ILLI-PAVE-Based Response Algorithms for Design of Conventional Flexible Pavements

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ABSTRACT

In a mechanistic design procedure a structural model is used to predict pavement responses (stresses, strains, displacements). The ILLI-PAVE structural model considers nonlinear, stress-dependent resilient modulus material models and failure criteria for granular materials and fine-grained soils. The computational techniques of the ILLI-PAVE computer program are too costly, complex, and cumbersome to be used for routine design. To incorporate ILLI-PAVE structural model concepts into a mechanistic design concept, simplified analysis algorithms that reliably predict ILLI-PAVE response solutions for typical flexible pavements are needed. ILLI-PAVE-based design algorithms for conventional flexible pavements [asphalt concrete (AC) surface plus granular base and subbase] are presented for AC radial strain, surface deflection, subgrade deviator stress, subgrade deviator stress ratio, subgrade vertical strain, and subgrade deflection. Pertinent design algorithm inputs are AC thickness, AC modulus, granular layer thickness, and subgrade resilient modulus (E_{Ri}). Additional algorithms relating AC radial strain and subgrade deviator stress ratio and surface deflection are also presented. The algorithms are sufficiently accurate for inclusion in mechanistic design procedures.

The various components of a mechanistic design procedure for conventional [asphalt concrete (AC) granular base and subbase] flexible pavements are shown in Figure 1. In this paper emphasis is placed on materials characterization, the structural model, and pavement response components. Concepts for a mechanistic design procedure based on the ILLI-PAVE structural model (1) and design algorithms developed from a comprehensive ILLI-PAVE data base (2) are presented. Development of a design procedure based on these concepts should include consideration of climatic effects and the establishment of appropriate transfer functions.

Climatic effects (temperature, moisture, freeze-thaw) can be considered by quantifying their effects on material characteristics (resilient moduli and shear strength). Such considerations should be based on an extensive study of local climatic and soil conditions.

Transfer functions relating pavement response and pavement performance are not proposed. Typical transfer functions consider pavement responses related to subgrade permanent strain (subgrade resilient strain, subgrade stress, subgrade stress ratio) and AC fatigue (AC strain). Transfer functions should be developed on the basis of consideration of the paving materials, soils, climate, and so forth relevant to local conditions. Laboratory testing information and field performance data are essential inputs to calibrating a transfer function.

Transfer functions are an important part of a total mechanistic design procedure. Transfer functions appropriate for use with the ILLI-PAVE procedure are not necessarily compatible with linear elastic (or other) analysis procedures.

The analyses and algorithms presented in this paper are only for 18,000-lb single axle load conditions. Mixed traffic should be converted to equiva-

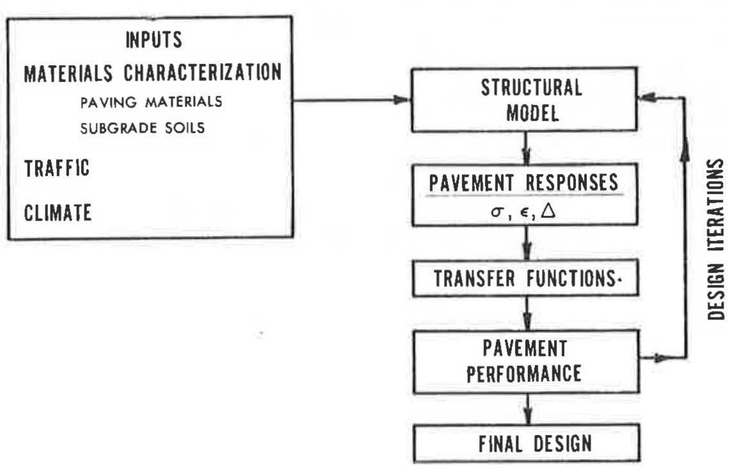

FIGURE 1 Components of a mechanistic design procedure.

lent 18,000-lb single axle loads when the ILLI-PAVE procedure is incorporated into a comprehensive design procedure.

ILLI-PAVE

In ILLI-PAVE (1) the pavement is considered an axi-symmetric solid of revolution. Nonlinear, stress-dependent resilient modulus material models and failure criteria for granular materials and fine-grained soils (1-3) are incorporated into ILLI-PAVE. The principal stresses in the granular and subgrade layers are modified at the end of each iteration so that they do not exceed the strength of the materials as defined by the Mohr-Coulomb theory of failure.

Studies comparing measured and ILLI-PAVE-predicted load deformation responses reported by Raad and Figueroa (1), Suddath and Thompson (4), Traylor (5), Hoffman and Thompson (6), Gomez and Thompson (7), and Elliott and Thompson (8) yielded favorable results. The ILLI-PAVE approach has been successfully used in developing a highway flexible pavement overlay design procedure based on nondestructive testing data analyses (9), as well as mechanistic thickness design procedures for secondary road flexible pavements (10) and soil-lime layers (11). Gomez and Thompson (7) and Elliott and Thompson (8) successfully used ILLI-PAVE procedures to analyze the pavement responses and predict the performance of the AC plus bituminous treated granular base sections (the "Base Type Studies") and the Loop 4 flexible pavement sections of the AASHO Road Test.

Although the computational techniques of the ILLI-PAVE computer program are too costly, complex, and cumbersome to be used for routine design, simplified analysis algorithms that reliably predict ILLI-PAVE response solutions for typical flexible pavements have been developed (8) to incorporate ILLI-PAVE structural model concepts into a mechanistic design concept. The algorithms can be easily programmed for inexpensive calculator or computer applications.

SOILS AND MATERIAL CHARACTERIZATION

General

The resilient behavior of a soil or material 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, and
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, whereas granular materials stiffen with increasing stress level.

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, and
θ = first stress invariant = $\sigma_1 + \sigma_2 + \sigma_3$.

Note that $\theta = \sigma_1 + 2\sigma_3$ in a standard triaxial compression test.

Figure 2 shows an E_R-θ relation for a sandy gravel. Rada and Witczak (12) have summarized and statistically analyzed extensive published resilient modulus data for a broad range of granular materials. The average values and ranges for K and n are given in Table 1 and shown in Figure 3 for several granular materials and coarse-grained soils. The relation between K and n developed by Rada and Witczak is shown in Figure 4.

The granular material model used in this study is $E_R = 9{,}000\ \theta^{0.33}$ (θ and E_R in psi). The values are typical for dense-graded crushed stone base materials and the AASHO crushed stone base (5). Other pertinent data for the crushed stone are given in Table 2.

Fine-Grained Soils

Two stress-dependent behavior models have been proposed for describing the stress softening behavior of fine-grained soils. The arithmetic model is shown in Figures 5 and 6, and the semilog model is shown in Figure 7. Extensive resilient laboratory testing, nondestructive pavement testing, and pavement analysis and design studies at the University of Illinois have indicated that the arithmetic model (Figure 5) is adequate for flexible pavement analysis and design activities.

In the arithmetic model, the value of the resilient modulus at the breakpoint in the bilinear curve, E_{Ri} (Figure 5), is a good indicator of a soil's resilient behavior. The slope values, K_1 and K_2, display less variability and influence pavement structural response to a smaller degree than E_{Ri}. Thompson and Robnett (13) 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) are included in this study. Pertinent subgrade properties and characteristics are given in Table 2. Resilient moduli-repeated deviator stress level relations used in the ILLI-PAVE model are shown in Figure 8.

Asphalt Concrete

A constant linear resilient modulus is used to represent the AC layer. AC modulus-temperature relations must be considered in selecting modulus values. Procedures for establishing AC modulus-pavement temperature relations are presented by the Asphalt Institute (14) and Shell (15) design procedures. The AC modulus values selected for this study are consistent with the range of AC moduli and temperatures expected to be encountered in Illinois. The modulus values and other properties used in the analyses are given in Table 2.

DESIGN ALGORITHM DEVELOPMENT

Elliott and Thompson (8) have demonstrated that type of aggregate base material (crushed stone or gravel)

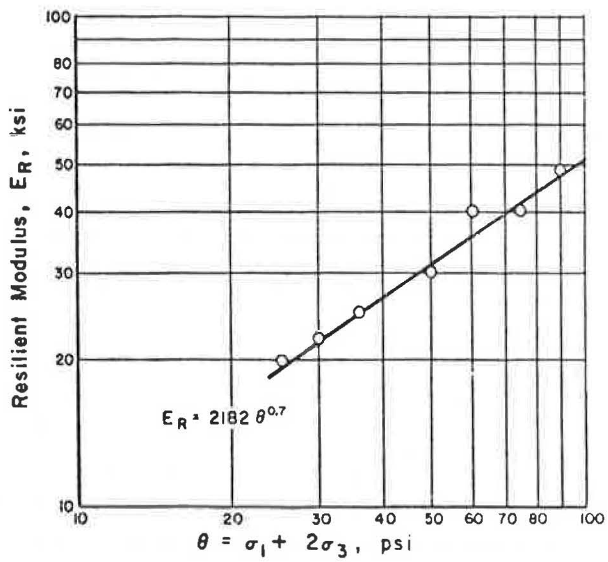

FIGURE 2 Resilient modulus-θ relation for a sandy gravel [AASHTO A-1-b(0)].

TABLE 1 Typical Resilient Property Data *(12)*

Granular Material Type	No. of Data Points	K (psi) Mean	K (psi) Standard Deviation	n Mean	n Standard Deviation
Silty sands	8	1,620	780	0.62	0.13
Sand-gravel	37	4,480	4,300	0.53	0.17
Sand-aggregate blends	78	4,350	2,630	0.59	0.13
Crushed stone	115	7,210	7,490	0.45	0 23

Note: $E_R = K\theta^n$ where E_R = resilient modulus (psi) and K, n = experimentally derived factors from repeated triaxial testing data.

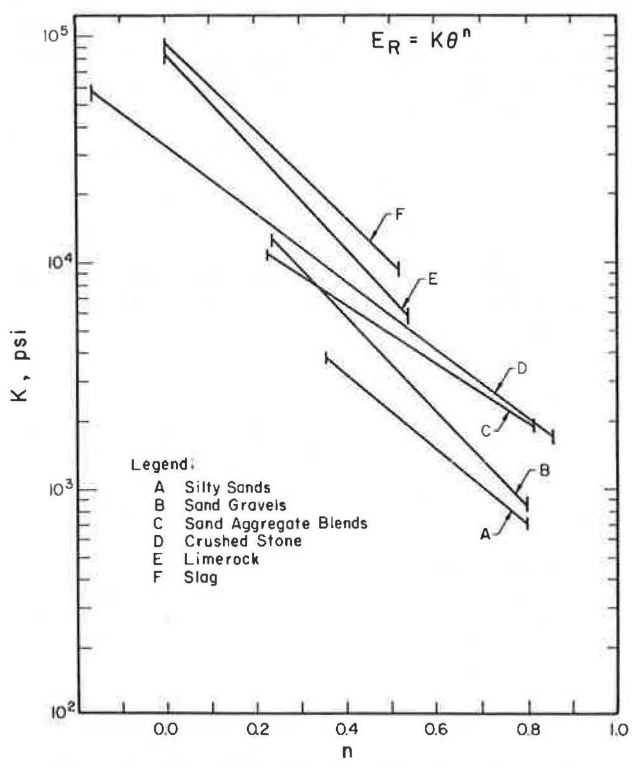

FIGURE 3 K and n relationships for various types of granular materials identified by Rada and Witczak *(12)*.

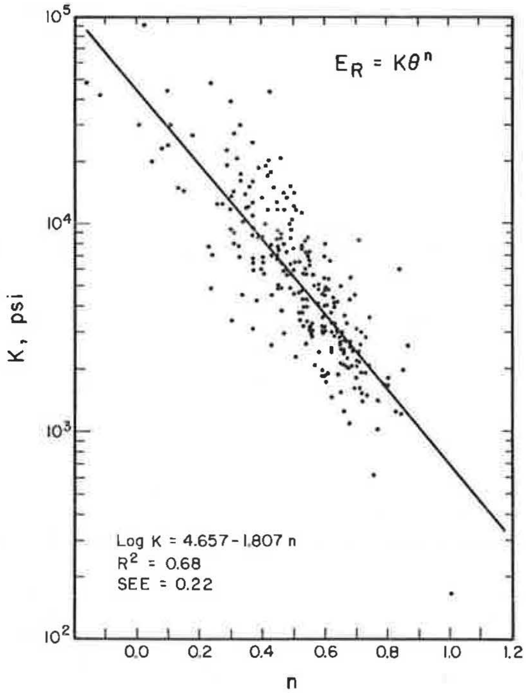

FIGURE 4 Relationship between K and n values for granular materials identified by Rada and Witczak *(12)*.

has a limited effect (10± percent) on ILLI-PAVE-calculated structural response (AC strain, surface deflection, subgrade deflection, subgrade strain, and subgrade deviator stress). Thus ILLI-PAVE structural response algorithms were developed only for the crushed stone base model. All ILLI-PAVE analyses were based on a 9,000-lb circular load (80 psi pressure) as a representation of one dual wheel of the standard 18-kip (18,000-lb) single axle load.

Design response algorithms were developed as the basis of a mechanistic design procedure. Algorithms for predicting the following pavement responses were established:

1. AC radial strain at the bottom of the AC surface layer,

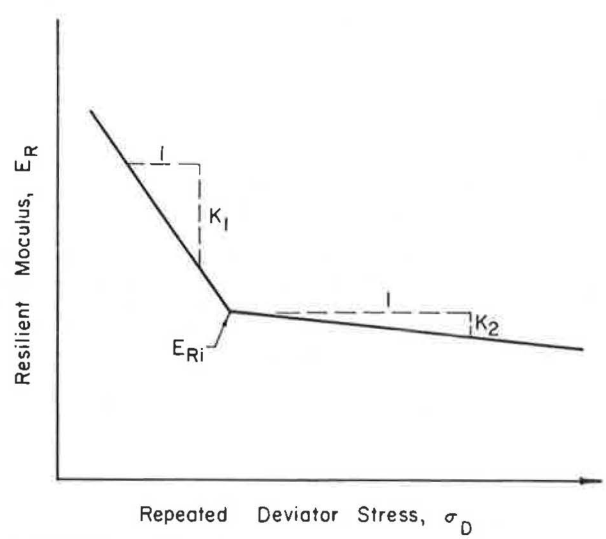

FIGURE 5 Arithmetic model for stress-dependent resilient behavior of fine-grained soils.

TABLE 2 Summary of Material Properties for ILLI-PAVE Solutions

	Asphalt Concrete			Crushed Stone	Subgrade			
	40°F	70°F	100°F		Stiff	Medium	Soft	Very Soft
Unit weight (pcf)	145.00	145.00	145.00	135.00	125.00	120.00	115.00	110.00
Lateral pressure								
Coefficient at rest	0.37	0.67	0.85	0.60	0.82	0.82	0.82	0.82
Poisson's ratio	0.27	0.40	0.46	0.38	0.45	0.45	0.45	0.45
Unconfined compression strength (psi)					32.80	22.85	12.90	6.21
Deviator stress (psi)								
Upper limit					32.80	22.85	12.90	6.21
Lower limit					2.00	2.00	2.00	2.00
K1 (ksi/psi)					-1.11	-1.11	-1.11	-1.11
K2 (ksi/psi)					-.178	-.178	-.178	-.178
Deviator stress at break-point (psi)					6.20	6.20	6.20	6.20
Eri (ksi)					12.34	7.68	3.02	1.00
E failure (ksi)				4.00	7.605	4.716	1.827	1.00
E constant modulus (ksi)	1,400.00	500.00	100.00					
Er model (psi)				$9{,}000\theta^{0.33}$				
Friction angle (degrees)				40.00	0.0	0.0	0.0	0.0
Cohesion (psi)				0.00	16.4	11.425	6.45	3.105

2. Subgrade deviator stress,
3. Subgrade stress ratio (subgrade deviator stress to unconfined compressive strength),
4. Subgrade vertical strain,
5. Surface deflection, and
6. Subgrade deflection.

These responses are those generally used in various transfer functions (see Figure 1) relating pavement response to pavement performance. Additional algorithms relating AC radial strain and subgrade stress ratio to surface deflection (all response parameters) were also developed.

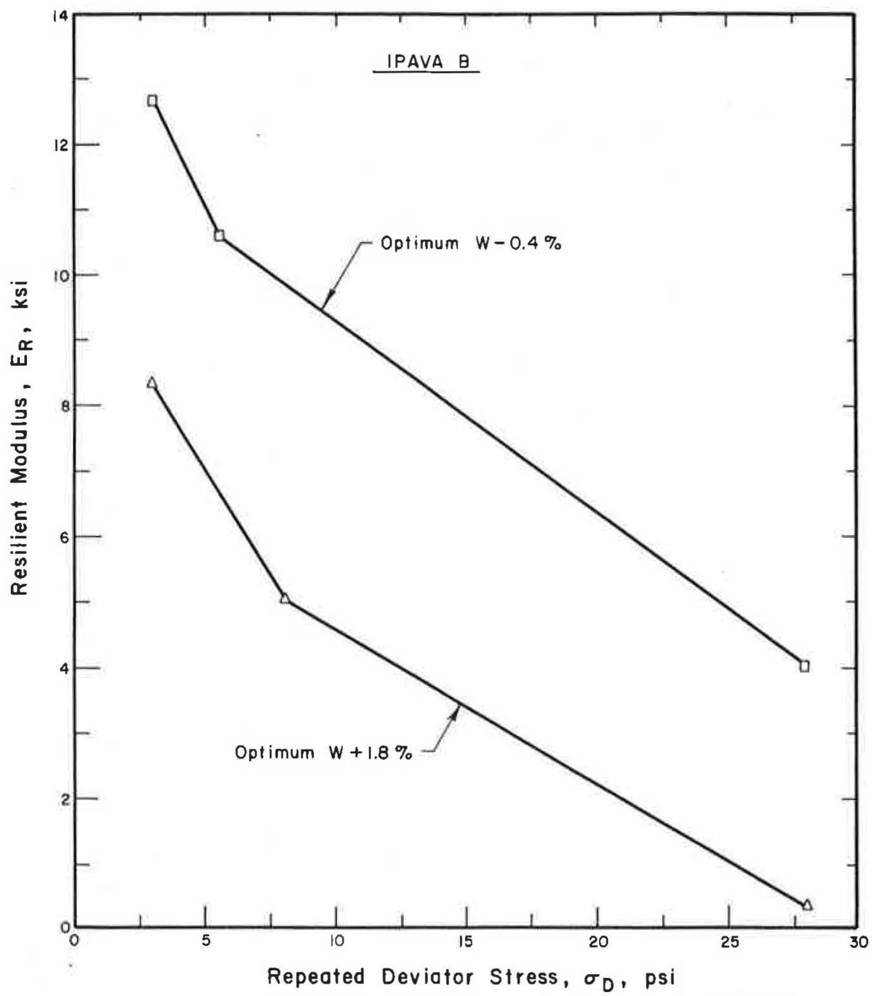

FIGURE 6 Typical stress-dependent resilient behavior of a fine-grained soil [AASHTO A-7-6(36)].

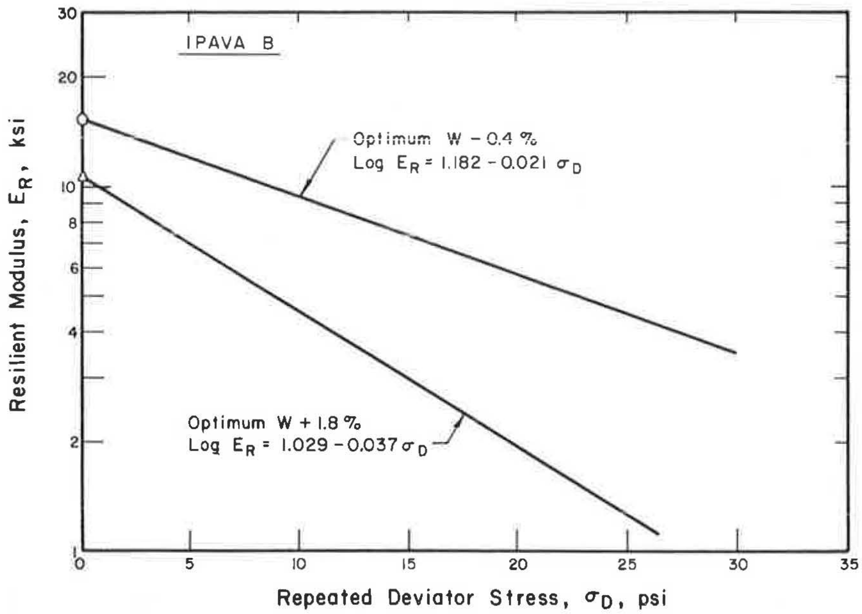

FIGURE 7 Semilog model for stress-dependent resilient behavior of a fine-grained soil [AASHTO A-7-6(36)].

Algorithms relating to AC and granular base and subbase rutting were not developed. It is intended that rut development within the AC portion of the pavement system be controlled by the proper selection of materials, mix design, and construction control. Similarly, rutting in the granular layer or layers is controlled by AC minimum thickness requirements and appropriate specifications to govern quality of, and placement procedures for, granular material.

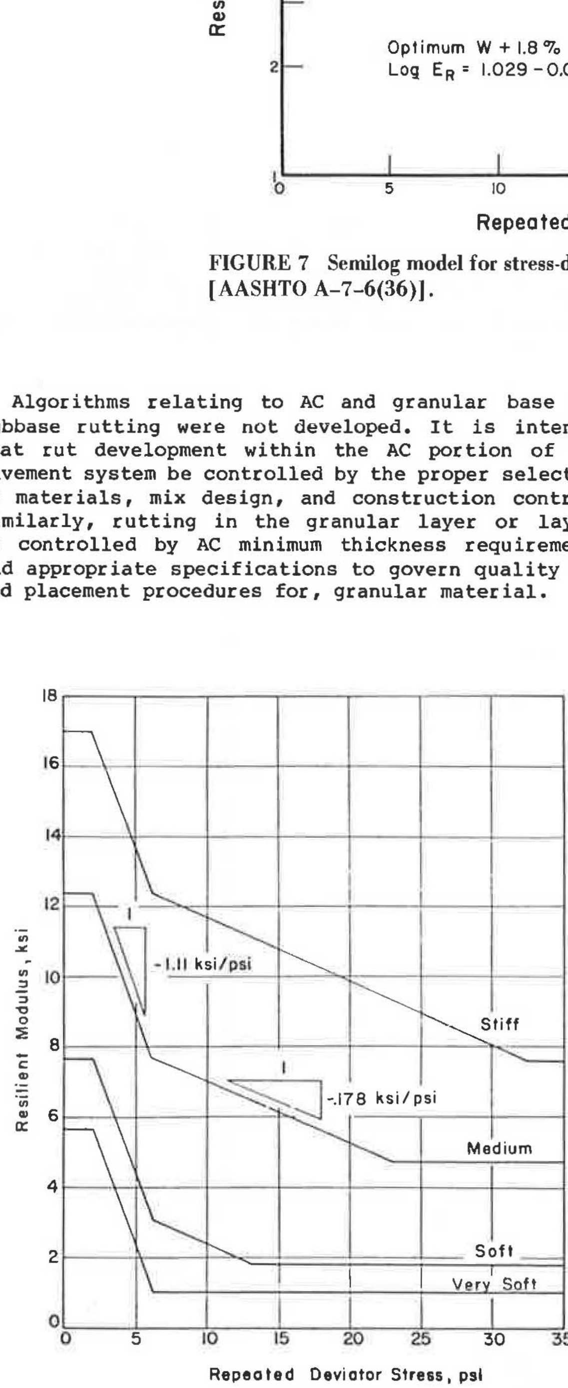

FIGURE 8 Resilient modulus-deviator stress relations for ILLI-PAVE subgrades.

Design Algorithms

The design algorithms were developed using the SPSS stepwise regression program (16). The regression equation is developed in a series of steps by entering the independent (prediction parameters) variables one at a time. At each step, the variable entered is the one that makes the greatest improvement in the prediction of the dependent variable (pavement response parameter). The pavement factors included in the analyses as independent variables were (a) thickness of AC, (b) thickness of granular base course, (c) AC modulus, and (d) subgrade E_{Ri}.

The ILLI-PAVE data base included information for 168 pavement configurations. These included AC thicknesses of 1.5, 3, 5, and 8 in. Granular base thicknesses were 4, 6, 9, and 12 in. for AC thicknesses of 1.5 and 3 in. For the 5- and 8-in. AC thicknesses, granular base thicknesses were 18 and 24 in. These thicknesses are representative of a broad range of typical flexible pavement designs. Four levels of subgrade moduli and strength (stiff, medium, soft, and very soft) and three levels of AC modulus (1,400, 500, and 100 ksi) were evaluated for each combination of AC and granular base thickness. The ILLI-PAVE response data are presented elsewhere (8).

Even though AC thicknesses of 2 to 3 in. are not uncommon on low-volume roads, the 1.5-in. data were not used in developing the algorithms for AC surfaced roadways. Examination of the 1.5-in. data in comparison with the 3- to 8-in. data revealed that the relative effect of AC thickness on some of the response parameters changes in the 1.5- to 3-in. thickness range.

For example, the strain in the bottom of the AC layer generally decreases with an increase in thickness. However, in most cases the strain in the 1.5-in. thickness was less than in the 3-in. thickness. It was concluded that inclusion of the 1.5-in. data would cause the algorithms to predict unconservative (low) strain values in some cases. Conversely, it was reasoned that exclusion of these data would permit the developed algorithms to more accurately fit the usual design thicknesses (3 to 5 in.) whereas

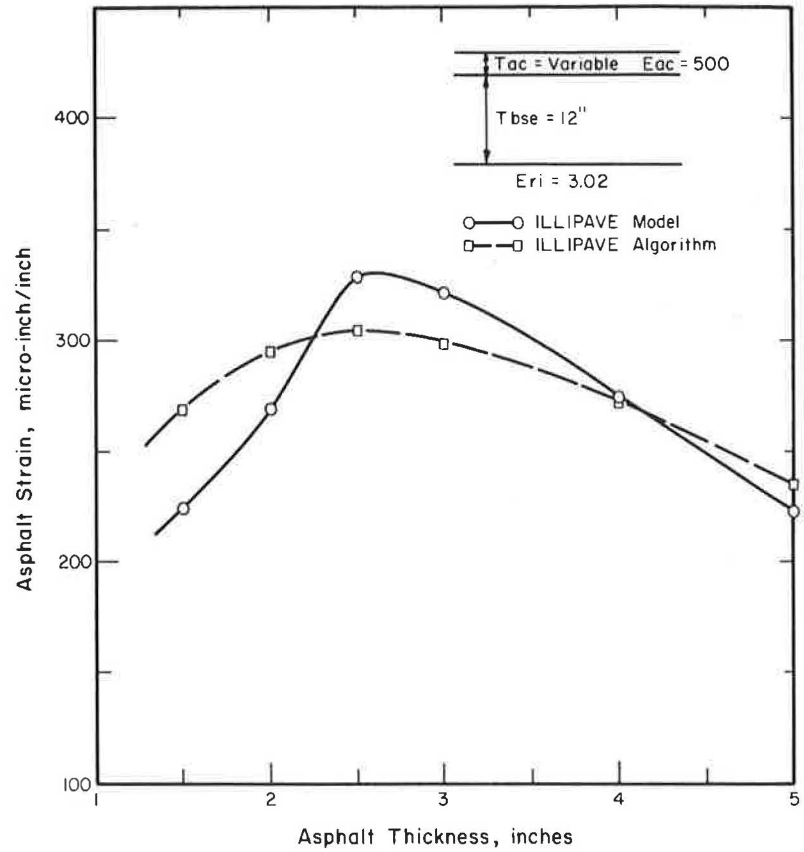

FIGURE 9 Comparison of ILLI-PAVE model and algorithm predictions of AC strain versus thickness for one design condition.

their extrapolation to lesser thicknesses would be somewhat conservative.

To demonstrate this effect, ILLI-PAVE predictions of AC strain for one design condition and AC thicknesses of 1.5 to 5 in. are shown in Figure 9. This plot shows a transition in the strain-thickness relationship at about 2.5 in. The cause of this transition has not been explored. A plausible explanation is that above approximately 2.5 in. the AC layer provides an "elastic structural layer" action, while a thinner AC layer exhibits a "membrane type" behavior.

For purposes of comparison, Figure 9 also includes a plot of the AC strains predicted by the developed algorithm. The algorithm predictions compare quite well with the model predictions and exhibit a similar, but less pronounced, transition.

The algorithms are shown in Figure 10. Included in the figure are the related statistical parameters that indicate the accuracy and reliability of the equations and the significance of the variables.

The various statistical parameters show that the algorithms are excellent. The standard errors of estimate and standard deviations of error are generally within the accuracy of the ILLI-PAVE model itself as determined by comparing the results of ILLI-PAVE analyses made using differing element mesh configurations.

The algorithms should not be used to solve for any of the independent variables. It might be tempt-

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ASPHALT STRAIN ALGORITHM

log eac =
       2.9496+.1289Tac-.5195(log Tbse)/Tac-.0807(log Eac)Tac-.0408(log Eri)
Std.Er.
Coef.    .0318 .0048     .0828                  .0015              .0089
Norm.
Coef            1.065   -.1378                 -1.917             -.0688
R = .990    Std. Dev. of Error = 26.9    Std. Err. of Est. = .03623 (1.087)

SUBGRADE DEVIATOR STRESS

log sd =
       1.7694-.0735Tac-.0222Tbse-.2539(log Eac)+.0223Eri
Std.Er.
Coef.    .0383 .0048     .0013     .0130          .0014
Norm.
Coef           -.4458    -.4786    -.3548         .2900
R = .985    Std. Dev. of Error = .901    Std. Err. of Est. = .06007 (1.148)
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FIGURE 10 Algorithms.

SUBGRADE DEVIATOR STRESS RATIO

log Sr =
.3056+.0560Tac-.0222Tbse-.0495(log Eac)Tac-.4242(log Eri)
Std.Er.
Coef. .0182 .0082 .0014 .0025 .0149
Norm.
Coef. .3105 -.4380 -.7897 -.4800
R = .987 Std. Dev. of Error = .0615 Std. Err. of Est. = .06074 (1.150)

SUBGRADE VERTICAL STRAIN

log ez =
4.5040-.0738Tac-.0334Tbse-.3267(log Eac)-.0231Eri
Std.Er.
Coef. .0392 .0049 .0014 .0133 .0014
Norm.
Coef -.3591 -.5789 -.3664 -.2404
R = .990 Std. Dev. of Error = 144 Std. Err. of Est. = .0615 (1.152)

SURFACE DEFLECTION

log DO =
1.9692+.0465Tac-.5637(log Tbse)/Tac-.0464(log Eac)Tac-.2079(log Eri)
Std.Er.
Coef. .0403 .0060 .1048 .0019 .0112
Norm.
Coef .4796 -.1872 -1.383 -.4383
R = .974 Std. Dev. of Error = 3.47 Std. Err. of Est. = .04586 (1.111)

SUBGRADE DEFLECTION

log Ds =
2.0169+.0375Tac-1.095(log Tbse)/Tac-.0405(log Eac)Tac-.2426(log Eri)
Std. Er.
Coef. .0549 .0082 .1430 .0026 .0153
Norm.
Coef. .4182 -.3920 -1.297 -.5515
R = .943 Std. Dev. of Error = 3.56 Std. Err. of Est. = .06258 (1.155)

ASPHALT STRAIN - DEFLECTION ALGORITHM

log eac =
.9102+1.1126(log DO)
Std. Er.
Coef. .0803 .0591
Norm.
Coef. .8889
R = .889 Std. Dev. of Error = 78.3 Std. Err. of Est. = .1147 (1.302)

SUBGRADE DEVIATOR STRESS RATIO - DEFLECTION ALGORITHM

log Sr =
-2.876+1.671(log DO)
R = 0.928 Std. Err. of Est. = 0.135 (1.36)

where:

eac = tensile strain in the bottom of the AC layer, in micro-in/in
ez = vertical strain at the top of the subgrade, in micro-in/in
sd = deviator stress at the top of the subgrade, in psi
Sr = deviator stress/unconfined compressive strength ratio
DO = surface deflection at the point of loading, in mils
Ds = subgrade deflection under the point of loading, in mils
Tac = thickness of the AC layer, in inches
Tbse = thickness of aggregate base course, in inches
Eac = resilient modulus of the AC layer, in ksi
Eri = "breakpoint" resilient modulus of the subgrade, in ksi

FIGURE 10 continued.

ing to use the surface deflection design algorithm as a pavement analysis tool to solve for or back calculate the subgrade resilient modulus. The general practice of using regression equations in this manner is not correct and can lead to unnecessary errors. The appropriate approach is to develop separate regression equations using each desired unknown parameter as the dependent variable. Analysis algorithms developed in this manner are reported elsewhere (8).

SUMMARY

ILLI-PAVE-based design algorithms for conventional flexible pavements (AC surface plus granular base and subbase) are presented. The algorithms are sufficiently accurate for inclusion in mechanistic design procedures. Pertinent design algorithm inputs are AC thickness, AC modulus, granular layer thickness, and subgrade E_{Ri}. The algorithms should not be extrapolated beyond the range of variables considered in the ILLI-PAVE data base unless check runs are conducted with ILLI-PAVE to determine the validity of the algorithms in the area of extrapolation.

Factors relating to climate, traffic, and transfer functions for local conditions must be appropriately evaluated and included in the development of a complete mechanistic design procedure.

ACKNOWLEDGMENTS

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