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A PROPOSED FULL-DEPTH ASPHALT CONCRETE THICKNESS DESIGN PROCEDURE

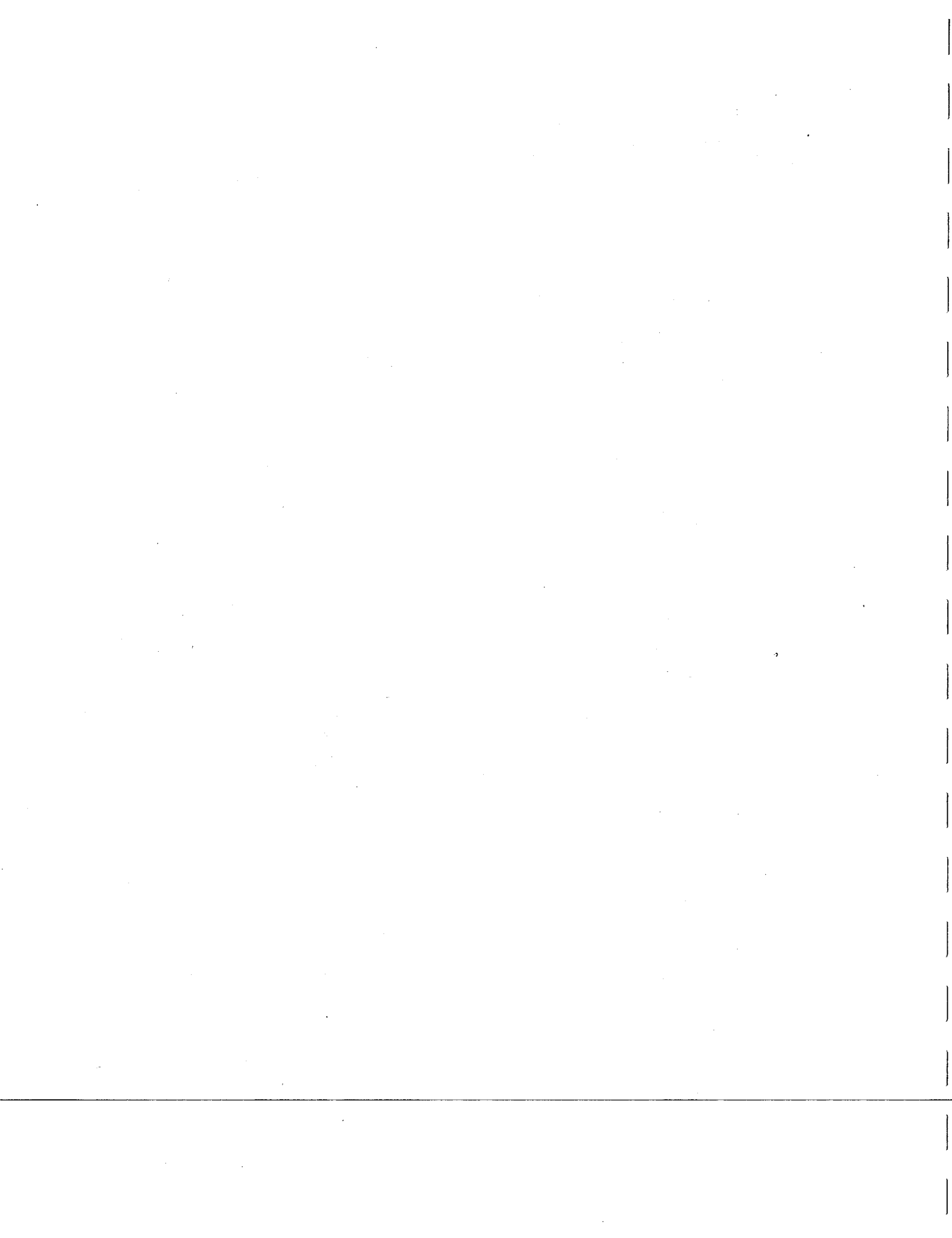
Report Preparation by
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A Report of the Investigation of
Mechanistic Evaluation of Illinois
Flexible Pavement Design Procedures
Project IHR-510
Illinois Cooperative Highway and Transportation Research Program

A Cooperative Investigation
conducted by the
TRANSPORTATION RESEARCH LABORATORY
DEPARTMENT OF CIVIL ENGINEERING
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

in cooperation with the
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16. Abstract The basic concepts and the development of a proposed FULL-DEPTH ASPHALT CONCRETE THICKNESS DESIGN PROCEDURE are presented. Traffic (IDOT traffic factor), subgrade modulus (fine-grained soils, granular type soils), location in the state (pavement temperature effects), asphalt cement grade (AC-10, AC-20), and design reliability factors are considered. ILLI-PAVE based design algorithms are utilized in the procedure. Asphalt concrete fatigue consumption is the design criteria. A "Design Time" concept is used to consider seasonal temperature effects. The procedure can be easily modified to accommodate conditions other than those considered in the procedure presented in Appendix A.			
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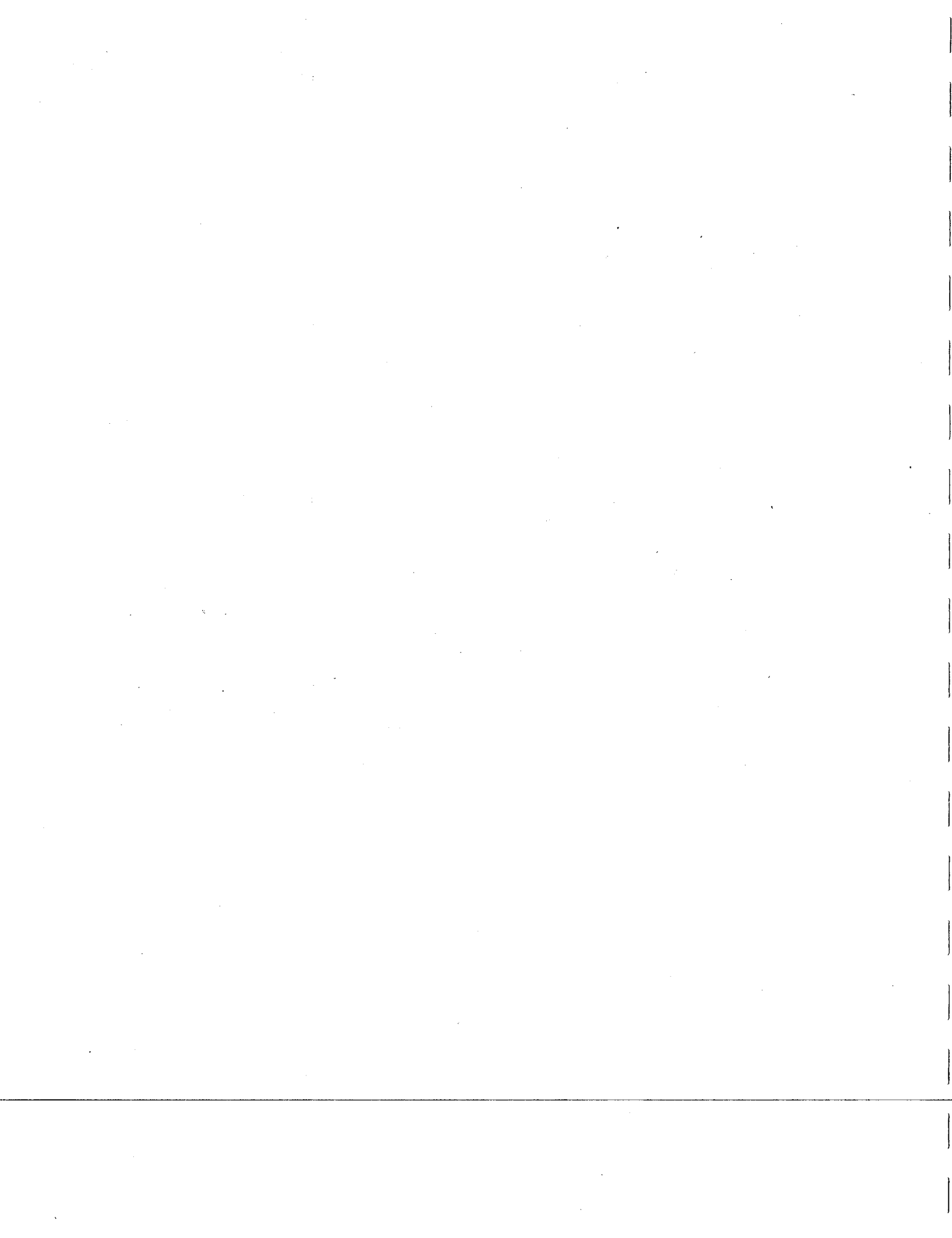


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MECHANISTIC EVALUATION OF ILLINOIS
FLEXIBLE PAVEMENT DESIGN PROCEDURES

Project Advisory Committee

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Graduate Research Assistants (K. Cation, C. Stenzel, D. Lippert, D. Tappendorf) contributed to the study and development of various components of the Proposed Full-Depth Asphalt Concrete Thickness Design Procedure. Relevant studies are summarized in an unpublished IHR-510 "Information Report" prepared by K. Cation, M. R. Thompson, and C. Stenzel.

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

This report does not constitute a standard, specification or regulation.

INTRODUCTION

The various components of a mechanistic design procedure for flexible pavements are shown in Figure 1. A comprehensive mechanistic design procedure for full-depth Asphalt Concrete (AC) pavements has been developed in IHR-510. The proposed procedure is based on resilient soil and material testing procedures, the ILLI-PAVE structural model, and design algorithms (Table 1) developed from an extensive ILLI-PAVE data base. Reference 1 is a detailed consideration of ILLI-PAVE mechanistic design concepts.

A typical full-depth AC pavement is shown in Figure 2. The primary failure modes for a full-depth AC pavement are AC rutting, subgrade rutting, and AC fatigue cracking. In the proposed procedure, it is assumed that AC rutting and thermal cracking are adequately considered in material selection and AC mixture design procedures and policies. Subgrade rutting can be controlled by limiting the deviator stress (See Figure 2) at the AC-subgrade interface to an acceptable level. AC fatigue cracking is related to the maximum tensile strain (ϵ_{AC} in Figure 2) at the bottom of the AC layer. Full-depth AC pavement thickness requirements for the design traffic levels considered (> 500,000 18k SAL) are sufficient to control subgrade rutting. Thus, the governing design criterion is AC tensile strain. Reduced ϵ_{AC} corresponds to increased fatigue life.

The AC strain (ϵ_{AC}) can be determined using ILLI-PAVE. Required ILLI-PAVE inputs are AC thickness (T_{AC}), AC dynamic modulus (E_{AC}) and subgrade resilient modulus properties. For a given T_{AC} , the asphalt concrete modulus (E_{AC}) is the major factor influencing ϵ_{AC} . Subgrade modulus effects on ϵ_{AC} are small.

E_{AC} varies over a wide range of values during the year. During cold periods E_{AC} is very high (> 2000 ksi). During the summer period it is very low (100 - 250 ksi). E_{AC} values (and thus fatigue life) will also show a wide range during the year. A "DESIGN TIME" concept is utilized to account for the seasonal effects.

In this report the basic concepts of the proposed FULL-DEPTH ASPHALT CONCRETE THICKNESS DESIGN PROCEDURE are summarized. Detailed information is available in previous IHR-510 publications and reports. The proposed procedure is presented in APPENDIX A.

THE DESIGN TIME CONCEPT

In the DESIGN TIME concept, pavement fatigue life (traffic applied throughout the year, variable E_{AC} , variable subgrade modulus) can be predicted based on the conditions (E_{AC} , subgrade modulus) of only one particular time (the DESIGN TIME) of the year. A fatigue transfer function is used to relate fatigue failure to the maximum tensile strain (ϵ_{AC}) in the AC layer. A comprehensive consideration of AC fatigue is presented in an IHR-510 report (1). The general relationship for monthly fatigue life based on a crack initiation failure criterion is:

$$N_a = K \left(\frac{1}{\epsilon_{AC}} \right)^n$$

where:

N_a = No. of load applications to initiate a fatigue crack for the conditions given for month i .

ϵ_{AC} = Maximum tensile strain in the AC layer for month i conditions.

K, n = Factors depending on the composition and properties of the AC mixture. In this study, K was equal to 5×10^{-6} , and the value of n was 3.0. These values are typical for IDOT (Illinois Department of Transportation) Class I type AC mixtures. K and n values for other mixture types can be established based on mixture composition (2) and AC split tensile strength characteristics (3).

In the IHR-510 study (1), a method for predicting the number of load repetitions to failure, N_f , based on Miner's Hypothesis was developed. According to Miner's theory of cumulative fatigue damage, failure will occur

when:

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

where:

- n = The loading of cycles applied at a particular strain level;
- N_i = The number of loading cycles to failure for the particular strain level.

For a given pavement structure, the following equation can be used to predict the number of load applications to failure, N_f.

$$N_f = \frac{12}{\sum_{i=1}^n \left(\frac{1}{N_a}\right)}$$

where:

- N_a = the number of load repetitions to failure for the conditions of month i.
- N_f = The number of load applications to failure when traffic is applied throughout the 12 months of the year.

A plot illustrating the DESIGN TIME concept is shown in Figure 3. There are two time periods (Spring/Fall) when N_f is equal to the fatigue life (N_a) predicted for the time period. In IHR-510, the Spring period is utilized since subgrade strength is normally lower at that time.

Northern, Central, and Southern Illinois conditions were considered in a comprehensive DESIGN TIME study. Mixture type (AC-10, AC-20), pavement thickness, and subgrade modulus effects were considered. Typical plots are shown in Figures 4, 5, and 6.

The study results indicated DESIGN TIME is only sensitive to location.

The DESIGN TIMES are: Northern Illinois, end-of-May to early June; Central Illinois, mid to late May; and Southern Illinois, mid-May.

The DESIGN TIME concept simplifies the full-depth AC thickness design process. Predicted pavement fatigue life for DESIGN TIME conditions (E_{AC} , subgrade modulus) approximates N_f (pavement fatigue life based on "monthly conditions" and Miner's cumulative damage model).

ASPHALT CONCRETE

A constant linear resilient modulus is used to characterize the AC layer. AC modulus/temperature relations must be considered in selecting modulus values. AC modulus/pavement temperature relations were developed based on the Asphalt Institute (AI) modulus prediction equation (4) and the SHELL (5) procedure for predicting pavement temperature.

The AI equation (shown in Appendix B) was developed from an extensive lab testing data base. The equation does not directly account for temperature susceptibility but the data base included asphalt binders from a variety of locations. Thus, the effects of temperature susceptibility are indirectly accounted for. A recent paper by Miller, Uzan, and Witczak (6) indicated that the equation is, "highly satisfactory for dense-graded crushed stone and gravel mixes". Field core modulus data developed in the Illinois Department of Transportation's Black Base study indicated the AI equation adequately predicted AC stiffness trends. The AI equation was utilized to predict AC modulus-temperature relations for Illinois DOT Class I type mixes (AC-10 and AC-20 asphalts). The following input values were used:

Asphalt Viscosity. Representative values were used for absolute viscosity of two different grades of asphalt (4):

<u>Asphalt Grade</u>	<u>Viscosity</u>	<u>Estimated</u>
	(70°F, 10 ⁶ poises)	Penetration
		(@ 77°F)
AC-10	1.0	110
AC-20	2.0	80

Frequency When a moving wheel load approaches and departs from a given point in a pavement, that point is subjected to a particular loading time duration. For mixed traffic conditions and different pavement thicknesses, a loading frequency of 10 Hz is appropriate (4).

Mixture Variables Asphalt content (P_{AC}), percent aggregate passing #200 sieve (P_{200}) and percent air voids (V_v) are also inputs to the AI equation. Mixture data for past IDOT construction indicated the following values are representative.

$$P_{AC} = 5\%$$

$$P_{200} = 5\%$$

$$V_v = 2\%$$

AC Mixture Temperature

The Shell air-mix temperature relationship (5) was used to relate mean monthly air temperatures (MMAT) to AC pavement temperatures. An average pavement thickness of 12 inches was used in this study. The effect of pavement thickness on mix temperature is very small, especially at lower air temperatures. Figure 7 is the MMAT-AC temperature relation utilized in this study. A mix temperature of 30°F was assigned to any MMAT less than 30°F (a conservative procedure).

Figure 8 shows E_{AC} - temperature relations for AC-10 and AC-20 Class I type mixtures. E_{AC} - temperature relations can easily be established for other AC mixtures (variable P_{AC} , P_{200} , V_v) by using the Asphalt Institute equation.

SUBGRADE SOIL CHARACTERIZATION

General

Soil resilient behavior is an important property for pavement analysis and design. A commonly used measure of resilient response is the "resilient modulus", defined by:

$$E_R = \sigma_D / \epsilon_r$$

where:

- E_R : resilient modulus;
- σ_D : repeated deviator stress;
- ϵ_r : recoverable axial strain.

Repeated unconfined compression or triaxial testing procedures are often used to evaluate the resilient moduli of fine grained soils and granular materials. Resilient moduli are stress dependent: fine-grained soils experience resilient modulus decreases with increasing stress, while granular materials stiffen with increasing stress level.

Fine-Grained Soils

An arithmetic stress dependent behavior model adequately describes the stress softening behavior of fine-grained soils. The model is demonstrated in Figure 9. Extensive resilient laboratory testing, nondestructive pavement testing, and pavement analysis and design studies at the University of Illinois have indicated that the arithmetic model is adequate for flexible pavement analysis and design activities.

In the arithmetic model, the value of the resilient modulus at the break-point in the bilinear curve, E_{Ri} (Figure 9) is a good indicator of a soil's resilient behavior. The slope values, K_1 and K_2 , are less

variable and influence pavement structural response to a smaller degree than E_{Ri} . Thompson and Robnett (7) developed simplified procedures for estimating the resilient behavior of fine-grained soils based on soil classification, soil properties, and moisture content.

Four fine-grained subgrade types (very soft, soft, medium, and stiff) were considered in the development (1) of the ILLI-PAVE algorithms. Pertinent subgrade properties and characteristics are summarized in Table 2. Resilient moduli-repeated deviator stress level relations used in the ILLI-PAVE model are shown in Figure 10.

Granular Materials

Granular materials stiffen as the stress level increases. Repeated load triaxial testing is used to characterize the resilient behavior of granular materials. Resilient modulus is a function of the applied stress state:

$$E_R = K\theta^n$$

where:

E_R = resilient modulus

K, n = experimentally derived factors

θ = first stress invariant = $\sigma_1 + \sigma_2 + \sigma_3$

(note: $\theta = \sigma_1 + 2\sigma_3$ in a standard triaxial compression test)

Rada and Witczak (8) have summarized and statistically analyzed extensive published resilient moduli data for a broad range of granular materials. The average values and ranges for K and n are presented in Table 3 and Figure 11 for several granular materials and coarse-grained soils. The relation between K and n developed by Rada and Witczak is shown in Figure 12.

Sandy/granular subgrades are not common in Illinois. Resilient testing data for typical Illinois sandy subgrade soils are sparse. Structural responses for typical full-depth AC pavements on sandy subgrades were determined using the ILLI-PAVE computer model. Granular subgrade resilient properties were estimated from available data in the literature and Minnesota DOT FWD deflection data. The "granular subgrade" condition was modeled as:

- a) Upper 15 inches - "stress hardening" sand

$$E_R = 2000 \sigma^{0.6}; \text{ cohesion} = 0; \phi = 30^\circ$$

(E_R and σ in psi)

- b) Remainder of subgrade depth modeled as a "constant modulus"

material - $E_R = 20$ ksi

The estimated values are conservative. The granular subgrade modelling can be refined as falling weight deflectometer data and/or improved laboratory testing information become available.

DESIGN RELIABILITY CONSIDERATIONS

Pavement response and performance data demonstrate that "pavement life" is not a "fixed value", but shows considerable variability (i.e. "all of the pavement" does not "fail" at the same number of load applications).

Statistical analysis of pavement surface deflection data indicate typical coefficient of variation values ((standard deviation/average) x 100) are in the range of 15% - 25%.

Pavement fatigue life has been correlated with surface deflection. In fact, pavement life-deflection relations have been widely utilized in various pavement analysis and design problems.

Based on the IHR-510 algorithm relating asphalt concrete strain to surface deflection and the IHR-510 proposed AC fatigue response, a relation between pavement fatigue life and deflection was established.

$$N_{18} = \frac{5.6 \times 10^{11}}{\Delta^{4.6}}$$

N_{18} = Number of 18k SAL to "fatigue" failure
 Δ = Surface Deflection for 18k moving axle load, mils

Note:

$$\text{Log } \epsilon_{AC} = 1.53 \text{ Log } \Delta + 0.319$$

$$N = 5 \times 10^{-6} (1/\epsilon)^{3.0}$$

where:

ϵ_{AC} = AC tensile strain (microstrain)

N = Number of strain repetitions (at ϵ level) to failure

ϵ = Tensile strain

The $N_{18} - \Delta$ relation is shown in Figure 13.

If the expected surface deflection variations (average +, - variation) are imposed, see Figure 14, a "design reliability" concept can be

established. Design reliability is the probability that a pavement segment will sustain the IDOT "Traffic Factor" (TF) number of load applications prior to failure. It is assumed that the algorithms and input values provide a 50% "design reliability" (on the average 50% of the pavement will "fail" before the TF number of 18k SAL applications and 50% will not fail). For a coefficient of variation of 20%, and full depth AC pavements in the range of 9-15 inches, the following approximate "multiplier" - design reliability relations were established. "Multiplier" values for increased levels of design reliability can easily be established.

<u>"Multiplier"*</u>	<u>Design Reliability**</u>
1	50 (AVERAGE)
2	80 (INTERMEDIATE)
3	92 (HIGH)

*The "Multiplier" is applied to the IDOT Traffic Factor (TF). If the TF is 1 (1×10^6 18k SAL) a full depth pavement designed for 2×10^6 SAL would have an 80% probability of sustaining 1×10^6 SAL without failure. To achieve 92% reliability, the pavement would be designed for 3×10^6 SAL.

**For an assumed surface deflection coefficient of variation of 20%.

In developing the "Proposed AASHTO Guide for Design of Pavement Structures" (9), a survey conducted by the AASHTO Pavement Design Task Force suggested the reliability levels shown in Table 4 for various functional highway classifications. Note that the IHR-510 "Design Reliability" values are comparable. The Design Asphalt Concrete Strain - Traffic Factor relation shown in Figure A3 can be easily adjusted to accommodate any desired "Design Reliability" or pavement deflection coefficient of variation.

THE PROPOSED DESIGN PROCEDURE

The current version of the proposed procedure is presented in Appendix A. To insure that the procedure would be easily understood, "user friendly," and conform to IDOT policies and procedures, frequent IHR-510 Project Advisory Committee meetings were held. Committee membership (as of November, 1985) is shown in the front of the report.

COMMENTS

To clarify and supplement Appendix A, the following comments are presented:

TRAFFIC FACTOR: The IDOT Traffic Factor (TF) as presented in Reference 10 is used to characterize mixed axle load traffic. TF is the number of equivalent 18 kip single axle loads (18k SAL) in millions (TF of 5 = 5×10^6). The thickness design procedure is based on 18k SAL and 80 psi tire pressure conditions. Thus, traffic inputs must be compatible.

CONSTRUCTION QUALITY: It is assumed that high quality construction is achieved throughout the entire depth of the AC layer. The IDOT "Subgrade Stability Policy" (11) should be enforced to provide adequate subgrade support for full-depth AC construction operations. Recommended (11) subgrade stability remedial procedures are lime treatment and undercut/backfill with granular material.

AC MIXTURE: The design procedure is appropriate for IDOT Class I mixtures prepared with AC-10 or AC-20 asphalt cement (AC content around 5%, Passing No. 200 around 5%, air void content in the range of 2-3.5%). Figures A2 and A3 are "mixture dependent." Other mixture types can be easily accommodated in the procedure by developing additional information similar to Figures A2 and A3.

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TABLE 1

ILLI-PAVE Algorithms for Full-Depth AC Pavements

$$1. \text{Log } \epsilon_{AC} = 5.746 - 1.589 \text{ LOG } T_{AC} - 0.774 \text{ LOG } E_{AC} \\ - 0.097 \text{ LOG } E_{Ri}$$

$$R^2 = 0.967 \quad \text{SEE} = 0.083$$

$$2. \text{LOG } S_{DEV} = 2.744 - 1.138 \text{ LOG } T_{AC} - 0.515 \text{ LOG } E_{AC} \\ + 0.289 \text{ LOG } E_{Ri}$$

$$R^2 = 0.976 \quad \text{SEE} = 0.053$$

$$3. \text{LOG } \Delta = 3.135 - 0.895 \text{ LOG } T_{AC} - 0.359 \text{ LOG } E_{AC} \\ - 0.287 \text{ LOG } E_{Ri}$$

$$R^2 = 0.984 \quad \text{SEE} = 0.033$$

T_{AC} in inches (AC layer thickness)

E_{AC} in ksi (AC modulus)

E_{Ri} in ksi (Subgrade modulus at repeated deviator of 6 psi)

ϵ_{AC} - Asphalt concrete strain (microstrain)

S_{Dev} - Subgrade deviator stress (psi)

Δ - Surface deflection (mils)

TABLE 2

Subgrade Soil Properties

	Subgrade			
	<u>Very Soft</u>	<u>Soft</u>	<u>Medium</u>	<u>Stiff</u>
Poisson's Ratio	0.45	0.45	0.45	0.45
E_{Ri} (ksi)	1.00	3.02	7.68	12.34
Friction Angle (degree)	0.0	0.0	0.0	0.0
Cohesion, psi	3.1	6.5	11.4	16.4
Unconfined Compressive strength, psi	6.2	13.0	22.8	32.8

TABLE 3

Typical Resilient Property Data (Ref. 8)

Granular Material Type	Number of Data Points	K* (psi)		n*	
		Mean	Standard Deviation	Mean	Standard Deviation
Silty Sands	8	1620	780	0.62	0.13
Sand-Gravel	37	4480	4300	0.53	0.17
Sand-Aggregate Blends	78	4350	2630	0.59	0.13
Crushed Stone	115	7210	7490	0.45	0.23

* $E_R = K\theta^n$ where

E_R = resilient modulus, psi

$\theta = \sigma_1 + 2\sigma_3$ (triaxial testing)

K, n = experimentally derived factors from repeated triaxial testing data

TABLE 4

AASHTO Suggested Levels of Reliability (Ref. 9)

Functional Classification	Recommended Level of Reliability	
	Urban	Rural
Interstate and other freeways	85-99.9	80-99.9
Principle Arterials	80-99	75-95
Collectors	80-95	75-95
Local	50-80	50-80

Note: Results based on a survey of the AASHTO Pavement Design Task Force

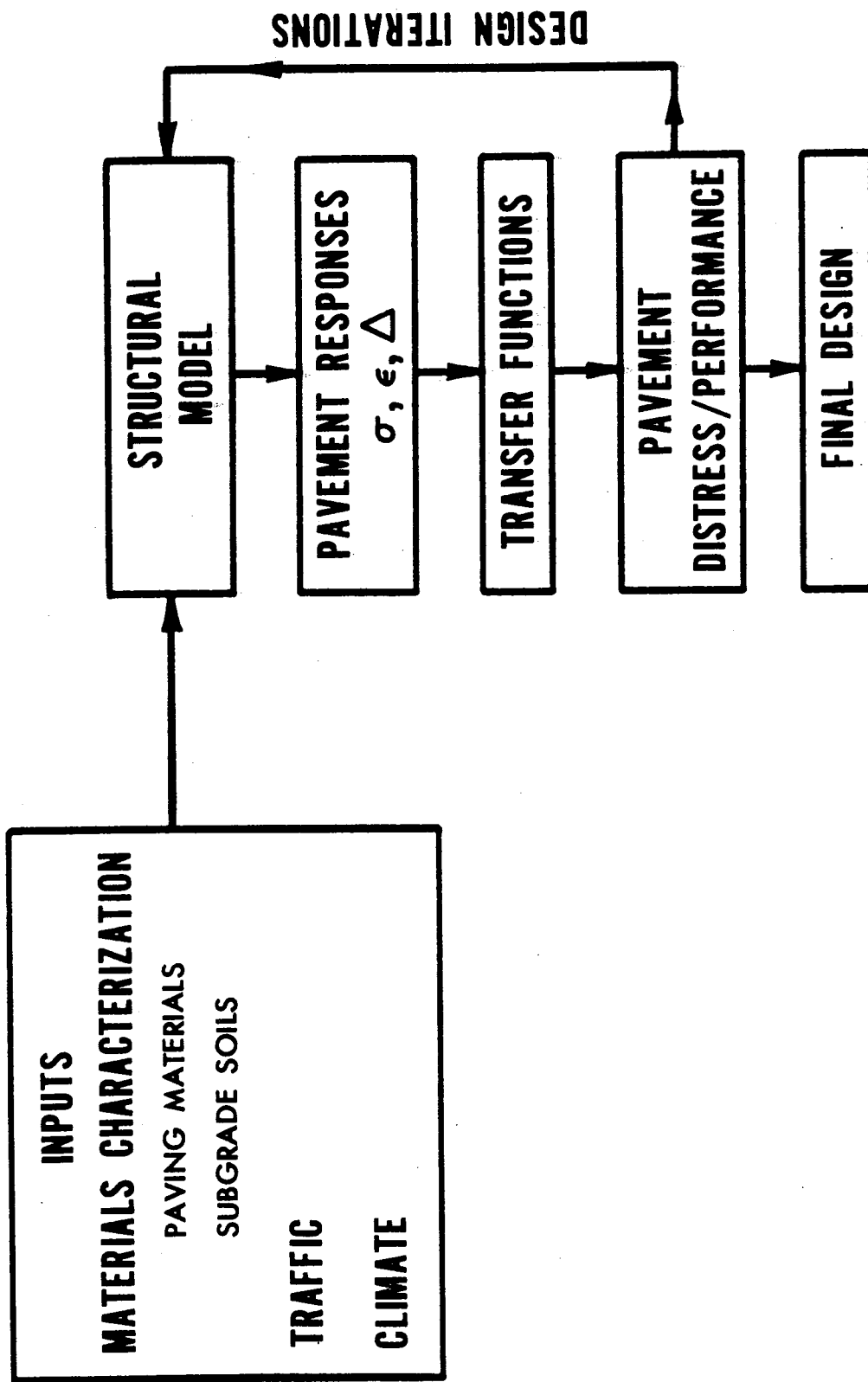


Figure 1. Components of a Mechanistic Design Procedure.

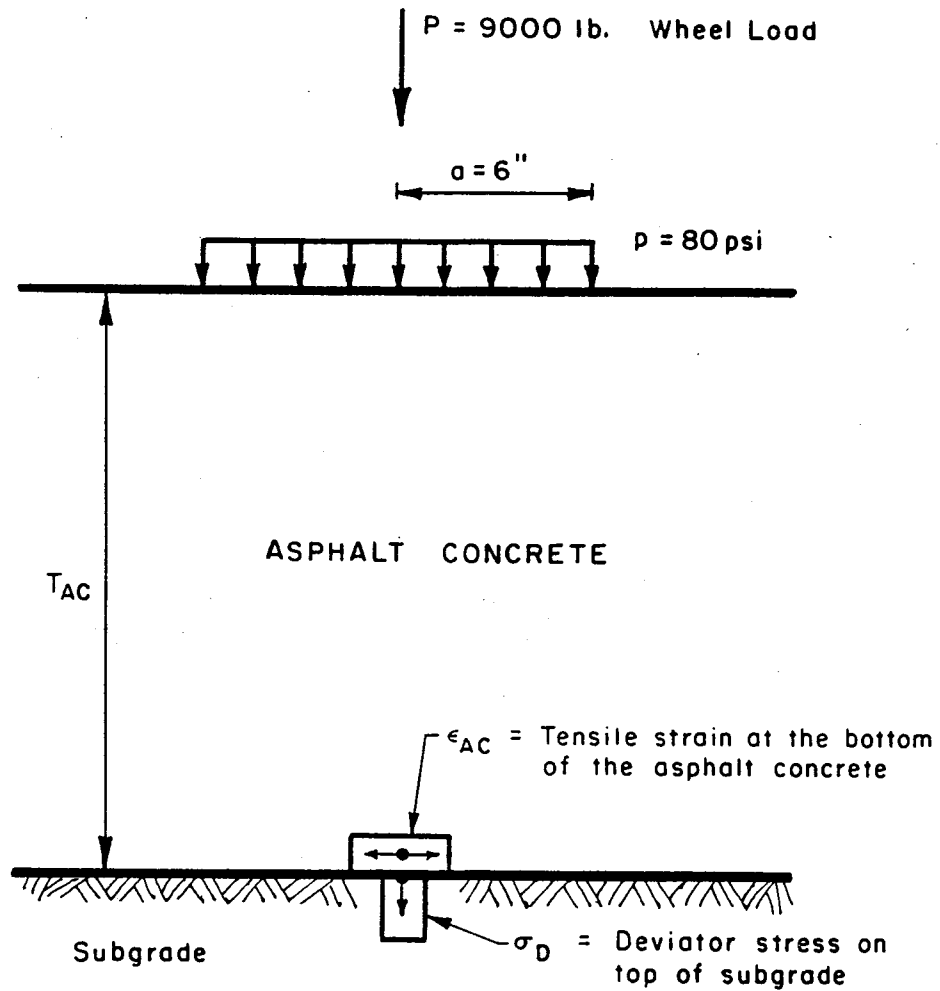


Figure 2. Typical Full-Depth Asphalt Concrete Pavement.

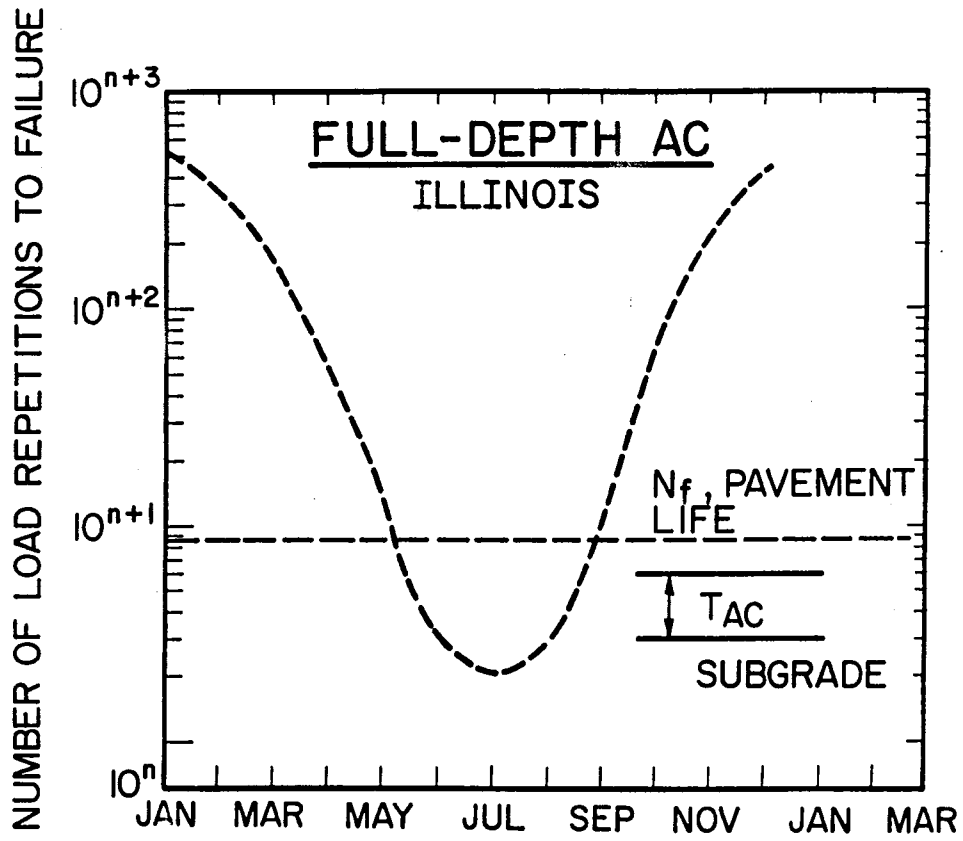


Figure 3. The Design Time Concept.

RELATIONSHIP OF PVMT LIFE AND ALLOWABLE LOAD REPS PER MONTH
NORTHERN ZONE, MIX TYPE=AC20

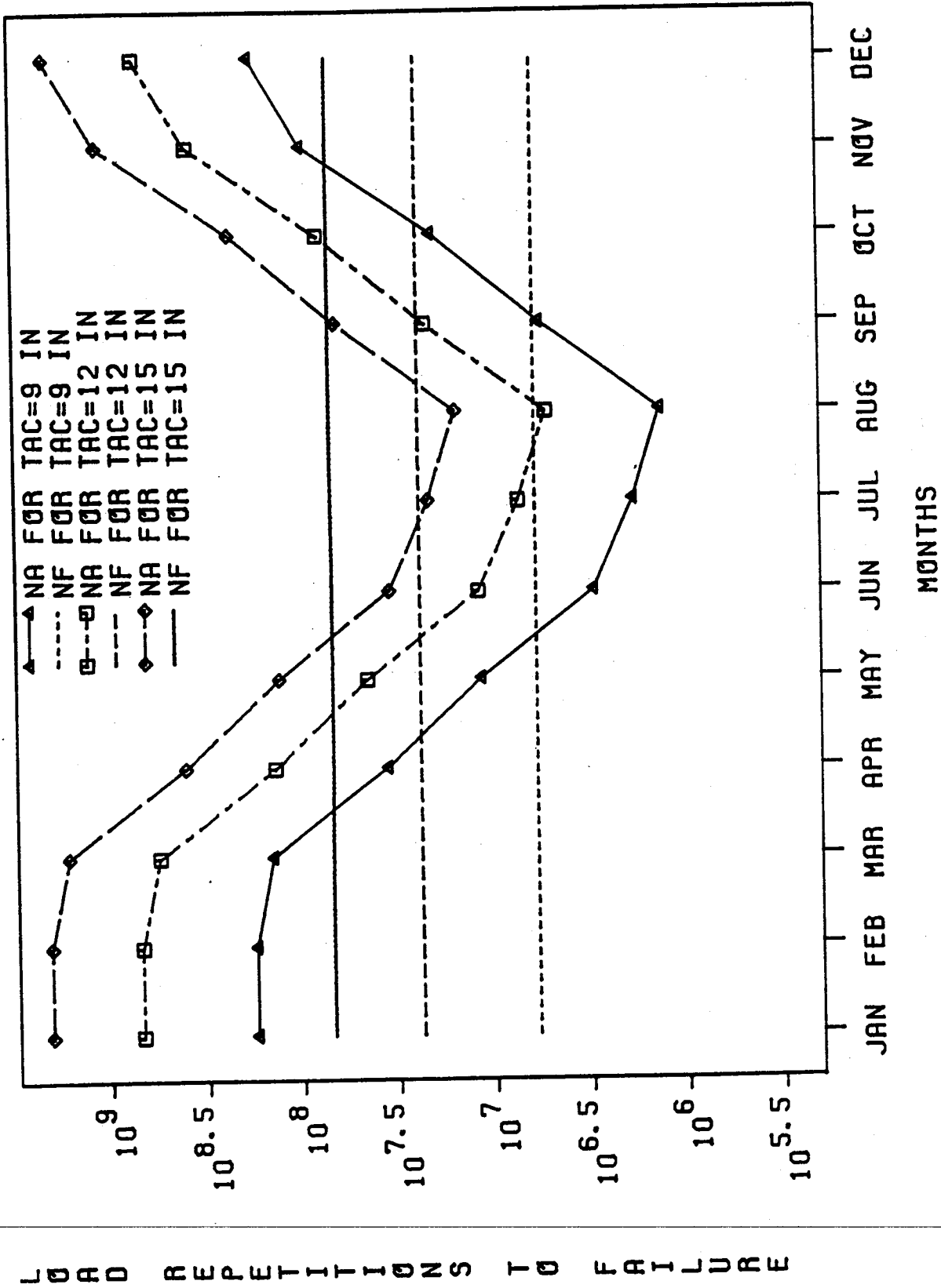


Figure 4. Design Time Data-Northern Illinois.

RELATIONSHIP PVMT LIFE AND ALLOWABLE LOAD REPS PER MONTH
CENTRAL ZONE, MIX TYPE=AC20

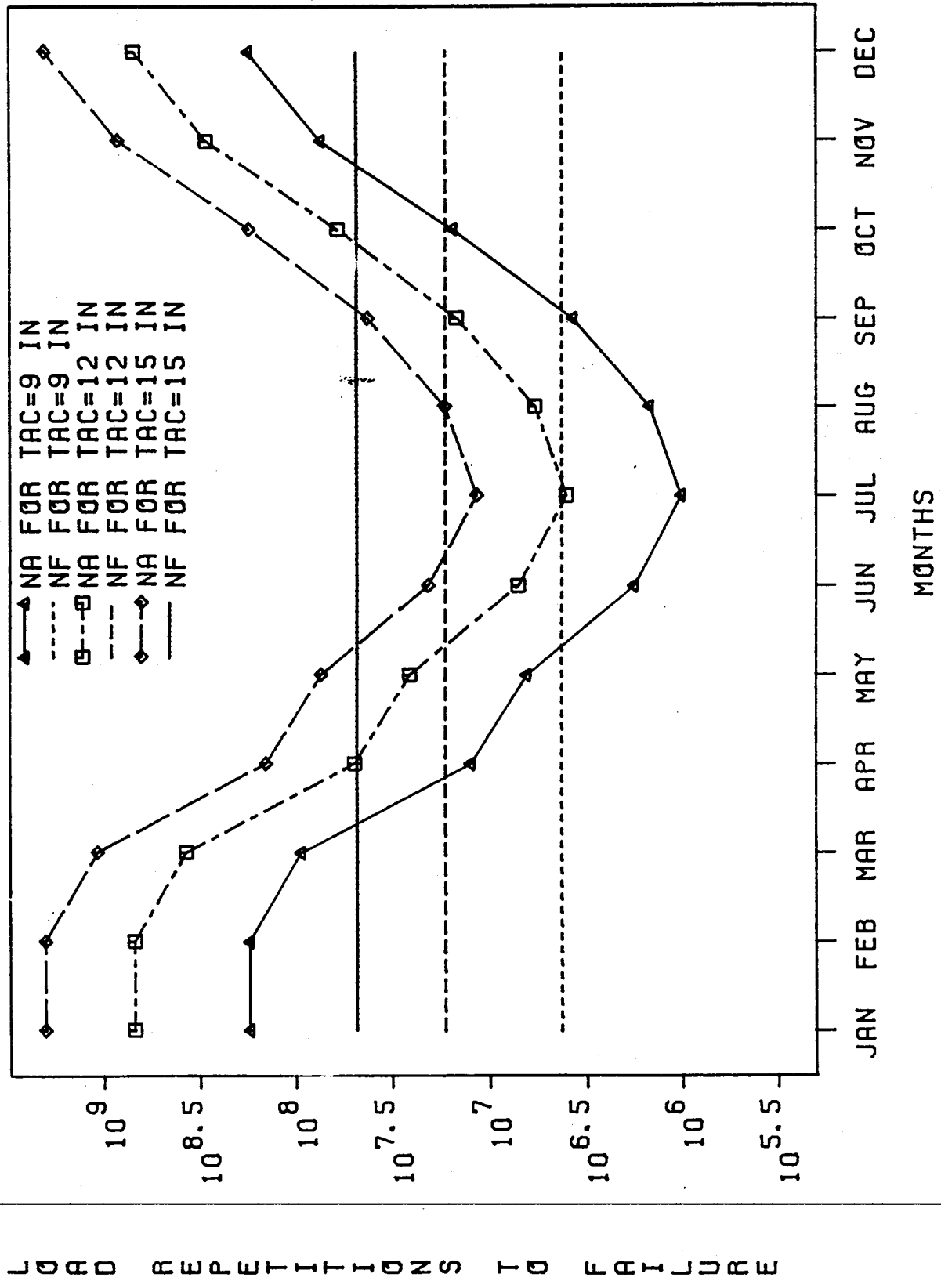


Figure 5. Design Time Data-Central Illinois.

RELATIONSHIP OF PVMT LIFE AND ALLOWABLE LOAD REPS PER MONTH
SOUTHERN ZONE, MIX TYPE=AC 20

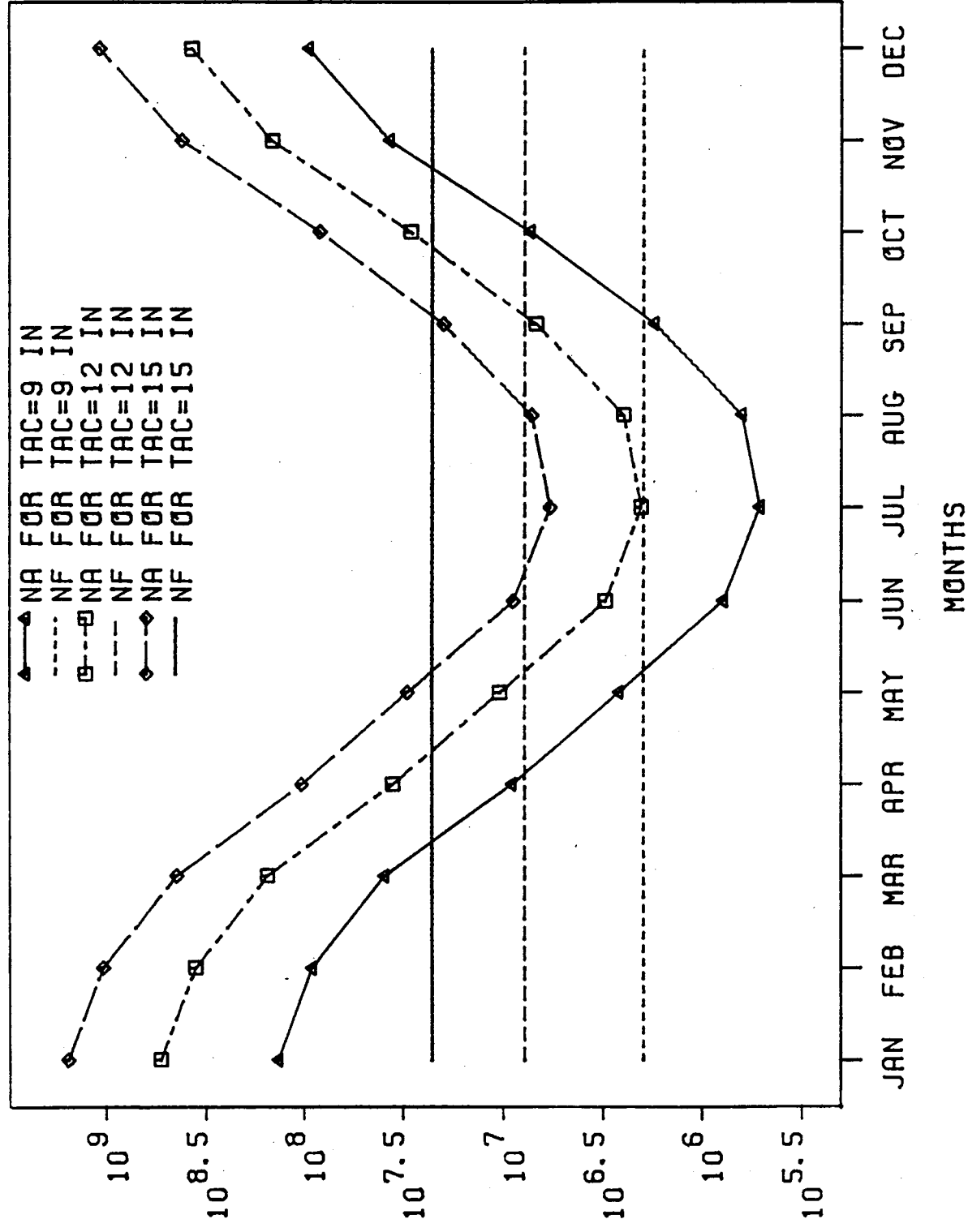


Figure 6. Design Time Data-Southern Illinois.

LOAD REPETITIONS TO FAILURE

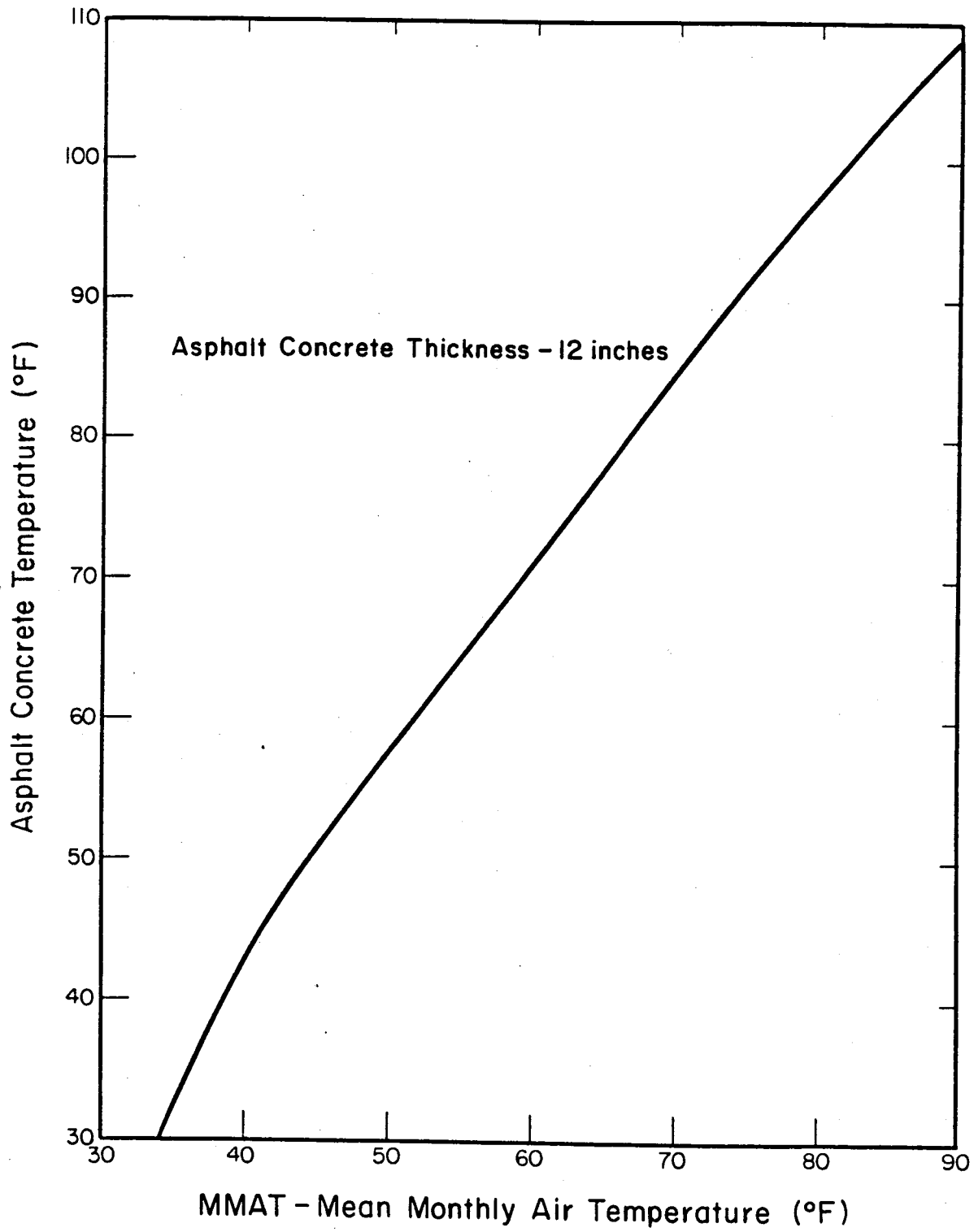


Figure 7. Mean Monthly Air Temperature - Asphalt Concrete Temperature Relation.

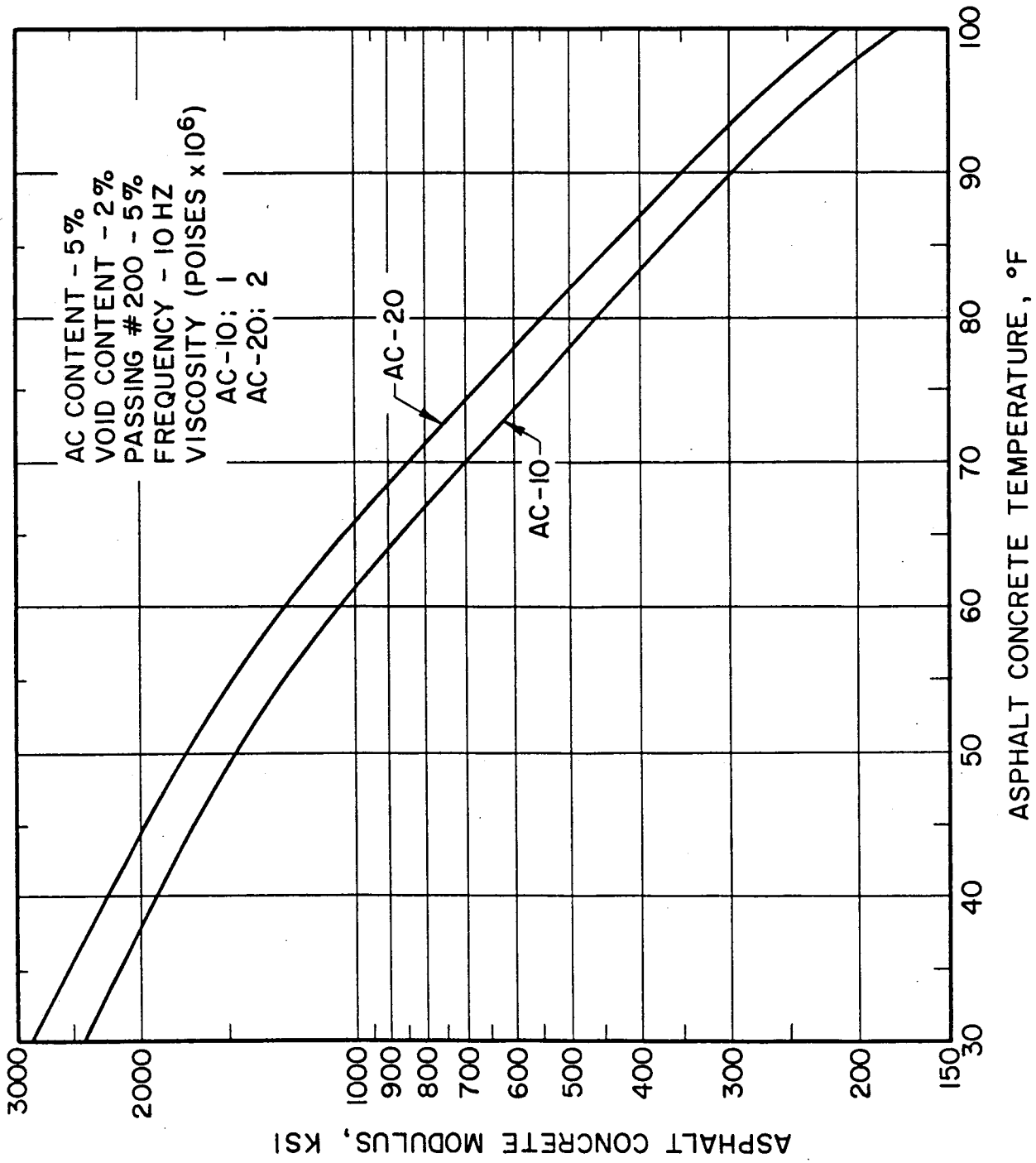


Figure 8. Asphalt Concrete Modulus-Temperature Relations for Typical IDOT Class I Mixtures.

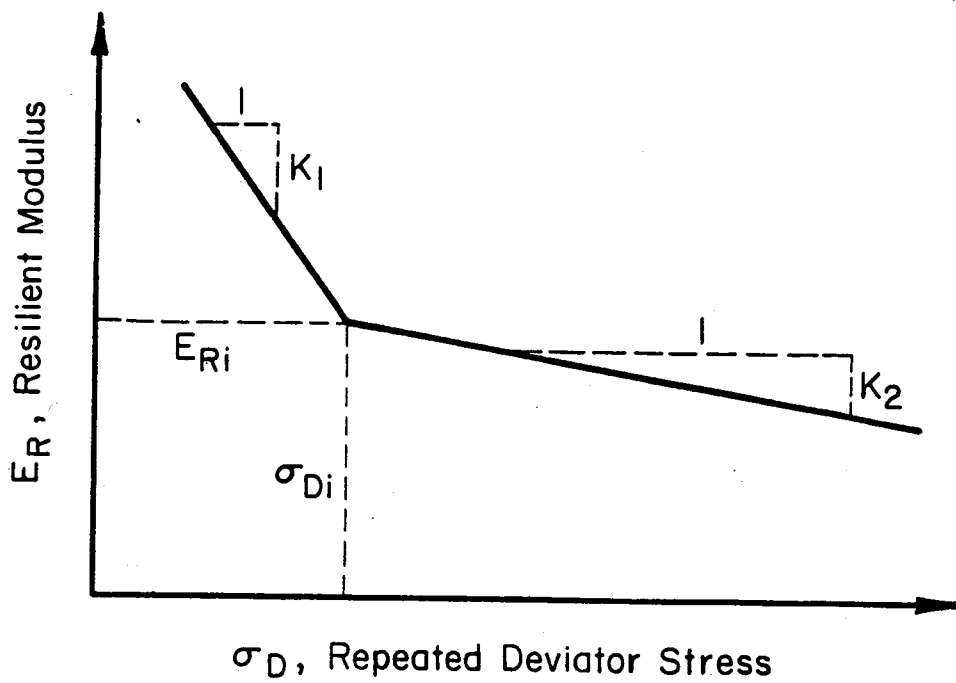


Figure 9. Resilient Modulus-Repeated Deviator Stress Relation for Fine-Grained Soils.

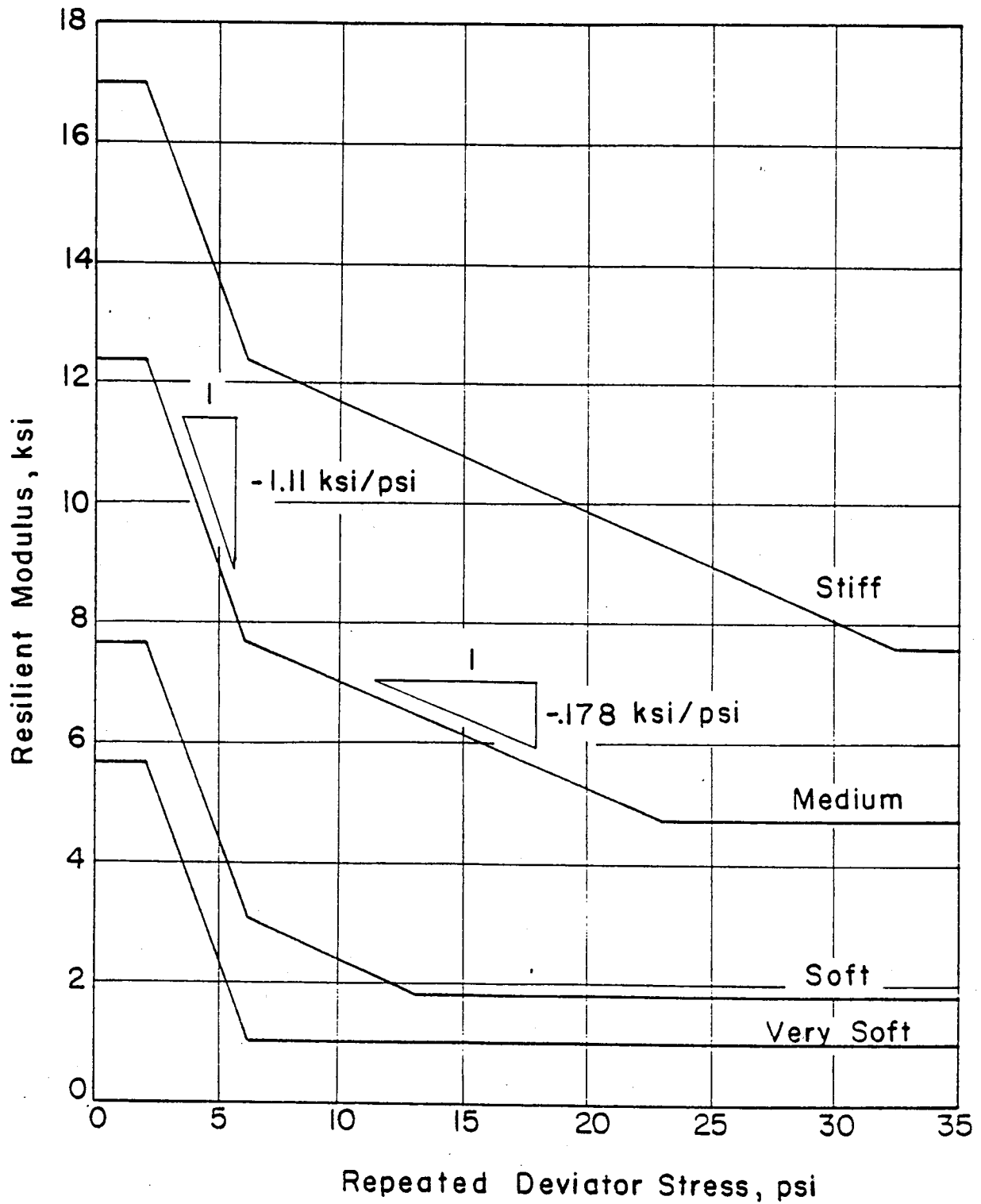


Figure 10. Resilient Modulus-Repeated Deviator Stress Relations for ILLI-PAVE Study.

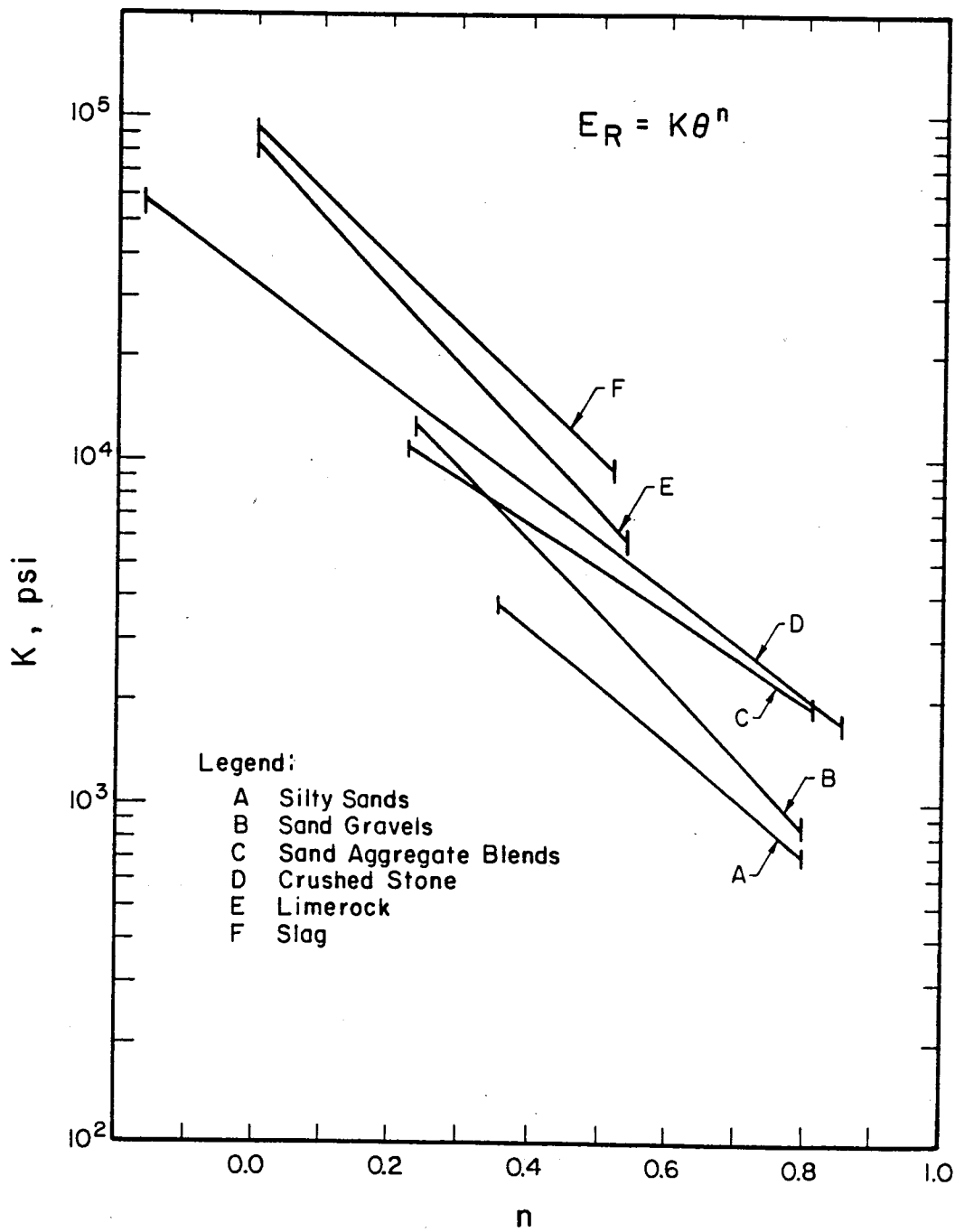


Figure 11. K-n Relations for Typical Granular Materials and Coarse-Grained Soils (Reference 8).

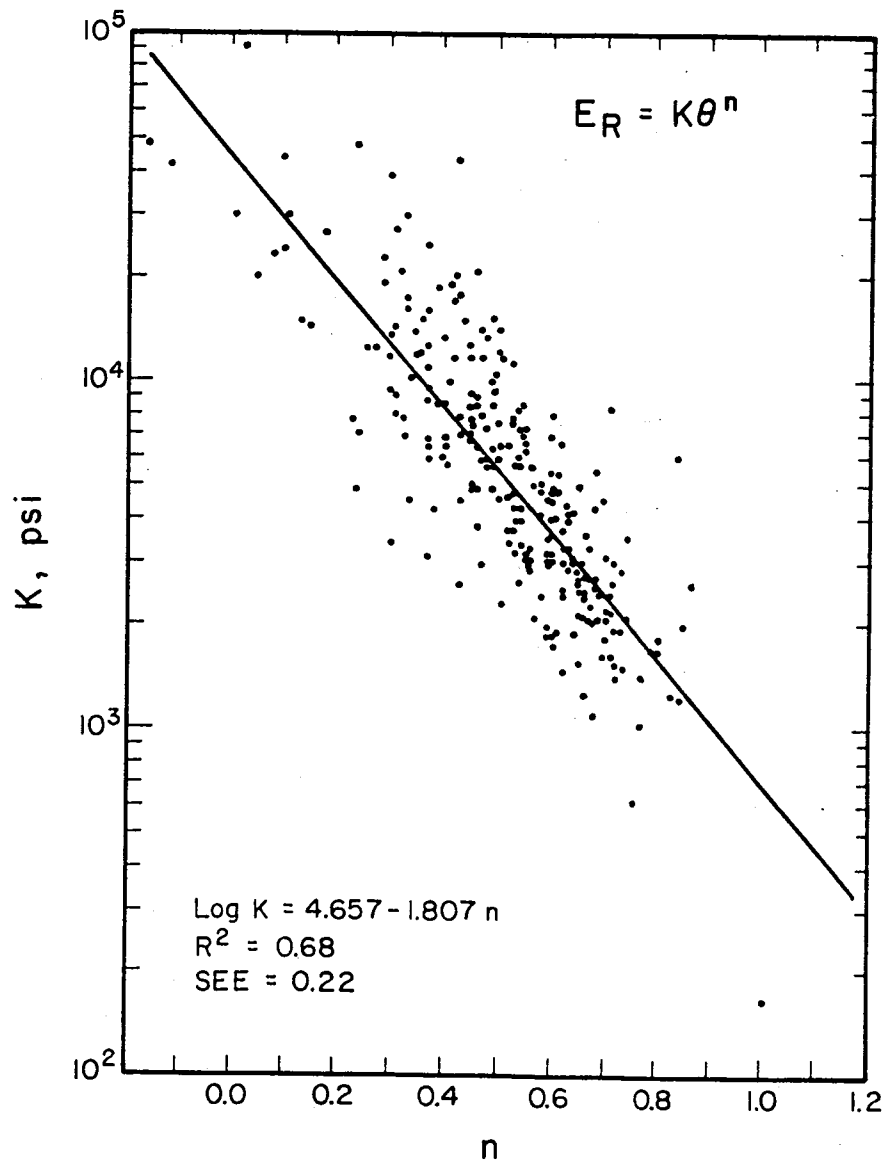


Figure 12. K-n Predictive Equation (Reference 8).

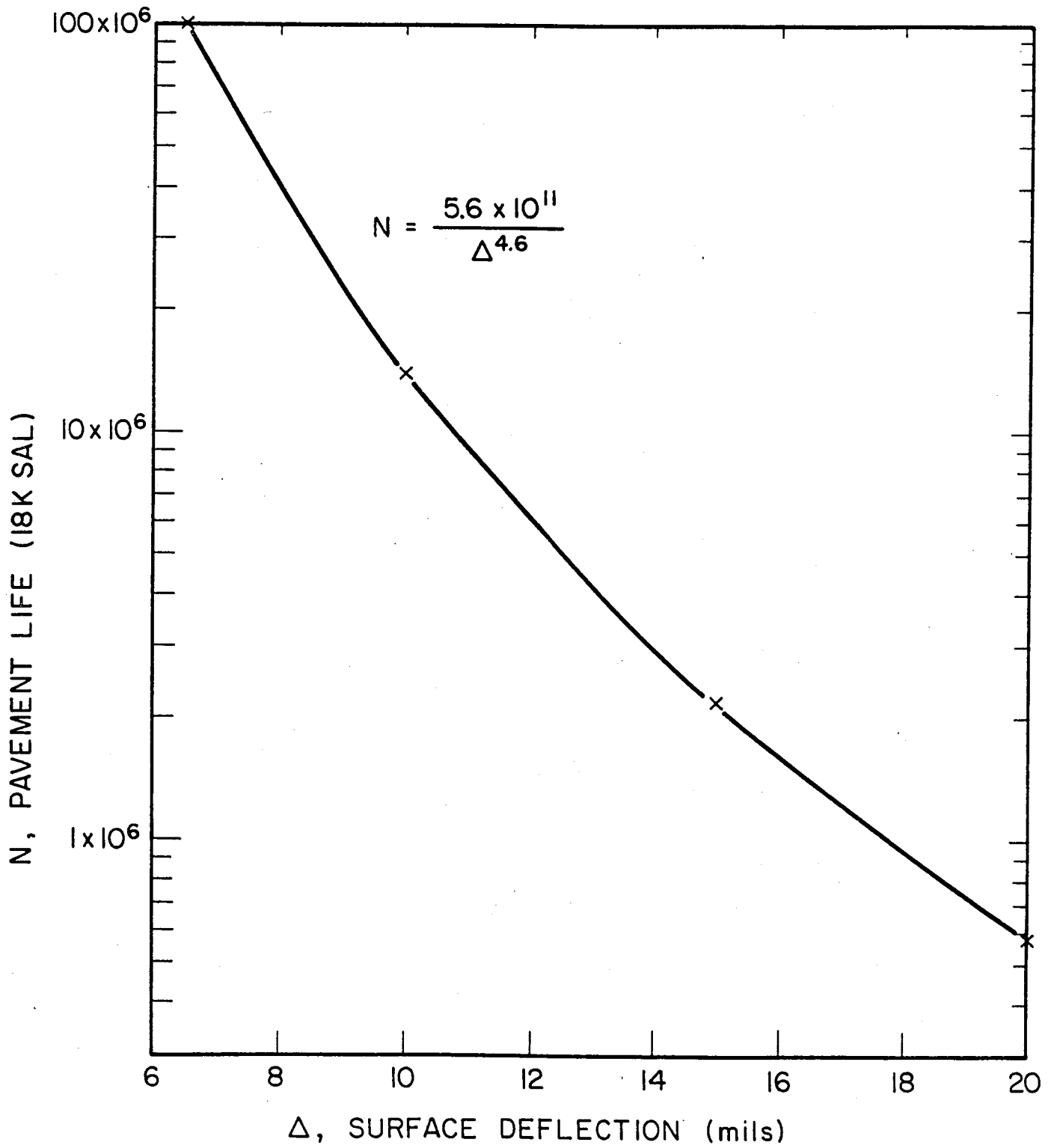


Figure 13. Pavement Life-Surface Deflection Relation for Full-Depth Asphalt Concrete Pavement.

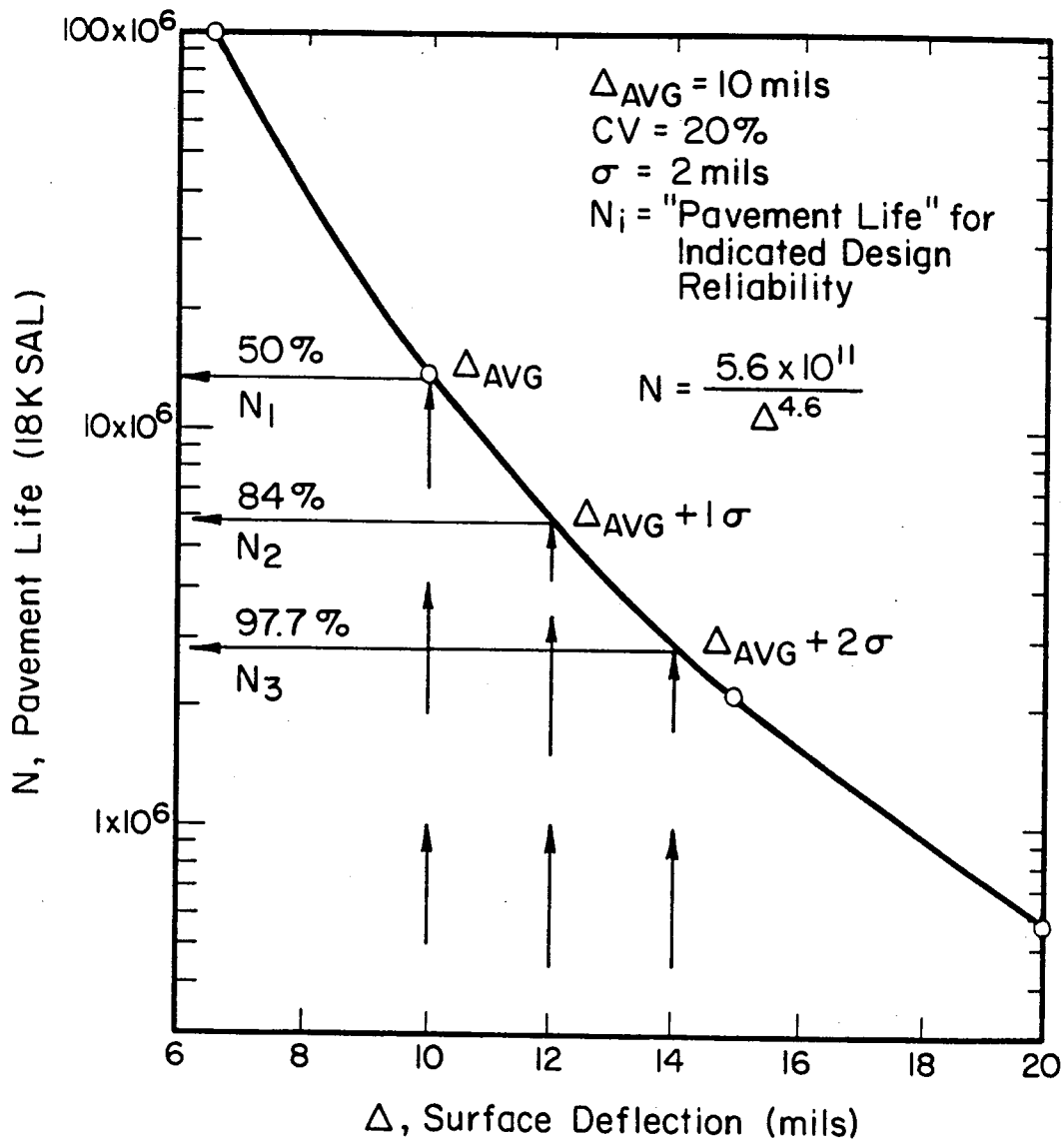
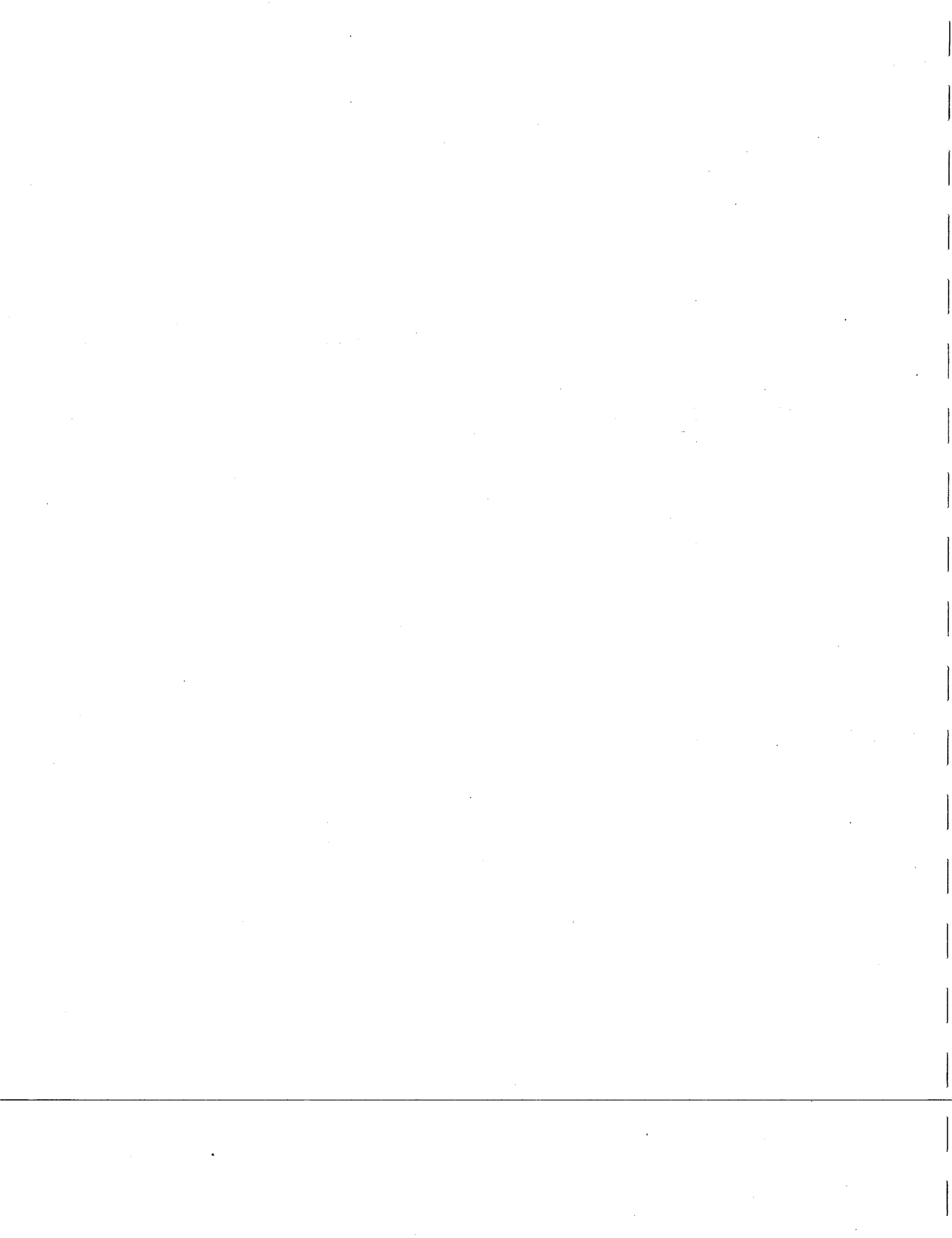


Figure 14. Illustration of "Design Reliability" Concept.



APPENDIX A

PROPOSED FULL-DEPTH ASPHALT CONCRETE (AC)

THICKNESS DESIGN PROCEDURE

DESIGN INPUTS

TF - Traffic Factor from current IDOT Pavement Design Manual procedures

Design E_{Ri} - Subgrade E_{Ri} for "Design Time"

The "Design Time" is mid-May for Southern Illinois; mid-to late- May for Central Illinois; and end-of-May to early June for Northern Illinois. Design E_{Ri} values are determined by the Bureau of Materials and Physical Research and are provided in the project "Soils Report". Fine-grained soil subgrade design E_{Ri} values are "FAIR" ($E_{Ri} \cong 5$ ksi) and "POOR" ($E_{Ri} \cong 2$ ksi). "GRANULAR" type subgrade soils are assigned a modulus of 20 ksi.

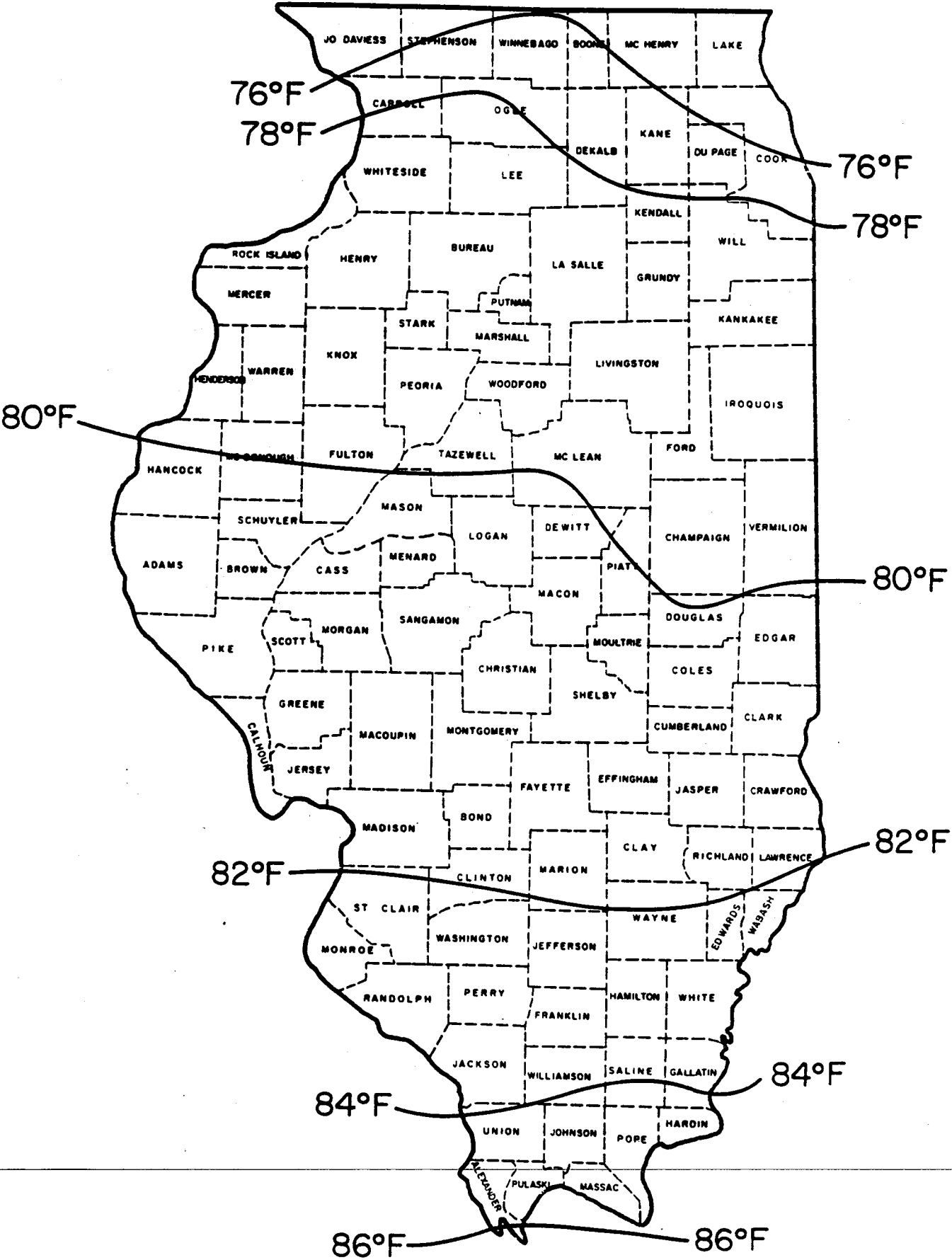
Design Pavement AC Mixture Temperature - The "Design Pavement AC Mixture Temperature" is selected from Figure A1 for the job location.

Design E_{AC} - The "Design E_{AC} " is the AC mixture modulus (in the pavement) corresponding to the "Design Pavement AC Mixture Temperature". E_{AC} is selected from the appropriate E_{AC} - AC Mixture Temperature Relation shown in Figure A2 for typical Class I mixtures with AC 10 and AC 20 asphalt cements.

THICKNESS DESIGN PROCESS

Based on the "Design Inputs", a "Design AC Strain" is established from Figure A3. "Design Reliability" is considered and may vary from "AVERAGE" (50%), to "INTERMEDIATE" (80%), to "HIGH" (92%). Enter the appropriate design chart (Figure A4, A5, or A6) with the "Design E_{AC} ," and "Design AC Strain" to determine the required T_{AC} (full-depth AC thickness).

FIGURE A1. Design Pavement AC Mixture Temperature



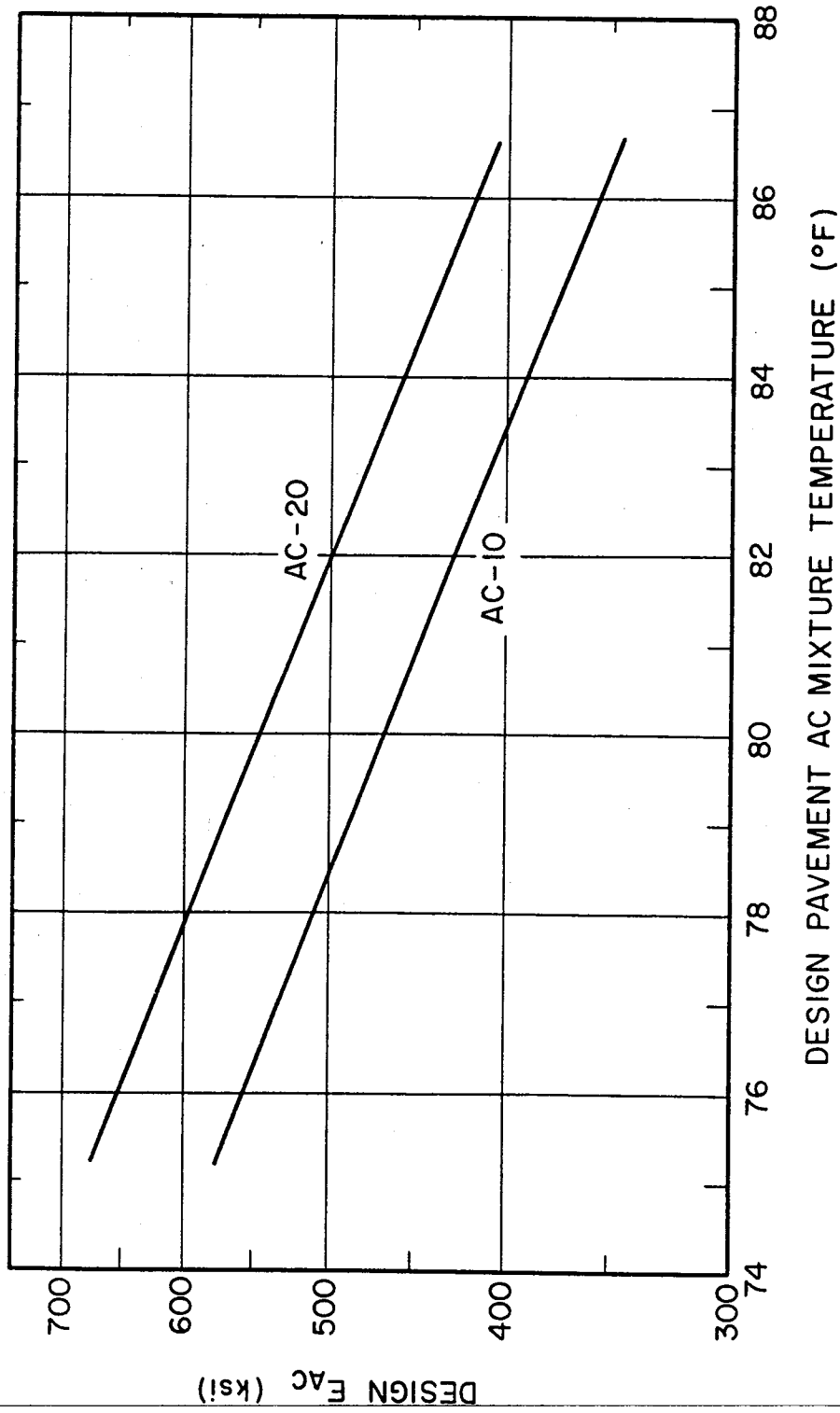


FIGURE A2. Design Pavement AC Mixture Modulus.

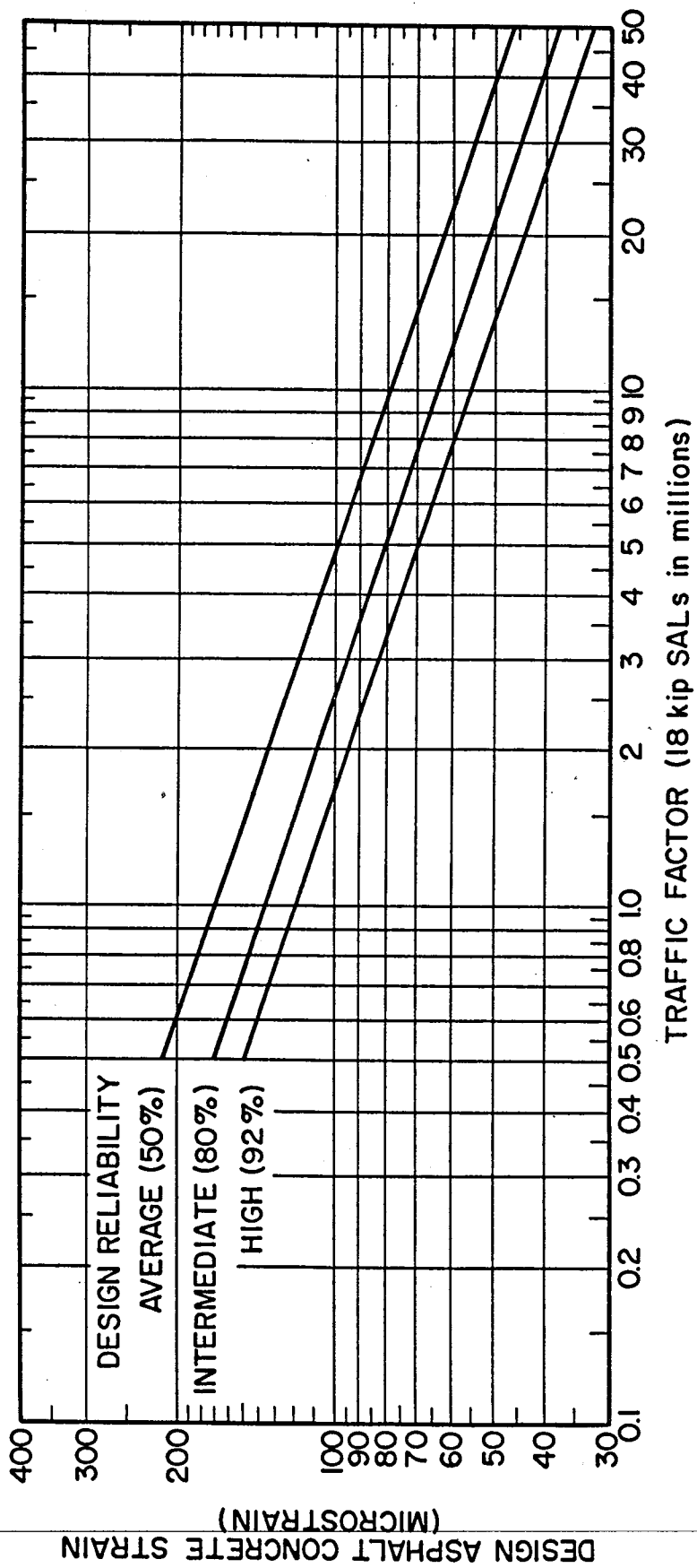
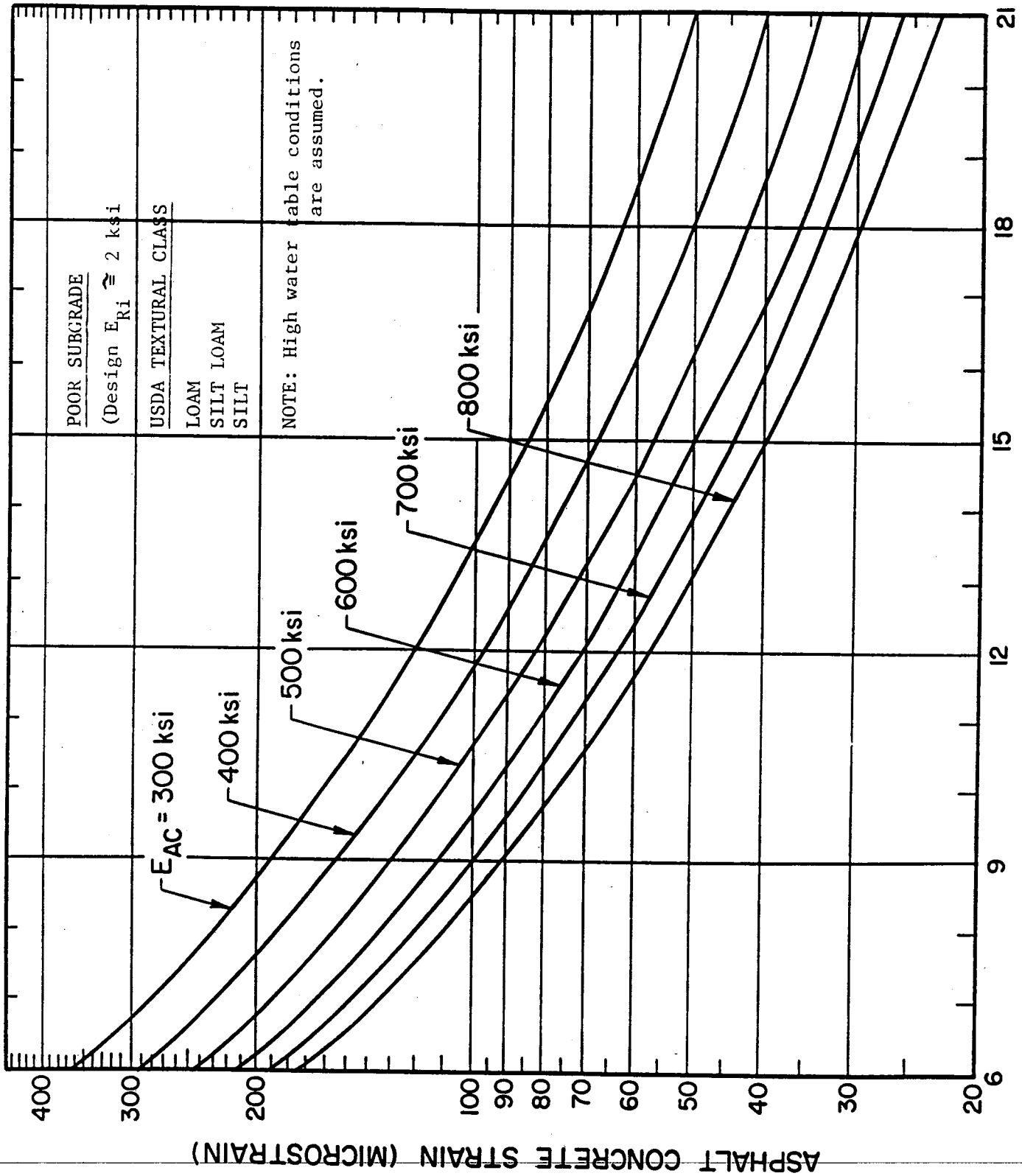


FIGURE A3. Determination of Design Asphalt Concrete Strain



ASPHALT CONCRETE THICKNESS (INCHES)

ASPHALT CONCRETE STRAIN (MICROSTRAIN)

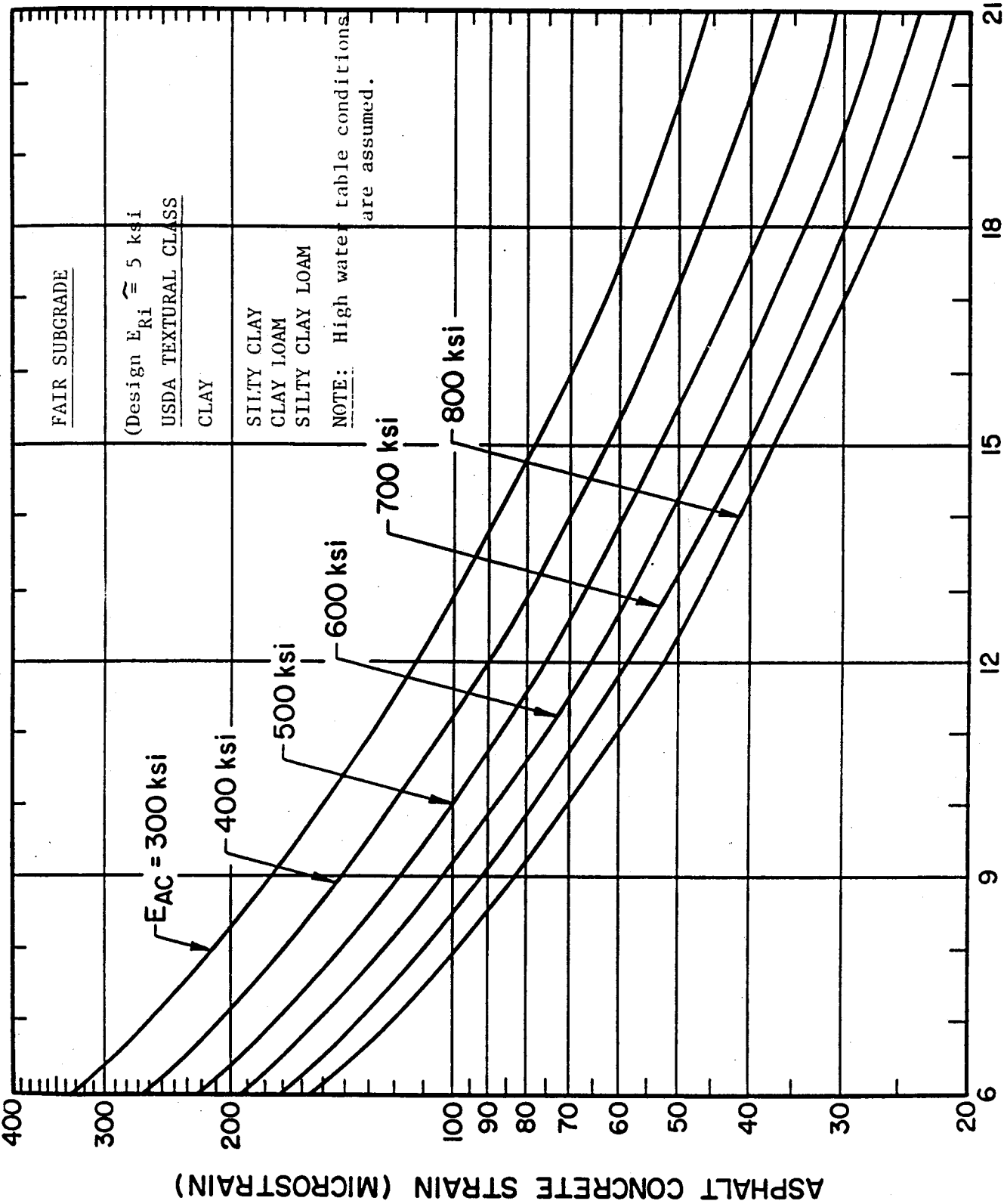
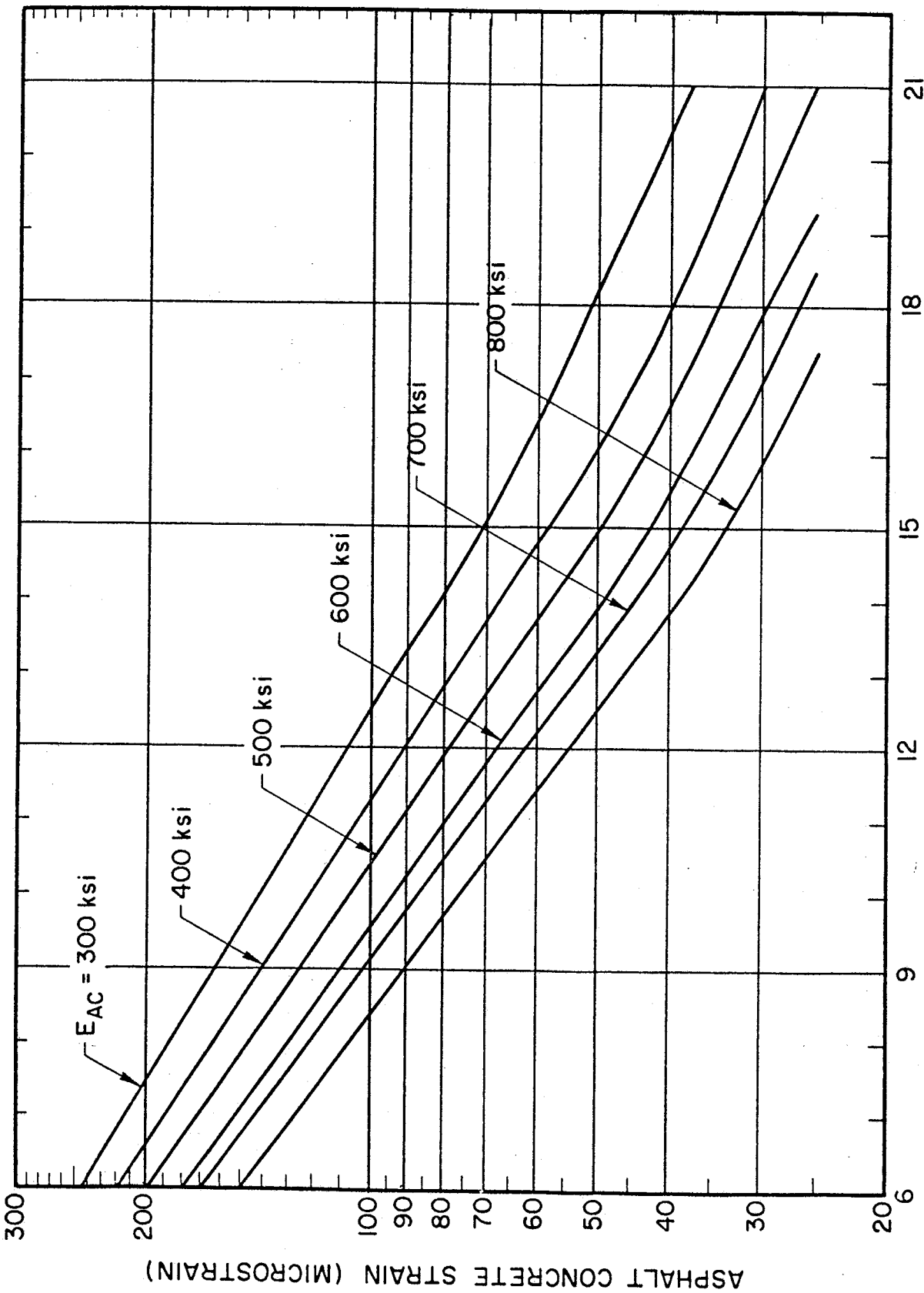


FIGURE A5. "FAIR" Subgrade Design Chart



ASPHALT CONCRETE THICKNESS (INCHES)

FIGURE A6. "GRANULAR" Subgrade Design Chart.

APPENDIX B

THE ASPHALT INSTITUTE EQUATION

The Asphalt Institute Equation for predicting mix stiffness is:

$$\log |E^*| = 5.553833 + 0.028829 \left(\frac{P_{200}}{f^{0.17033}} \right) - 0.03476 (V_v) \\ + 0.070377 (\eta_{70^\circ F, 10^6}) + 0.000005 [t_p^{(1.3+0.49825 \log f)} P_{ac}^{0.5}] \\ - 0.00189 [t_p^{(1.3+0.49825 \log f)} \frac{P_{ac}^{0.5}}{f^{1.1}}] + 0.931757 \left(\frac{1}{f^{0.02774}} \right)$$

where:

$|E^*|$ = dynamic modulus (stiffness) of asphalt concrete, psi;

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

f = frequency, Hz;

V_v = percent air voids;

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

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

t_p = temperature, F.

This equation has a multiple square correlation coefficient, R^2 , equal to 0.939, and a Mean Square Error (MSE) of 0.01525.

Therefore, the Root Mean Square Error (RMSE), better known as the Standard Error of Estimate (SEE), is 0.1235.

