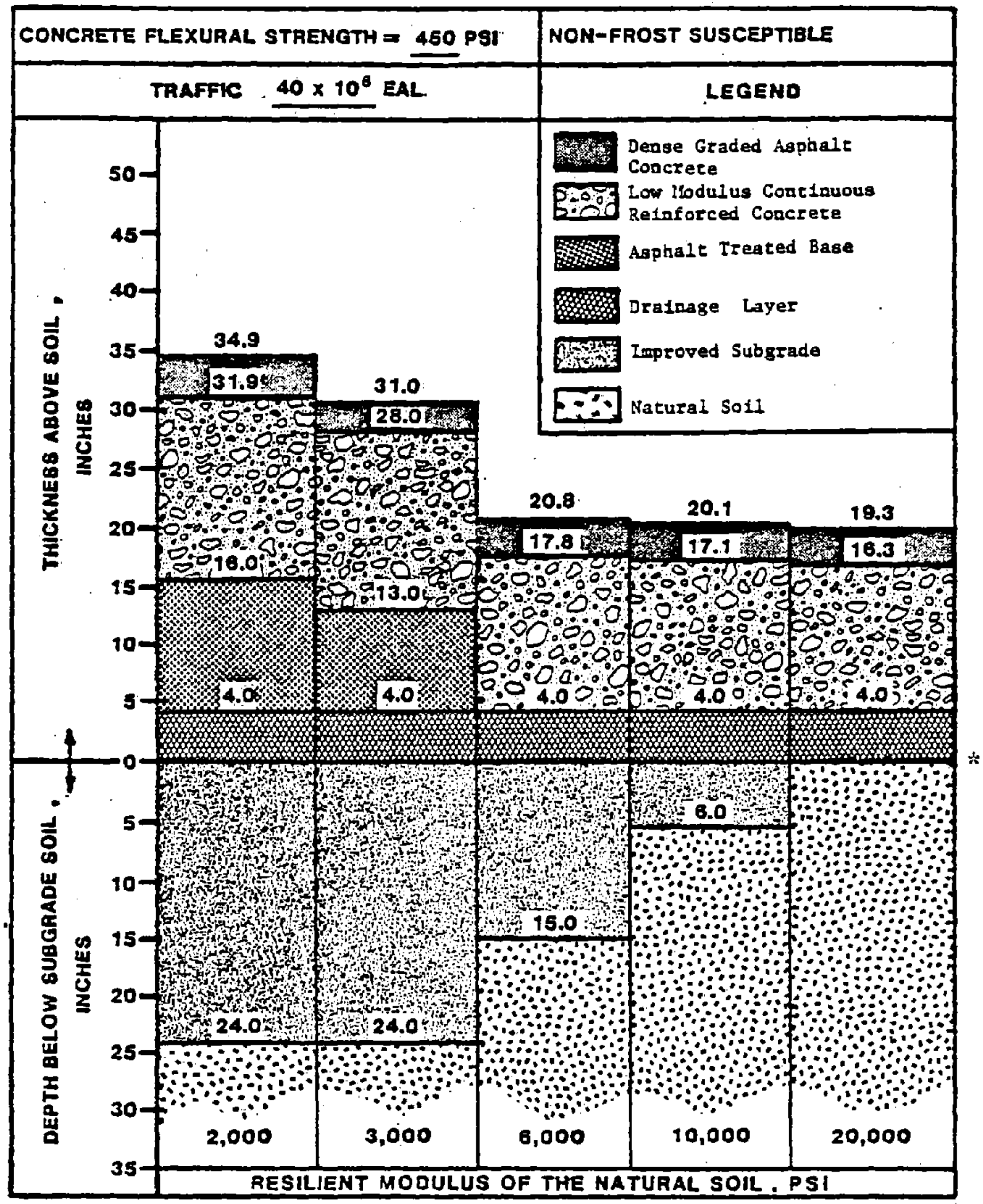
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.20 Composite Pavement Cross-Sections, Low Modulus CRC Base.



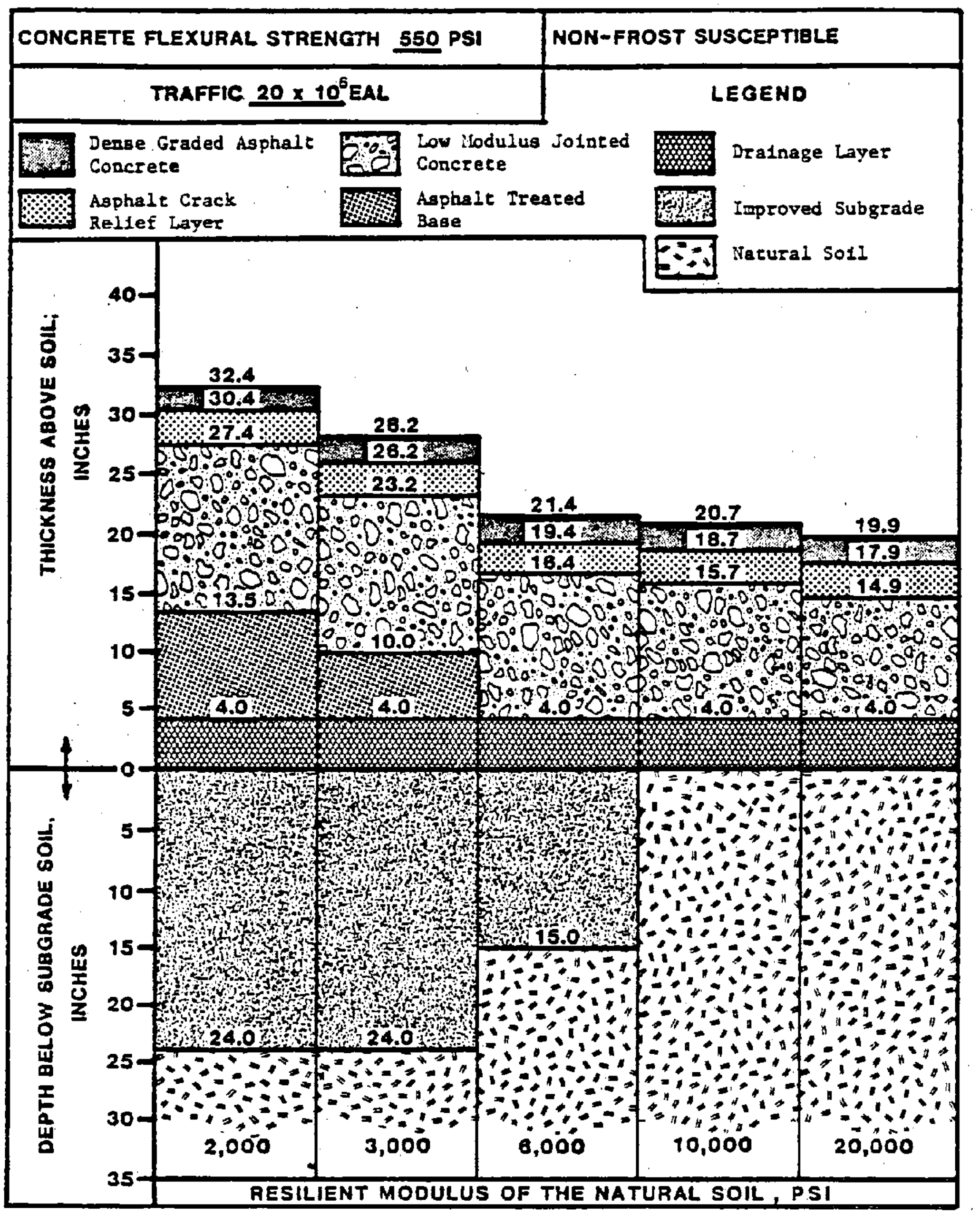
*Filter layer located between drainage and underlying layers, if required.

Figure A.21 Composite Pavement Cross-Sections, Low Modulus CRC Base.



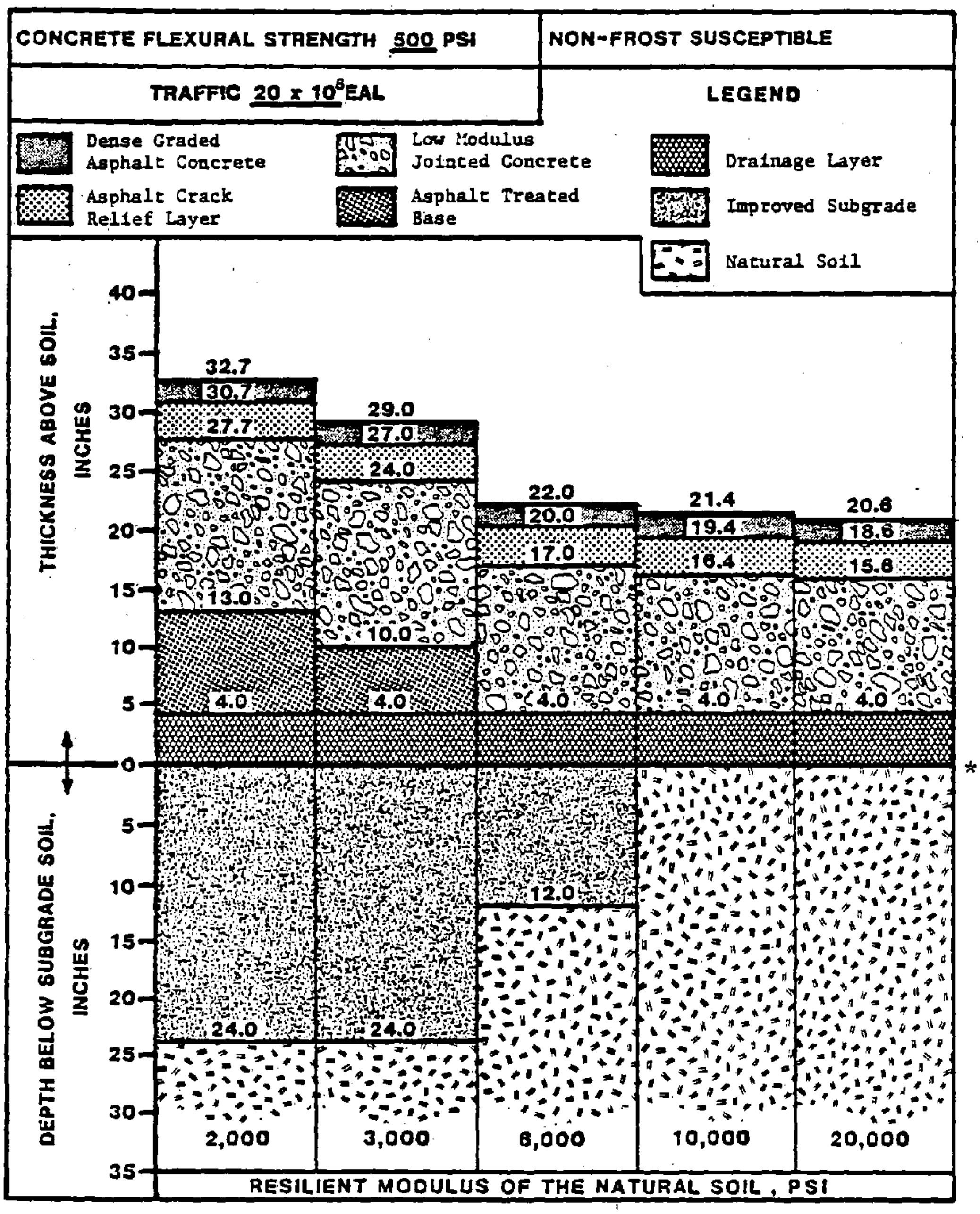
* Filter layer located between drainage and underlying layers, if required.

Figure A.22 Composite Pavement Cross-Sections, Low Modulus CRC Base.



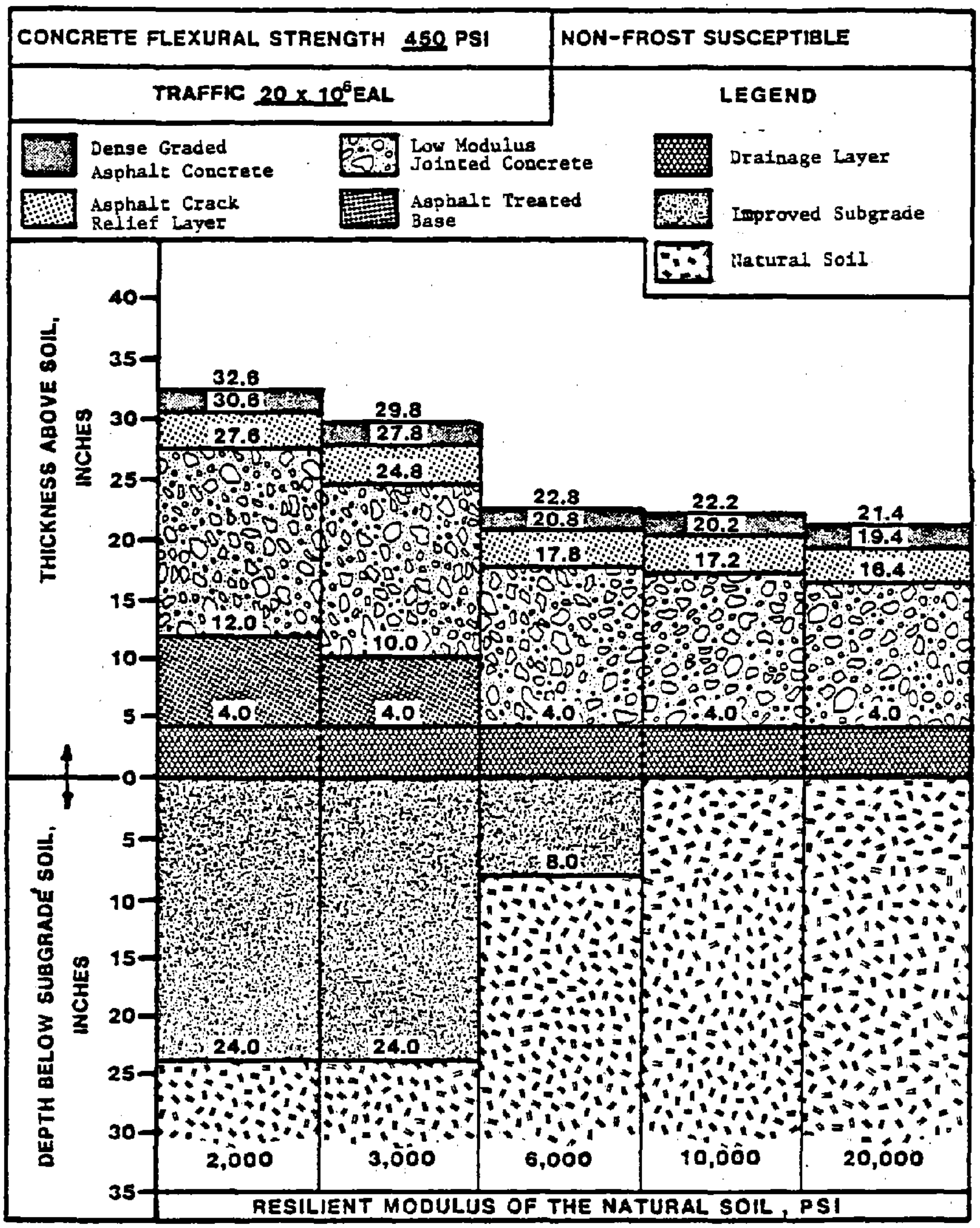
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.23 Composite Pavement Cross-Sections, Low Modulus Jointed Concrete Base.



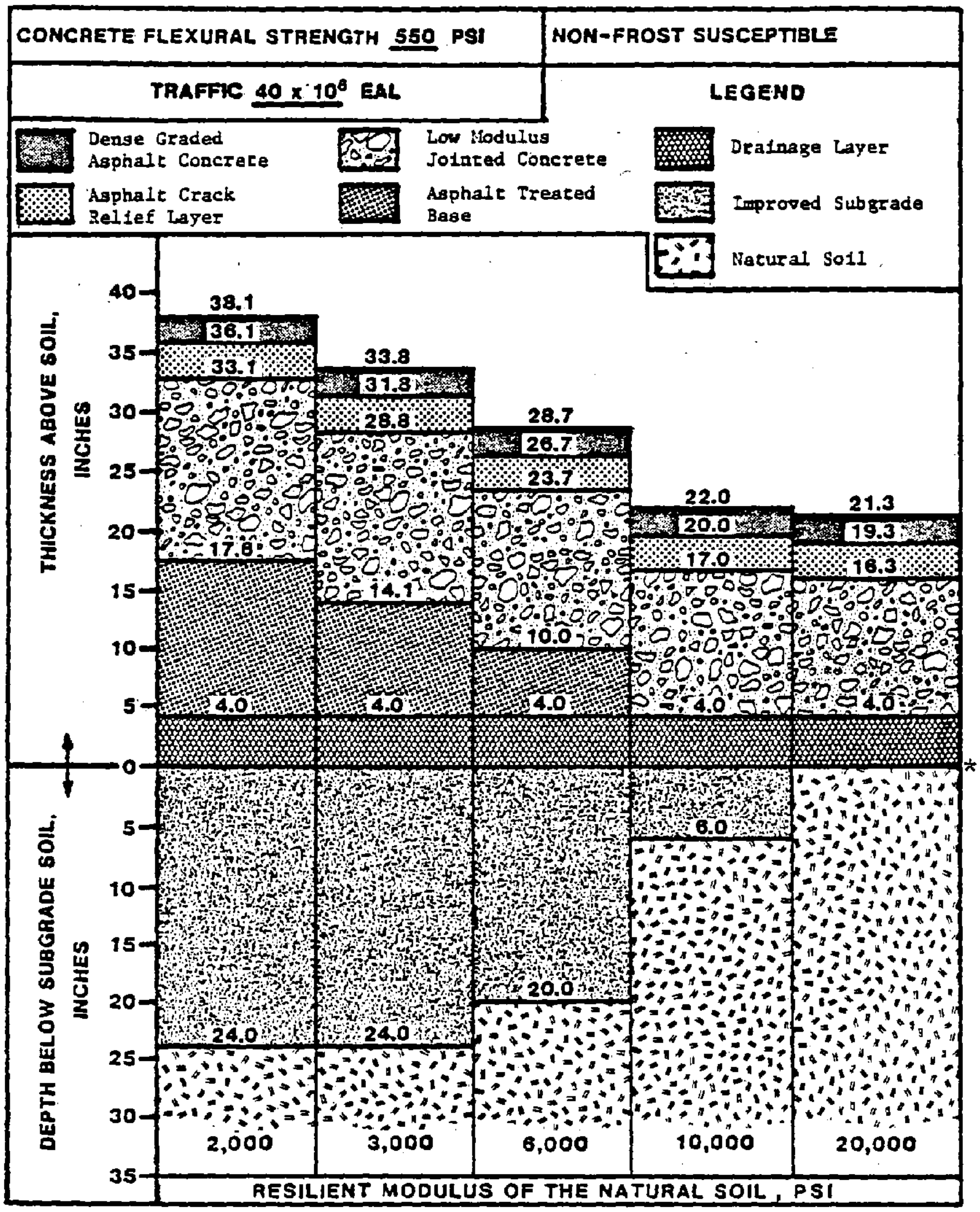
*Filter layer located between drainage layer and underlying layers, if required.

Figure A.24 Composite Pavement Cross-Section, Low Modulus Jointed Concrete Base.



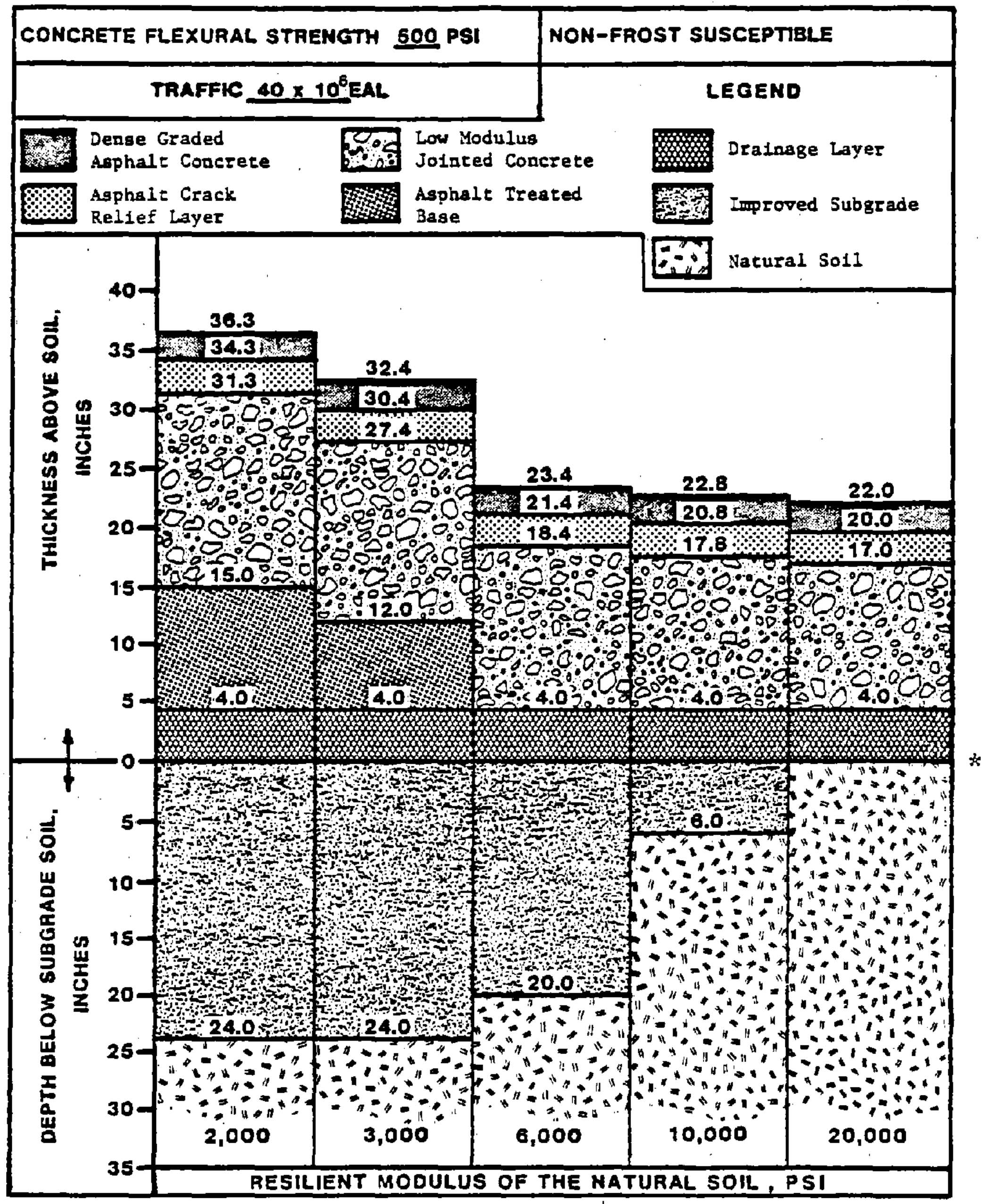
* Filter layer located between drainage and underlying layers, if required.

Figure A.25 Composite Pavement Cross-Section, Low Modulus Jointed Concrete Base.



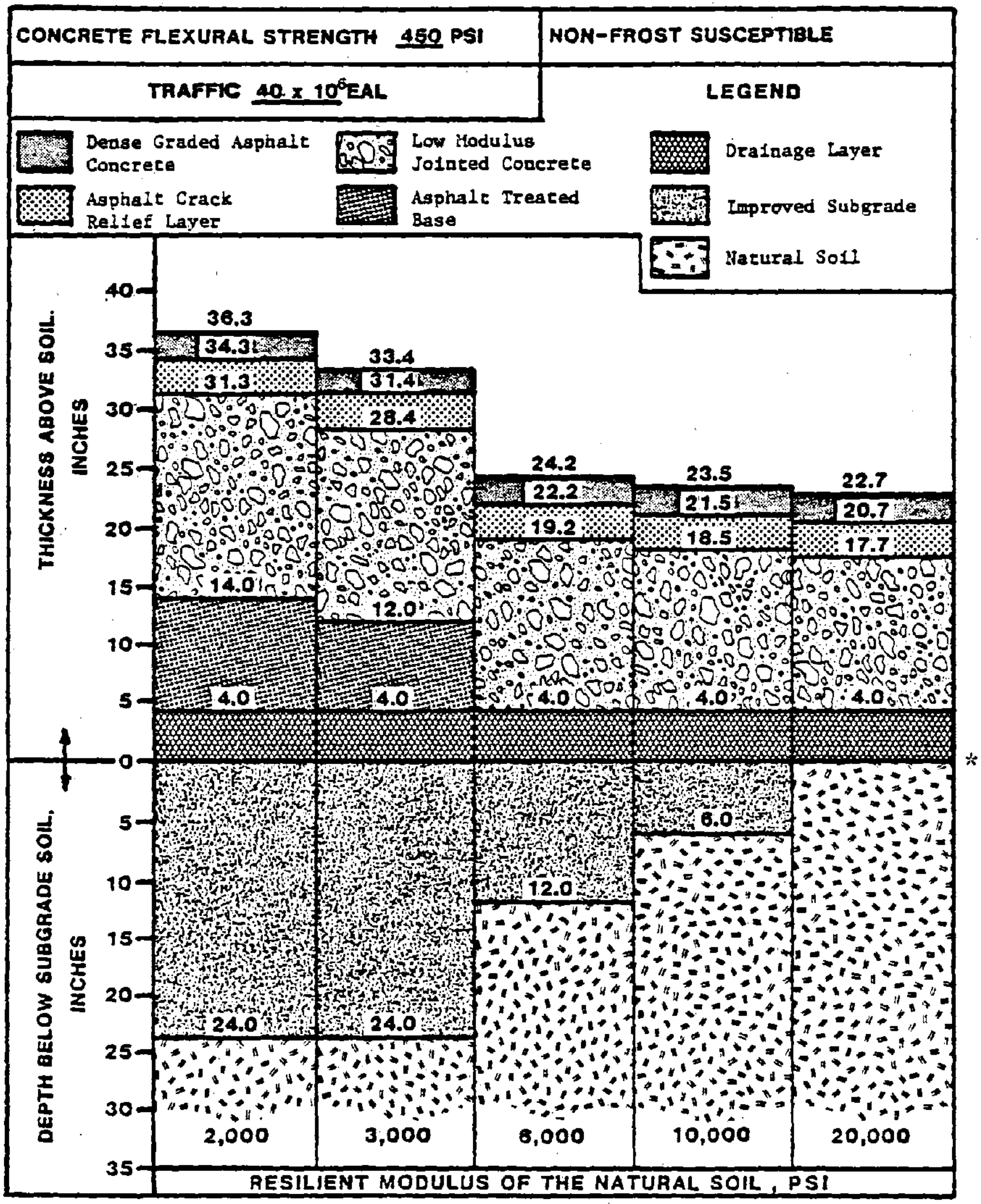
* Filter layer located between drainage layer and underlying layers, if required.

Figure A.26 Composite Pavement Cross-Section, Low Modulus Jointed Concrete Base.



* Filter layer located between drainage layer and underlying layers, if required.

Figure A.27 Composite Pavement Cross-Section, Low Modulus Jointed Concrete Base.



*Filter layer located between drainage and underlying layers, if required.

Figure A.28 Composite Pavement Cross-Section, Low Modulus Jointed Concrete Base.

"ZERO-MAINTENANCE" DESIGN

INPUT-WORKSHEET A

Project:____________________ Date:____________________

Location:____

ENVIRONMENTAL DATA

(1) Mean Annual Air Temperature (MAAT), °F	
(2) Warmest Mean Monthly Air Temperature (WMMAT), °F . .	
(3) Coldest Mean Monthly Air Temperature (CMMAT), °F . .	
(4) Mean Monthly Air Temperature Change, (MMATC), °F (MMATC = WMMAT - CMMAT)	
(5) Design Air Freezing Index (Figure 2.2)	

NATURAL SOIL DATA

	Soil I	Soil II	Soil III
(6) Boring Number			
(7) Boring Location			
(8) Soil Type: Unified Soil Classification and P. I. ( ) . . .	( )	( )	( )
Percent finer than 0.02 mm . . .			
Frost Soil Classification (Table 2.2, Figure 2.3)			
(9) Subgrade Stiffness (Appendix A) .			
(10) Water Table Depth, ft.			

TRAFFIC DATA

(11) Design Applications 18-kip (80 kN) Equivalent Axle Loads (EAL) in Design Lane (Worksheet B, Figure 2.4)	

Figure A. 29 Worksheet Tabulating the Input Information Required to Use This Design Manual.

"ZERO-MAINTENANCE" DESIGN

TRAFFIC-WORKSHEET B

Project:____________________ Date:____________

Location:________________

(1) Axle Load L, kips	(2) Projected Number of Axles per day (Design Lane), N	(3) Equivalency Factor, E (Appendix B)	(4) Projected Equivalent Number of 18 kip (80 kN) axles per day (Design Lane), Ne

(5) Total Projected Number of Equivalent 18-kip (80 kN) axles per day (Design Lane) ------------------

(6) Total Projected Number of Equivalent 18 kip (80 kN) per year (Design Lane), (5)x365= ----

(7) Growth Rate Projected for Design Period ----------------

(8) Design Life of Pavement for Zero-Maintenance, Years--------

(9) Traffic Summation Factor (Table 2.5)-------------------------

(10) Total Projected Number of 18-kip (80 kN) axles in Design Lane, (6)x(9) = ------------------

Figure A.30 Worksheet for Obtaining the Design Number of 18 kip (80kN) Equivalent Axle Loads.

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C*

Project ______________________________ Date ____________

Location ____

(1) Pavement Type: ____________________________________

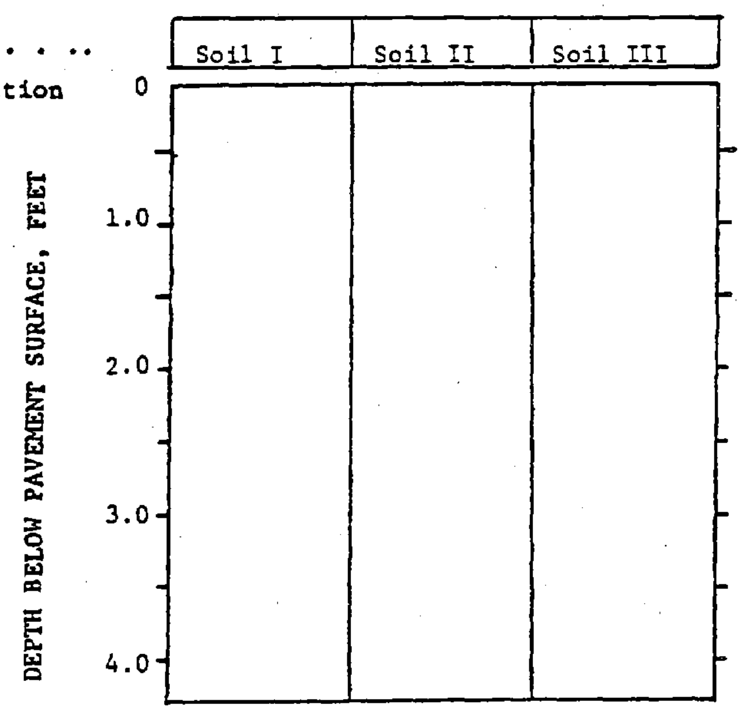
(2) Environmental Region No. (Figure 3.3)... ____________

(3) Asphalt Cement Grade (Figure 3.6). . ______________

(4) Effective Asphalt Concrete Modulus
(Figure 3.7 line 13), psi ______________________

(5) Design Section . . . .

(6) Cross-Section Selection
(Appendix A)



(7) Frost Penetration Below
Pavement Surface (Figure 3.15 -
3.17) feet . . . .

(8) Increased Thickness of Non-
Frost Susceptible Material
(Figures 3.15 - 3.20). . . . . .

1 psi = 6.89 kPa
1 ft = 0.3048 m

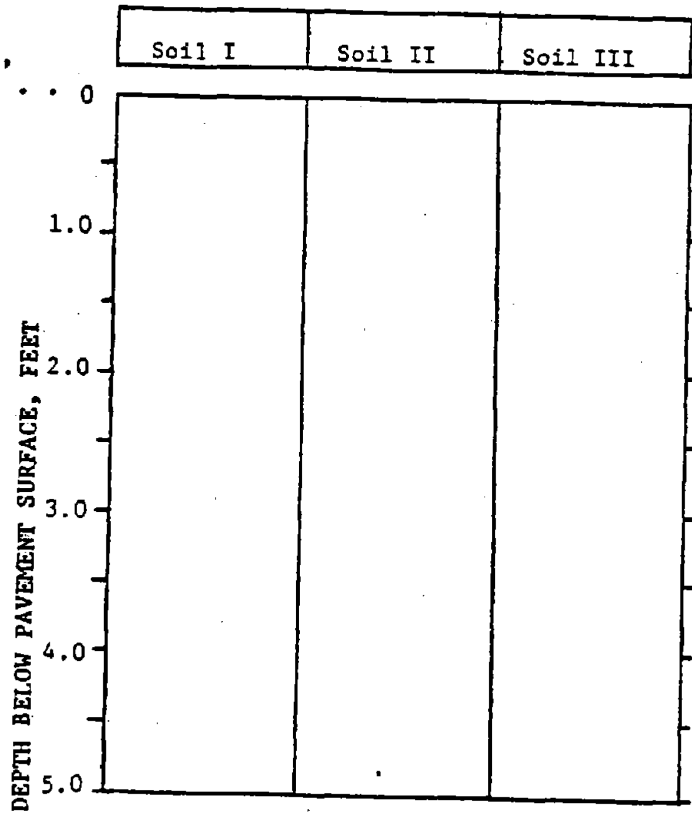
*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure A.31 Worksheet for Determining the Initial Zero-Maintenance Structural Cross-Sections.

PREMIUM PAVEMENT DESIGN

CROSS-SECTION WORKSHEET C*

(9) Cross-Section Thickness Determination, (6), (7), (8) in . . . .



1 ft = 0.3048 m
1 in = 2.54 cm

*Steps (5) through (9) shall be completed for the selected pavement type for each different category of soil data (I, II, or III) as defined in Figure 2.1.

Figure A.32 Worksheet for Determining the Final Zero-Maintenance Structural Cross-Section.

PREMIUM PAVEMENT DESIGN

EFFECTIVE MODULUS WORKSHEET D

Project:____________________ Date:____________________

Location:____

(1) Mean Annual Air Temperature
Worksheet A, °F . . . . ________________

(2) Mean Yearly Temperature Change, °F . . . . ________________

(3) Environmental Region (Figure 3.3) . . . . ________________

(4) Minimum Pavement Temperature, (Figure 3.4, 3.5), °F . . . . ________________

(5) Allowable Minimum Original (Figure 3.6) Penetration . . . . ________________

(6) Asphalt Cement Grade . . . . ________________

(7) Season	(8) Mean Pavement Temperature (Figure 3.8 - 3.12) °F	(9) Asphalt Concrete Modulus (Figure 3.13) psi	(10) Fatigue Factor (Figure 3.14)	(11) (9) x (10)
Fall				
Winter				
Spring				
Summer				
	(12) Total			
	(13) Asphalt Concrete Effective Modulus, psi ($\sum(11) \div \sum(10)$)			

°C = (°F - 32)/1.8 1 psi = 6.89 kPa

Figure A.33 Worksheet for Computing the Asphalt Concrete Effective Modulus.

APPENDIX B

PROCEDURE FOR DETERMINING THE RESILIENT MODULUS OF ELASTICITY OF UNBOUND MATERIALS

GENERAL

The purpose of this test procedure is to determine a modulus of elasticity for unbound soils in a condition that simulates the actual response of the soil to applied wheel loads. The test is similar to the standard triaxial compression test, except that the deviator stress is applied repetitively at several stress levels to model wheel load intensity and duration typically encountered in a pavement under a moving wheel load. A repetitive load triaxial machine should be used since it provides a capability to simulate field conditions. Parameters that are varied include deviator stress, lateral pressure, load period from 1/10th of a second upward, rest period between cycle loads on the specimen, sequence of loading and cycles of loading prior to reading test values.

EQUIPMENT

A triaxial load cell, shown in Figure B.1, is used because it is suitable for simulating a sample of soil in-place under a pavement. The triaxial chamber allows application of a vertical load and lateral pressure to the specimen. The lateral pressure in the cell simulates the resistance of the surrounding soil to lateral displacement under vertical load. The chamber is sealed with o-rings and has access holes through which the lateral or confining pressure can be applied. Loading heads with porous stones are attached at the ends of the specimen. Pore pressure can be monitored and specimens saturated or drained through the porous stones. The vertical load is applied to the loading head through a loading piston which is sealed with o-rings (removed to reduce friction) and guided by ball bearings. The bottom loading head rests on either a load cell or base plate.

The external loading source may be any device capable of providing a variable load of fixed cycle and load duration. These devices may range from single cam-and-switch control of static weights or air pistons to a closed-loop electro-hydraulic system.

A 3 gallon (11.4 l) surge tank can be used to store air at a required pressure for use in the Bellofram for pneumatic loading to reduce surges which could damage the gauges and reduce the flow to the Bellofram. The Bellofram converts a pulse of air pressure to a mechanical load. It contains a piston sealed by a rolling diaphragm to eliminate wall friction.

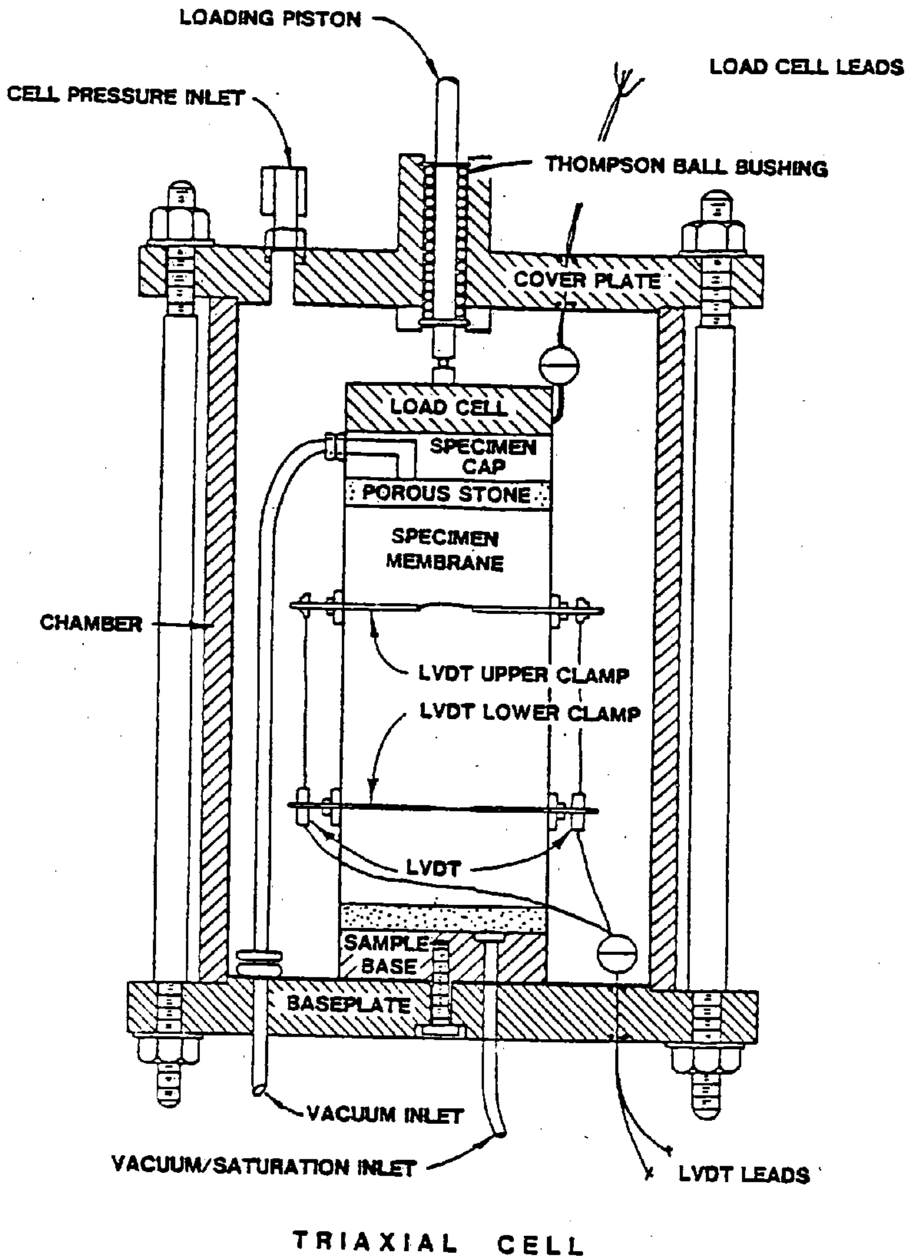


Figure B.1 Triaxial Cell

Pressures in the surge tank and chamber should be monitored by gauges. Two gauges in the surge tank line allow accurate reading of high and low pressure ranges. The pressures can be controlled by regulators.

The deformation measuring equipment consists of linear variable differential transformers (LVDT's) attached to the specimen with a pair of clamps. LVDT's produce electronic signals proportional to the amount of movement in the sample. Two LVDT's are used for the measurement of axial deformation. In addition to the measuring devices, it is also necessary to maintain suitable recording equipment. It is desirable to have simultaneous recording of load and deformation. The number of recording channels can be reduced by wiring the leads from the LVDT's so that only the average signal from each pair is recorded. These signals are conditioned for input to a strip recorder which plots the deformation versus time.

In addition to the equipment described above, the following items are also recommended:

1. A 10- to 30-ton (9 to 27 tonnes) capacity loading machine.

2. Calipers, a micrometer gauge, and a steel rule (calibrated to 0.01 in (0.254 mm).

3. Rubber membranes, 0.01 to 0.025 in (0.254 to 0.635 mm) thick.

4. Rubber o-rings.

5. A vacuum source with a bubble chamber and regulator.

6. A back-pressure chamber with pressure transducers.

7. A membrane stretcher.

8. Porous stones.

SAMPLE PREPARATION

Resilient modulus testing may be conducted on undisturbed specimens representing the natural state, specimens compacted to optimum density or specimens compacted to some intermediate density. Specimens may be delivered to the laboratory as undisturbed specimens wrapped to avoid moisture change and packed to protect the structural integrity of the specimen or as disturbed sample or to be compacted at an appropriate density.

Various diameter soil specimens may be used in this test but the recommended specimen diameter is 2.5 to 3.0 in (6.35 to 7.62 cm) or approximately four times maximum aggregate size. The specimen height should be at least twice the diameter. A 3-inch (7.6 cm) thin-wall tube should be used for collection of undisturbed samples whenever possible.

If the material to be tested is to be recompacted as an improved subgrade, the density must be furnished or determined. This test density should be consistent with the density control planned in the field; i.e., if 95 percent of modified AASHTO compaction is to be specified, the optimum density can be established using modified AASHTO compactive energy and compacting the sample to 95 percent of the amount. If some natural density is desired, it may be specified and the samples can be compacted to that amount. Samples to be compacted in the laboratory may be sent in disturbed state in bags. Four pounds (1.82 kg) is sufficient for a single triaxial specimen.

Soil specimens should be tested at moisture contents that exist under the pavement. For soils two feet (0.61 m) or more below the subgrade surface, specimens should be tested at the existing moisture content. For specimens taken 0-2 feet (0-.61 m) below the subgrades surface, the moisture content should be increased to account for such effects as hydrogenesis. This can be done by placing the compacted or undisturbed specimens in a moist environment for approximately 3 days or until the moisture content stabilizes.

TEST PROCEDURE

Once the soil specimen has been prepared and a membrane applied, the specimen is placed on the triaxial cell base and the LVDT's clamped in place to measure vertical deformation of the middle third of the specimen. A vacuum is then applied to the specimen with a vacuum chamber to insure that there are no leaks in the membrane. The triaxial cell is then assembled and placed in the triaxial machine. The same is conditioned by applying 1,000 cycles of a 1 psi (6.89 kPa) deviator stress and 7 psi (48.2 kPa) lateral pressure. All measuring equipment should then be zeroed, before specimen testing begins.

For soils located above the existing water table, a drained test should be conducted but for soils located below the water table an undrained test should be used.

Resilient properties are highly dependent on the magnitude of the deviator stress. It is therefore necessary to conduct the tests using a range in deviator stress and confining pressure. The following values are recommended:

Confining Pressure: 1, 4, 7 psi (6.9, 27.6, 48.2 kPa)

Deviator Stress: 1, 2, 5, 10, 20 psi (6.9, 13.8, 34.5, 68.9, 137.8 kPa)

Begin the test procedure by applying 200 repetitions of a deviator stress of 1 psi (6.89 kPa) and a confining pressure of 7 psi (48.2 kPa) until the resilient deformation stabilizes, record load and corresponding cyclic deformation. Increase the deviator stress and record the results at 200 stress repetitions for each deviator stress level listed above. An example of the data form for recording results of the modulus test is shown in Figure B.2. Reduce the confining pressure to 4 and 1 psi (27.6 and 6.9 kPa) and repeat the same procedure.

TEST RESULTS

The recorded cyclic deformation plus the established deviator stress and specimen dimensions provide all the information necessary to calculate the resilient modulus at any load level. A resilient modulus is calculated as follows:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{B.1}$$

where:

M_R = Resilient Modulus

σ_d = Deviator Stress

ε_r = Resilient Strain

The resilient modulus, M_R, is the ratio of stress to resilient strain taken after an appropriate number of cycles of loading and at an appropriate level of vertical stress. Calculations can be recorded on the data form shown in Figures B.2 and B.3.

The resilient moduli at the various load levels is then plotted on log paper to give clear insight as to the variation in resilient modulus with stress intensity and confining pressure as illustrated in Figure B.4. A graph of this type should be prepared for each soil in each boring hole, so that all soil information at a particular location can be compared.

EVALUATION OF TEST RESULTS

In order to obtain a reliable resilient modulus using triaxial tests, confining pressures and load associated deviator stresses must be based on existing in-situ pressure at the mid-depth of each layer to be tested. To determine these values, densities and layer thicknesses of the pavement structure must be estimated. The following procedure can be used to determine a resilient modulus of elasticity that is representative of the particular subgrade soil under the pavement structure.

RESILIENT MODULUS TEST

IDENTIFICATION:

Job ______________________________

Bore Hole, Station or Sample Number __________ Depth __________

UNDISTURBED SPECIMEN ______________________________

COMPACTED SPECIMEN ____________________ Date __________

Standard Proctor __________ Modified AASHO ________ Other __________

Remarks ______________________________

SPECIMEN DATA

Average diameter (in) ______________________________

Average Height (in) ______________________________

Area (in^2) ______________________________

Volume (cft) ______________________________

MOISTURE DATA AT TESTING:

Weight of Sample, membrane and end plates ______________

Weight of membrane and end plates ______ Weight of wet sample ______

Container # __________ Wt. ______________

Wt. wet soil and cont. __________ Wt. dry soil and cont. __________

Wt. Dry Soil ________________ Wt. of Water ________________

Moisture Content ______________________________

Wet Density (pcf) ______________ Dry Density (pcf) ______________

TEST DATA

Loading time/cycle __________ Unloaded time/cycle ______________

Gage length (in) __________ Undrained ________________

DATE TESTED ____________________ TESTED BY ______________

1 in = 2.54 cm   1 ft = 0.3048 m   1 lb = 0.454 kg

Figure B.2 Example Data Form for Recording Sample Data for the Resilient Modulus Test Data.

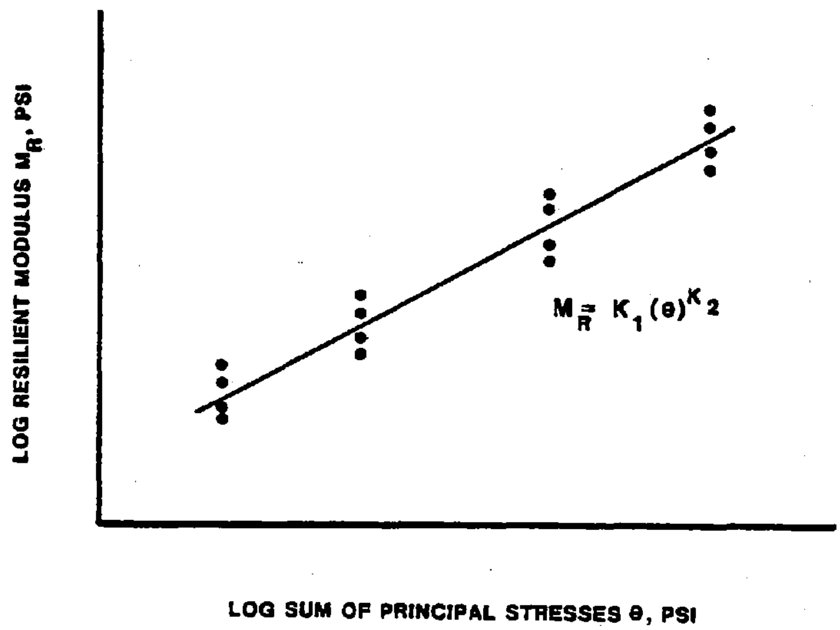
RESILIENT MODULUS TEST DATA FORM

σ_3 (psi)	σ_d (psi)	TIME / N	Trace (in)	Calibration Factor	RESILIENT		
					Vertical Deformation in x 10⁻	Strain in/in x 10⁻	Modulus M_R psi x 10

Remarks: Gage Length: Area:

1 psi = 6.89 kPa
1 in = 2.54 cm

Figure B.3 Example Data Form for Recording Resilient Modulus Test Results.



1 psi = 6.89 kPa

Figure B.4 Presentation of Test Results of the Resilient Modulus Test.

1. Select an initial estimate of the resilient modulus for the subgrade soil. Figure B.5 can be used as a guide for the first estimate.

2. Select a particular cross-section from Appendix A for the estimated resilient modulus derived in step 1.

3. Compute the in-situ confining pressure of the subgrade soil. Confining pressures are based on load computations made with elastic layer theory and estimated unit weights for each layer in the pavement structure. The confining pressure for each subgrade layer can be calculated using equation B.2.

$$\sigma_3 = \sigma_3' - p_n \qquad (B.2)$$

where:

$$p_n = K_o \left[1/2\, D_n \gamma_n + \sum_{i=1}^{n-1} \gamma_i D_i \right] \qquad (B.3)$$

σ_3 = In-situ Confining pressure simulating in-field conditions of layer n.

σ_3' = Load related lateral stress computed with elastic layer theory at mid-depth of layer n. Table B.1 can be used to estimate the load related lateral stresses.

p_n = At-rest earth pressure at mid-depth of layer n.

γ_i = Unit weight of layer i

D_i = Thickness of layer i

γ_n = Unit weight of layer n

D_n = Thickness of layer n

K_o = The at-rest earth pressure coefficient.

The at-rest earth pressure coefficient is dependent on the type of material being evaluated. For cohesionless soils, K_o can be estimated using the following equation:

$$K_o = \frac{\nu}{1-\nu} \qquad (B.4)$$

where:

ν = Poisson's Ratio

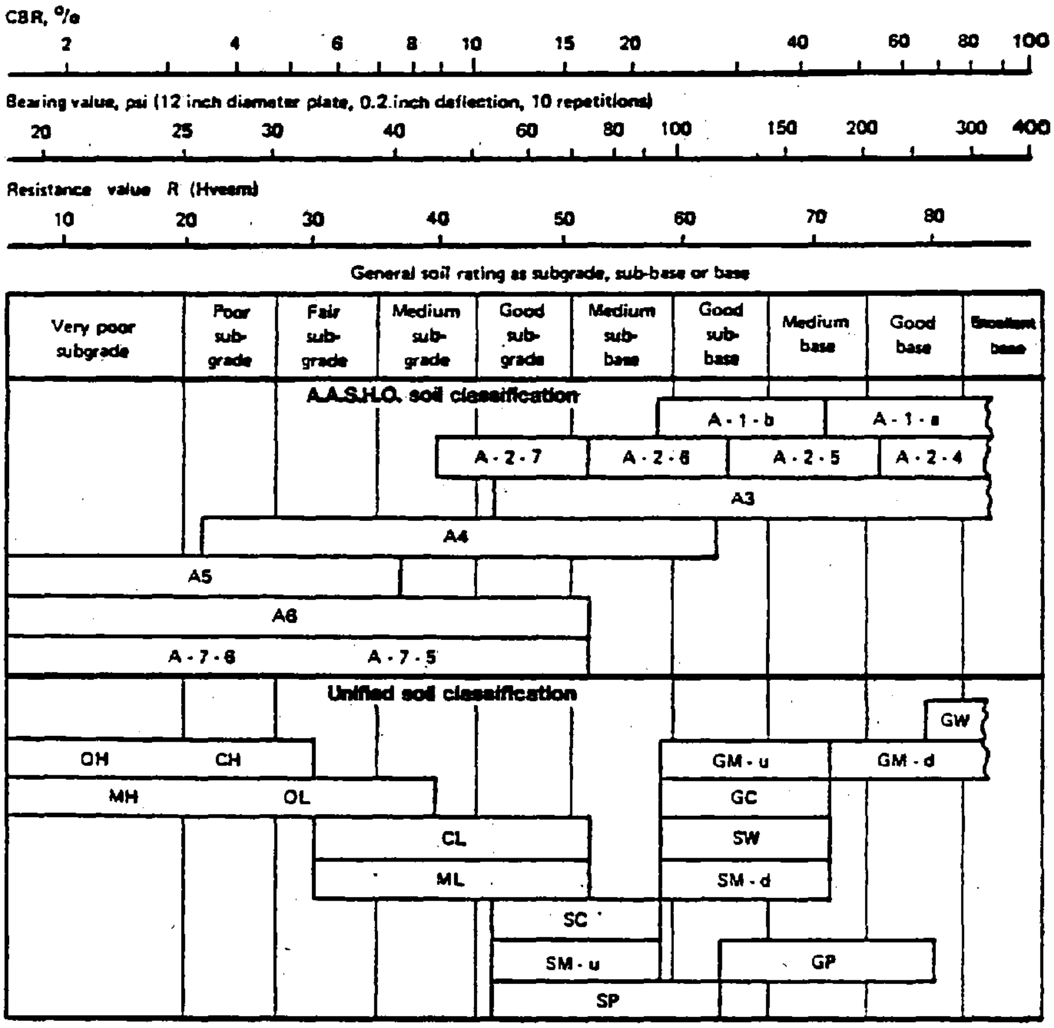


Figure B.5 Estimate of the Resilient Modulus of Unbound Subgrade Materials Using Soil Classification.

TABLE B.1. ESTIMATED WHEEL LOAD LATERAL STRESSES COMPUTED WITH ELASTIC LAYER THEORY.

Subgrade Resilient Modulus, psi	Wheel Load Lateral Stresses, psi	
	Flexible Pavements	Composite Pavements
20,000	1	.5
10,000	.5	.3
6,000	-	- *
3,000	-	-
2,000	-	-

* Insignificant value when compared to the at-rest earth pressures.

Note: Above values are reasonable estimates for the expected thicknesses and material properties.

1 psi = 6.89 kPa

For cohesive soils K_o can be derived from:

$$K_o = 1 - \sin \emptyset_e$$

where

$\emptyset_e$ = Angle of shearing resistance

Therefore, using equation B.2 the in-situ confining pressure can be computed.

4. Compute the in-situ deviator stress of the subgrade soil. Load associated deviator stresses can be calculated using equation B.5.

$$\sigma_d' = \sigma_1 - 2\sigma_3 \qquad \text{(B.5)}$$

where:

σ_d' = Load related deviator stress, Table B.2

σ_1 = Load related vertical stress computed from elastic layer theory.

Based on load computations made with elastic layer theory, deviator stresses can be computed at mid-depth of each layer. Combining these load related deviator stresses with the existing or at-rest stresses results in an estimation of the actual in-field condition. This can be represented by equation B.6.

$$\sigma_d = \sigma_d' + p_o - p_n \qquad \text{(B.6)}$$

where:

σ_d = In-situ deviator stress simulating in-field conditions.

p_o = Overburden pressure of the pavement structure.

and since:

$$p_o = \frac{p_n}{K_o} \qquad \text{(B.7)}$$

Equation B.6 reduces to:

$$\sigma_d = \sigma_d' + p_n \left(\frac{1}{K_o} - 1\right) \qquad \text{(B.8)}$$

Table B.2. ESTIMATED DEVIATOR STRESSES COMPUTED WITH ELASTIC LAYER THEORY.

Subgrade Resilient Modulus, psi	Wheel Load Related Deviator Stress, psi: Flexible Pavements	Wheel Load Related Deviator Stress, psi: Composite Pavements
20,000	6	2
10,000	4	1
6,000	1	1
3,000	- *	-
2,000	-	-

* Insignificant value when compared to the at-rest earth pressures.

Note: Above values are reasonable estimates for the expected thicknesses and material properties.

1 psi = 6.89 kPa

Therefore, using equation B.8, the in-situ deviator stress can be computed.

5. Using the confining pressure and deviator stress from steps 3 and 4, estimate the resilient modulus from the laboratory test results and plot as shown in Figure B.4.

6. If the resilient modulus predicted in step 5 is not equal to the modulus selected in step 1. Use the modulus in step 5 and repeat steps 2-6 until the resilient moduli from steps 1 and 5 are equal. Once this occurs the resilient modulus of the subgrade material has been determined.

APPENDIX C

AASHTO EQUIVALENCY FACTORS FOR
A TERMINAL PSI OF 3.0 (REF. 13)

TABLE C.1 FLEXIBLE PAVEMENTS - AASHTO EQUIVALENCY FACTORS FOR SINGLE AXLE LOADS FOR A TERMINAL SERVICEABILITY INDEX OF 3.0.

Axle Load Kips	Structural Number SN					
	1.	2.	3.	4.	5.	6.
2.	.00077	.00086	.00056	.00032	.00022	.00018
4.	.00448	.00833	.00619	.00364	.00249	.00205
6.	.01358	.03035	.02810	.01763	.01232	.01019
8.	.03536	.06973	.07966	.05532	.04007	.03358
10.	.08230	.13182	.16846	.13211	.10078	.08623
12.	.17278	.23075	.29639	.26052	.21222	.18692
14.	.33220	.38827	.46788	.44693	.39154	.35780
16.	.59398	.63292	.69561	.69302	.65188	.62198
18.	1.00054	1.00059	1.00069	1.00071	1.00065	1.00060
20.	1.60421	1.53539	1.41120	1.37673	1.44051	1.51033
22.	2.46818	2.29044	1.96132	1.83463	1.97237	2.16205
24.	3.66737	3.32873	2.69130	2.39456	2.59896	2.96113
26.	5.28930	4.72384	3.64786	3.08242	3.32754	3.90939
28.	7.43497	6.56064	4.88463	3.92901	4.17118	5.00782
30.	10.21968	8.93606	6.46271	4.96971	5.14893	6.25942
32.	13.77389	11.95976	8.45109	6.24441	6.28526	7.67141
34.	18.24401	15.75481	10.92719	7.79758	7.60949	9.25653
36.	23.79321	20.45840	13.97724	9.67858	9.15523	11.03353
38.	30.60224	26.22248	17.69675	11.94187	10.96005	13.02709
40.	38.87022	33.21445	22.19091	14.64728	13.06535	15.26735

1 in = 2.54 cm
1 kip = 4.44 kN

TABLE C.2. FLEXIBLE PAVEMENTS - AASHTO EQUIVALENCY FACTORS FOR TANDEM AXLE LOADS FOR A TERMINAL SERVICEABILITY INDEX OF 3.0.

Axle Load Kips	Structural Number SN					
	1.	2.	3.	4.	5.	6.
10.	.01103	.02373	.01955	.01181	.00816	.00672
12.	.08168	.04175	.03865	.02424	.01695	.01401
14.	.03058	.06566	.06809	.04477	.03179	.02644
16.	.04864	.09592	.10958	.07610	.05511	.04619
18.	.07523	.13378	.16401	.12094	.08971	.07589
20.	.11321	.18132	.23172	.18172	.13862	.11861
22.	.16601	.24138	.31281	.26040	.20599	.17777
24.	.23767	.31741	.40769	.35836	.29192	.25712
26.	.33286	.41344	.51736	.47637	.40228	.36058
28.	.45696	.53408	.64359	.61478	.53859	.49217
30.	.61606	.68453	.78898	.77370	.70288	.65590
32.	.81705	.87061	.95684	.95328	.89669	.85556
34.	1.06761	1.09882	1.15116	1.15393	1.12101	1.09467
36.	1.37628	1.37636	1.37649	1.37651	1.37643	1.37636
38.	1.75251	1.71117	1.63796	1.62244	1.66322	1.70327
40.	2.20666	2.11199	1.94117	1.89375	1.98148	2.07753
42.	2.75006	2.58833	2.29226	2.19307	2.33134	2.50073
44.	3.39508	3.15059	2.69788	2.52361	2.71308	2.97399
46.	4.15511	3.81003	3.16521	2.88912	3.12730	3.49800
48.	5.04461	4.57881	3.70200	3.29382	3.57498	4.07315

1 in = 2.54 cm
1 kip = 4.44 kN

TABLE C.3. RIGID PAVEMENTS - AASHTO EQUIVALENCY FACTORS FOR SINGLE AXLE LOADS FOR A TERMINAL SERVICEABILITY INDEX OF 3.0.

Axle Load Kips	Slab Thickness D - Inches					
	6.	7.	8.	9.	10.	11.
2.	.00029	.00024	.00022	.00021	.00020	.00020
4.	.00303	.00253	.00228	.00217	.00213	.00211
6.	.01430	.01195	.01077	.01029	.01009	.01000
8.	.04514	.03800	.03436	.03283	.03220	.03192
10.	.11098	.09513	.08652	.08284	.08131	.08065
12.	.22798	.20189	.18581	.17869	.17569	.17438
14.	.40810	.37804	.35499	.34410	.33940	.33733
16.	.66020	.64017	.61868	.60742	.60237	.60011
18.	.99967	.99966	.99965	.99964	.99964	.99964
20.	1.45613	1.46699	1.51545	1.55121	1.56975	1.57857
22.	2.07237	2.06062	2.17859	2.28849	2.35210	2.38396
24.	2.90004	2.81304	3.00184	3.23156	3.38355	3.46506
26.	3.99726	3.77040	4.00623	4.39550	4.69534	4.87033
28.	5.42837	4.98897	5.22677	5.79577	6.31166	6.64422
30.	7.26449	6.53219	6.71340	7.45562	8.25131	8.82439
32.	9.58422	8.46940	8.52836	9.41221	10.53279	11.44077
34.	12.47428	10.87580	10.74303	11.71893	13.18121	14.51715
36.	16.03000	13.83293	13.43570	14.44431	16.23478	18.07564
38.	20.35580	17.42914	16.69064	17.66908	19.74872	22.14312
40.	25.56553	21.76023	20.59798	21.48333	23.79586	26.75787

1 in - 2.54 cm
1 kip = 4.44 kN

TABLE C.4. RIGID PAVEMENTS - AASHTO EQUIVALENCY FACTORS FOR TANDEM AXLE LOADS FOR A TERMINAL SERVICEABILITY INDEX OF 3.0.

Axle Load Kips	Slab Thickness D - Inches					
	6.	7.	8.	9.	10.	11.
10.	.01773	.01483	.01338	.01277	.01252	.01242
12.	.03586	.03015	.02724	.02603	.02552	.02531
14.	.06557	.05561	.05040	.04820	.04729	.04689
16.	.11059	.09512	.08661	.08296	.08144	.08078
18.	.17438	.15298	.14029	.13473	.13240	.13138
20.	.25963	.23365	.21646	.20869	.20539	.20395
22.	.36829	.34126	.32050	.31069	.30645	.30459
24.	.50218	.47927	.45789	.44716	.44242	.44032
26.	.66408	.65032	.63385	.62492	.62086	.61904
28.	.85861	.85649	.85299	.85090	.84991	.84946
30.	1.09257	1.09997	1.11907	1.13183	1.13815	1.14109
32.	1.37469	1.38393	1.43506	1.47390	1.49431	1.50407
34.	1.71518	1.71331	1.80343	1.88255	1.92703	1.94901
36.	2.12536	2.09508	2.22679	2.36223	2.44455	2.48679
38.	2.61747	2.53825	2.70866	2.91659	3.05437	3.12831
40.	3.20456	3.05356	3.25412	3.54874	3.76309	3.88417
42.	3.90053	3.65311	3.87026	4.26182	4.57630	4.76440
44.	4.72019	4.35011	4.56632	4.05967	5.49863	5.77823
46.	5.67930	5.15862	5.35357	5.94750	6.53408	6.93384
48.	6.79464	6.09354	6.24504	6.93239	7.68649	8.23831

1 in = 2.54 cm
1 kip = 4.44 kN

APPENDIX D

PROCEDURE TO ESTIMATE THE DYNAMIC MODULUS OF ELASTICITY OF ASPHALT CONCRETE MIXTURES

It has generally been recognized that the stress-strain response of bituminous concrete, for a specific mixture design, is a function of temperature as well as the rate of loading. Tests to measure this dynamic modulus as a function of temperature are uncommon especially for design purposes. Therefore, estimates of this modulus may have to be determined using indirect methods. Although several methods exist, a regression equation developed by Witczak (Ref. 15) was selected to characterize the asphalt concrete material as a function of temperature. This equation was developed using a comprehensive set of test data and has been checked for accuracy using measured laboratory results. The regression equation has an $R^2 = .969$ and a standard error for residuals equal to .08866. The regression equation is shown as equation D.1.

$$\text{Log } E^* = .553833 + .028829\,(P_{200})\,f^{-.17033}$$
$$- .03476V_v + .070377(\eta_{10^6,70})$$
$$+ .000005\left[t_p^{(1.3 + .49825 \text{ Log } f)}P_{ac}^{0.5}\right]$$
$$- .00189\left[t_p^{(1.3 + .49825 \text{ Log } f)}P_{ac}^{0.5}(f^{-1.1})\right]$$
$$+ .931757f^{-.02774} \qquad \text{D.1}$$

where:

$$\eta_{(10^6,\ 70)} = 29508.2\ (\text{Pen}_{77})^{-2.1939} \qquad \text{D.2}$$

= Viscosity at 70°F, 10^6 poises

$$P_{ac} = 0.483V_{be} \qquad \text{D.3}$$

= Percent asphalt by weight of mix, %

E^* = Dynamic modulus of asphalt concrete mixes, $x10^5$ psi

P_{200} = Percent aggregate passing No. 200 sieve, %

V_v = Percent air voids, %

t_p = Test temperature of the asphalt concrete, °F

f = Loading frequency, Hertz (cps)

Pen_{77} = Penetration at 77° F, mm.

V_{be} = Effective bitumen volume, %

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