ODE Computer Program: Mechanistic-Empirical Asphalt Concrete Overlay Design

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This paper outlines a procedure for the design of asphaltic concrete overlays on existing asphalt concrete and portland cement concrete pavement surfaces. It discusses the type and form of information required by the microcomputer-based design program and all elements necessary for the user to design an overlay. The program provides an estimate of the time and number of traffic loads to failure by reflective cracking. The design equations are based on fracture mechanics and represent the existing pavement as a beam on an elastic foundation. The equations address fracture in the slab due to bending and shear caused by moving wheel loads and due to opening caused by thermal movement of the cracked existing pavements.

This paper is based on a report prepared for the Federal Highway Administration Office of Research (*1*) and outlines design procedures to address reflective cracking in asphalt concrete overlays.

Design equations were developed for six climatic zones using the approach developed in NCHRP Project 20-7, Task 17 (*2*). The equations were developed for flexible overlays of flexible as well as rigid pavements for each climatic zone for which data were available. A complete package of computer programs has been assembled to design overlays capable of resisting reflective cracking in the six geographic/climatic regions of the United States shown in Figure 1. The programs are designed for use on an IBM-compatible microcomputer.

This paper describes the type and form of information required by the program and discusses all elements necessary for the user to design an overlay. It does not cover in detail the theory or logic underlying the procedure.

SUMMARY OF DESIGN METHOD

The basic mechanisms generally believed to lead to reflection cracking are the vertical and horizontal movements of the underlying pavement layers. These damaging movements can be caused by traffic loadings, thermally induced contractions and expansions, or a combination of these mechanisms. Figure 2 illustrates the changes in bending and shear stresses that occur within an overlay as a wheel load passes over a crack in the original, underlying pavement. Cyclic shearing and bending movements cause the crack to propagate into the overlay. In addition, contraction and expansion of the pavement and the underlying layers with changes in temperature also contribute to the growth of reflection cracks with repeated traffic applications.

The overlay design procedure is mechanistic-empirical in concept. Mechanistic equations represent the existing pavement as a beam on an elastic foundation. In-situ deflection testing was used to determine the structural parameters needed to characterize the pavement. Basic asphalt concrete properties are used with fracture mechanics concepts to calculate the rate at which cracks in the existing pavement will propagate through the overlay.

The rate of crack propagation in asphalt concrete was predicted using the empirical power law relation developed by Paris and Erdogan (*3*):

$$(dc/dN) = A(DK)^n$$

where

DK = change in stress intensity factor amplitude,
A, n = fracture parameters of the material,
c = crack length, and
N = number of load applications.

Integrating this equation yields

$$N_f = o^h \{dc/[A(DK)^n]\}$$

where

N_f = number of load applications to failure, and
o^h = thickness of overlay.

The use of the above equations to determine the life of an overlay requires a knowledge of the stress intensity factor, K, and the material constants A and n within the overlay. Detailed procedures to determine these parameters are presented by Jayawickrama et al. (*1*). The stress intensity factor in the overlay for each of the crack growth mechanisms was determined by using a formulation that combines beam-on-elastic foundation theory and the finite-element method. The mechanistic equations were calibrated with in-service data for each of the climatic zones.

To use these equations, the design engineer supplies information on the types and thicknesses of layers in the existing pavement, the deflection data for the pavement, the material properties of the asphalt concrete being considered for use in

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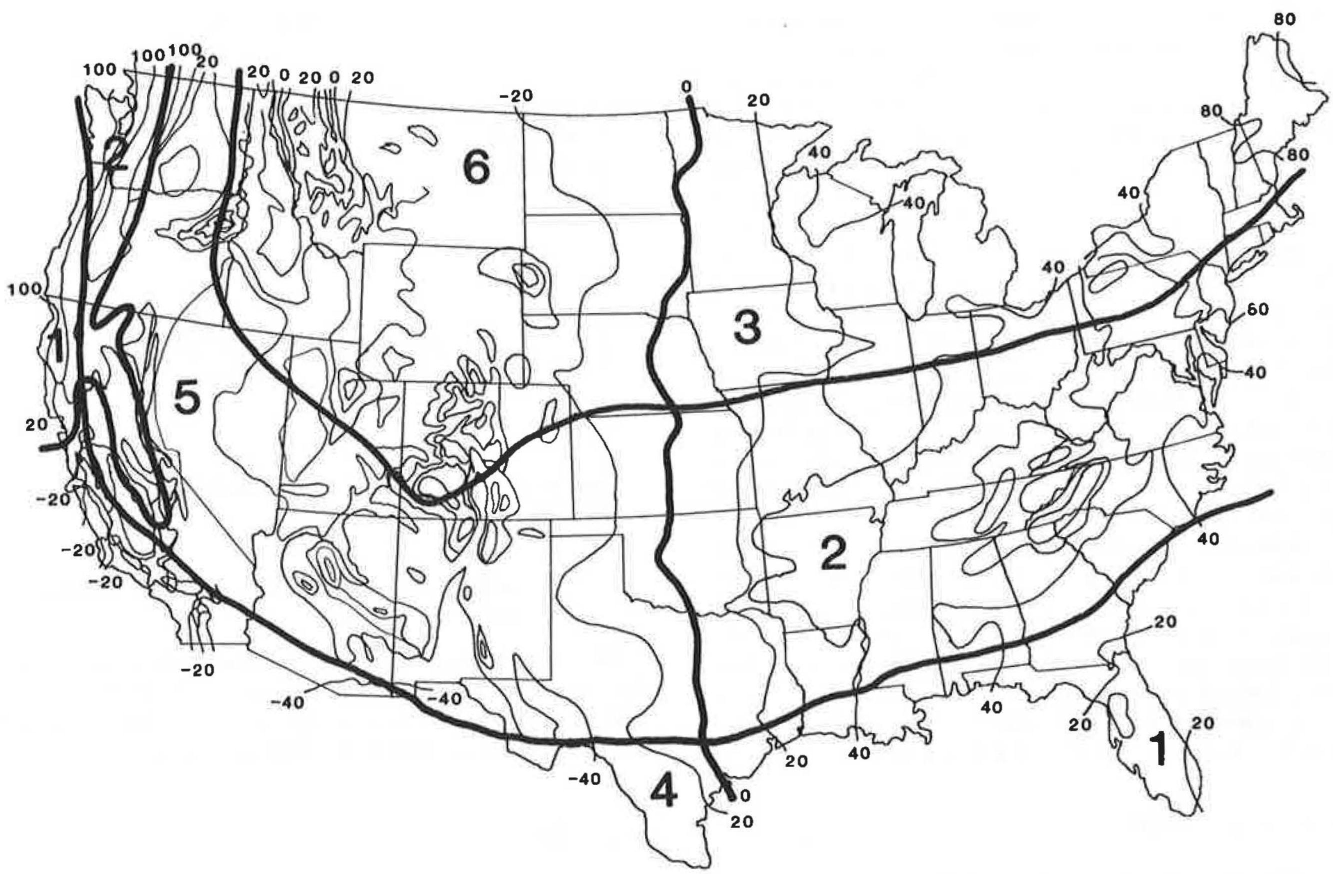

FIGURE 1 The six climatic regions in the United States are characterized as follows: (1) wet, no-freeze; (2) wet, freeze-thaw cycling; (3) wet, hard-freeze, spring thaw; (4) dry, no-freeze; (5) dry, freeze-thaw cycling; (6) dry, hard-freeze, spring thaw.

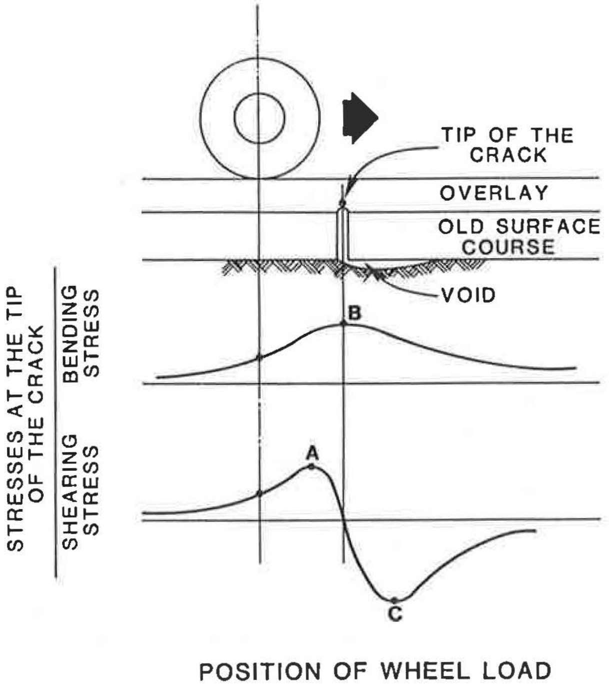

FIGURE 2 Stresses induced at the cracked section by a moving wheel load.

the overlay, thicknesses of overlay being considered, the environmental zone in which the pavement is located, and the traffic to which the overlay is expected to be subjected. The time and number of traffic loads to failure by reflective cracking are predicted by the ODE program. Failure can be set at three different levels of damage. A detailed description of the development is presented by Jayawickrama et al. (*1*).

ODE DESIGN GUIDE

Selection of Input Data

In this design procedure, the following data are required:

1. environmental data,
2. past construction history,
3. traffic data,
4. material characterization,
5. deflection data, and
6. condition evaluation (distress).

Environmental Data

Climatic and geographic factors influence performance. The United States can be divided into the six climatic zones

(Fig. 1) based on moisture availability and freeze-thaw activity (*2*). The boundary separating the wet zones 1, 2, and 3 from the dry zones 4, 5, and 6 is the major North-South contour on which the Thornthwaite Index is zero. [The Thornthwaite Index is a measure of moisture balance between rainfall and potential evapotranspiration (*4, 5*).] The boundary separating the nonfreeze zones 1 and 4 from the freeze-thaw cycling zones 2 and 5 is taken from U.S. Weather Bureau data as reported in Highway Research Board Special Report 1 (*6*). The boundary line represents an extreme frost penetration of 5 in. (13 cm), which corresponds to the typical minimum depth of pavement. The boundary separating the freeze-thaw cycling zones 1 and 5 from the hard-freeze zones 3 and 6 is based on a Corps of Engineers contour representing a 60-day duration of the normal freeze index (*7*). Any area in which freezing conditions persist for more than two months is considered to be in the hard-freeze zone. (See Figure 1 for a description of the zones.)

Pavements are expected to perform differently and exhibit different types of predominant distress as the climate changes from warm and wet to dry with a hard freeze every winter. In addition to the determination of the climatic region, the 24-hr temperature drop for the pavement location is needed. It is calculated as the monthly maximum temperature minus the monthly minimum temperature. This can be obtained from a National Climate Center publication (*8*).

Past Construction History

The following construction history data are required:

1. type of overlay: AC/AC (asphaltic concrete overlay on existing asphalt concrete) or AC/PCC (asphaltic concrete overlay on existing portland cement concrete pavement surfaces),
2. thickness of layer or layers of asphalt concrete,
3. thickness of underlying PCC slab, and
4. joint load transfer across PCC joints.

The above data are used in conjunction with nondestructive deflection testing data to back-calculate the in-situ modulus of elasticity of the surface and supporting base layers. For this analysis, the base and subgrade are combined into one homogeneous layer. The in-situ layer thicknesses of the pavement surfaces(s) should be obtained by coring at selected locations where deflection testing was conducted. The use of as-built records to define surface thickness will generally lead to appreciable errors in the back-calculated modulus of the surface and is therefore not recommended.

The existing load transfer across cracks and PCC joints can be determined from deflection testing data, provided that at least one deflection sensor is placed on the unloaded slab during testing while the load plate is positioned near the pavement crack or joint. The existing load transfer can be calculated as follows:

$$\% LT = (dU/dL)100$$

where

$\% LT$ = percent load transfer,
dU = deflection of the pavement on the unloaded side of the crack or joint, and
dL = deflection of the pavement on the loaded side of the crack or joint.

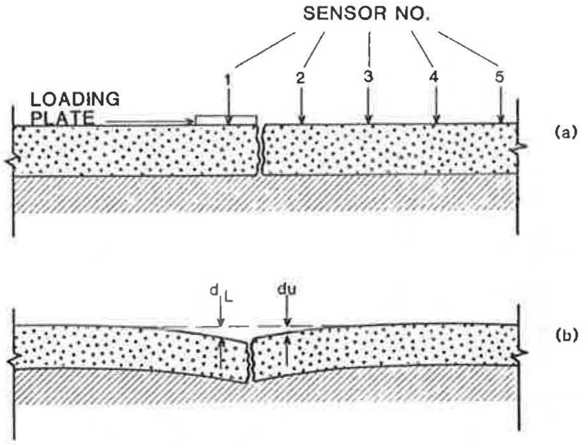

FIGURE 3 Measurement of load transfer with a deflection device.

Measured load transfers are grouped into three categories: low, medium, and high, which correspond to 0–40, 40–70, and 70–100 percent, respectively. A method generally used for making this measurement is illustrated in Figure 3.

Traffic Data

The amount of accumulated 18-kip single-axle loads (ESALs) expected to occur in each lane is necessary to determine life of the overlay. This information is typically collected from the traffic bureau, W-4 tables, or traffic maps published by highway agencies. Traffic is expressed in terms of ESALs per day.

Material Characterization

Both the existing materials and the materials in the overlay affect the life of the overlay. The program uses nondestructive deflection testing (NDT) data in conjunction with pavement layer thicknesses in an idealized two-layer pavement system to back-calculate the stiffness of the asphalt concrete and supporting layers.

For sections with rigid pavements (AC/PCC), the modulus of the subgrade reaction, *K*, is used by the program to determine the modulus of elasticity of the support. Representative values for the modulus of subgrade reaction, *K*, for the subsoil are shown in Table 1, based on classification.

Programs are supplied to determine the modulus of elasticity of the asphalt overlay. These programs are based on the Van der Poel (*9*) and McLeod (*10*) nomographic procedures, which use basic material properties of the bitumen and asphalt concrete to compute the resulting mix stiffness.

The Van der Poel method is based on the results of experimental research by the Shell Oil Company and requires the following properties of the bitumen: penetration at 77°F, ring and ball softening point, asphalt percent by weight of aggregate, time of loading, age of mix or time in service, and volume concentration of minerals.

TABLE 1 MODULUS OF SUBGRADE REACTION *K* FOR DIFFERENT SOIL TYPES

Classification	K(pci)
Plastic clays	75
Silts and silty clays	150
Sands and gravels	300
Cement or asphalt treated base	500

The McLeod method utilizes a different quantitative measure for temperature susceptibility, the pen-vis number, which is based on an asphalt cement's penetration at 77°F (25°C) and viscosity in centistokes at 275°F (135°C). To use McLeod's method, the following properties of the bitumen and mix are required: penetration at 77°F (25°C), penetration index, asphalt percent in the mix, viscosity in centistokes, service temperature, and *CV* (volume concentration of minerals).

Deflection Data

Deflection testing is used to back-calculate the in-situ modulus of elasticity of the existing pavement surface and supporting layers. The design procedure accepts the following types of deflection testing devices: Dynaflect, falling-weight deflectometer, Road Rater 400B, Road Rater 2000, and Road Rater 2008.

The program contains default values for the typical sensor configuration of each of the devices mentioned above (*11*). Data from at least five test locations are required to compute the mean and standard deviation of the pavement and supporting layer stiffnesses for any given section. The distribution of moduli values around the mean is assumed to be normal; therefore, the Student *t*-distribution is used to calculate a design modulus value for the pavement based on the desired confidence level selected by the user. Confidence levels of 50, 80, 90, 95, and 99 percent are allowed.

The deflection data should be carefully screened to ensure that they are relatively uniform within a design section. If the data are dramatically different, the design project may need to be divided into subprojects that exhibit relatively uniform deflection responses.

The deflection data that are to be used for back-calculating material properties should be collected in areas of the pavement that are relatively free from transverse cracking. In general, the load plate should be positioned at least 6 ft from any surface cracks during testing. Additional deflection testing may be obtained across transverse cracks for load transfer measurements, as described earlier; however, these data are *not* used to determine the layer stiffnesses.

Condition Evaluation (Distress)

Because this study is concerned with the potential for reflection cracking of overlays, only this type of distress was used in this analysis. Two forms of reflection cracking were considered: transverse and longitudinal. However, it is suggested that quantitative visual observations of all existing pavement distress be made at the time of testing. This survey will serve as a valuable guide when maintenance alternatives are considered.

The program requires the average transverse crack spacing, in inches, to perform the calculations. For overlays on existing asphalt pavements, a damage level of 1.0 is assumed to equal one crack completely across the lane every 1 ft or the equivalent length of transverse and longitudinal cracks. A damage level of 0.0 is assumed to equal no cracking. A linear relation between damage levels of 0.0 and 1.0 is assumed.

For overlays of portland cement concrete pavements, a damage level of 1.0 is assumed to occur when one crack completely crosses the lane every 10 ft or the equivalent length of transverse and longitudinal cracks. A damage level of 0.0 is assumed to equal no cracking, and a linear relationship between 0.0 and 1.0 is assumed.

Program Description

The program computes either the number of years to reach specific damage levels of reflective cracking for a given AC overlay thickness or the required thickness of an AC overlay when the expected service life is identified. This process is based on the use of the mechanistic model to calculate the material properties of the surface and subgrade support, and the use of finite-element analysis, which determines the magnitudes of stress intensity factors occurring within an actual pavement structure with variable crack length and load transfer values.

The following major steps are used in the design process:

1. selection of input data according to Tirado-Crovetti et al. (*12*) as detailed in chapter 2 of their report;
2. determination of layer properties from measured surface deflections of the existing pavement. The program searches for the elastic moduli that fit the measured basin to the calculated basin with the least average error. This computer program, developed at the Texas Transportation Institute (*13*), uses a pattern-search technique to fit deflection basins with elliptic integral function-shaped curves. These curves are solutions to the differential equations used in elastic-layer theory. The theoretical development of the deflection equation used in the program is discussed by Lytton and Michaleak (*13*). The required data include thickness of AC and granular base layers, force applied and radius of loading plate, and measured deflection values as well as their radial distances from center of loading plate;
3. determination of the mix stiffness of the overlay and the slope *m*. described by Tirado-Crovetti et al. (*12*) in the "Material Characterization" section of chapter 2 of their report, and;
4. calculation of the number of cycles to failure of the overlay using integration of Paris' crack growth law.

Output Description and Data Interpretation

The output format of the ODE program has been designed to best inform the engineer of anticipated reflection cracking problems. Although the required overlay thickness is of ultimate interest to the user, the results of intermediate computations can also be of value when evaluating alternate maintenance strategies other than an overlay. An example design is provided to illustrate the input and output of the program.

Sample Design

The following example illustrates the design of an asphaltic concrete overlay on an existing asphalt concrete pavement surface (AC/AC). The design requirements for this example are described in the same order as they appear during program execution.

Identification Information

Highway Name: USTH 61
Mile Post Start: 0.000
Mile Post End: 2.000
Project Number: 100
County: Carlton

Environmental Information

24-Hour Temperature Drop (°F): 22 (12.2°C)
Climatic Region (1–6): 2

The site of this highway construction project is in a location that can be environmentally classified as U.S. Climatic Region 2, i.e., wet, freeze-thaw cycling (as shown in Figure 1). In addition to the determination of the climatic region, the 24-Hour Temperature Drop for that particular area is needed. This is calculated as:

24-Hour Temperature Drop = Max. Temp. – Min. Temp
24-Hour Temperature Drop = 22°F (12.22°C)

Construction Information for Asphalt Concrete Pavement

AC Thickness (in.): 6.0 in. (15.24 cm)
Degree of Aggregate Outerlock: (L)ow, (M)edium, (H)igh: M

The program requires the thickness of the existing AC pavement and the type of section (AC/AC or AC/PCC). In addition to this information, the program requires the degree of aggregate interlock in order to calculate the bending efficiency factor for the cracked pavement.

Traffic Information

Traffic in 18-kips ESAL per Day: 500

Material Characterization for AC/AC

Base and Subbase Properties
Fixed Modulus of Support (PSI): ________

Surface Properties
Fixed Modulus of the AC (PSI): ________

"Fixed modulus" requires that the user enters his or her own values. If these values are to be calculated based on deflection data, a "0" is entered.

The modulus of elasticity of the asphalt overlay is determined using material properties of the bitumen. Five options are provided based on the available data as described below:

Selection of Asphalt Properties

Select Paths A–E:
Path A–
Viscosity at 275°F in CST
Penetration at 77°F in 0.1 mm
Service temperature
CV
Path B–
Viscosity at 140°F in poises
Penetration at 77°F in 0.1 mm
Service temperature
CV
Path C–
Penetration index
Softening point R & B
Service temperature
CV
Path D–
Penetration at 77°F
Softening point R & B
Service temperature
CV
Path E–
Penetration at 77°F
Pen. w/specified temp
Service temperature
CV

The path used is governed by the available material data. For this example, path A will be used:

Viscosity at 275°F in CST: 250
Penetration at 77°F in 0.1 mm: 85
Service Temperature: 60
CV: 0.883

Deflection Data

Deflection testing is used to determine the stiffness of the in-service pavement. For this example, the FWD deflection data listed below are used:

FWD Load: 9,226 lbf
Maximum Deflection: 13.54 mils
Deflection at 12 in.: 8.9 mils
Deflection at 24 in.: 7.56 mils
Deflection at 36 in.: 5.2 mils

If five or more deflection sets are used to define deflection basins, confidence levels need to be defined.

TABLE 2 SAMPLE COMPUTER OUTPUT: CALCULATED PROJECT RESULTS FOR AC/AC

Parameter	Value
Highway name	USTH 61
Mile post start	0.000
Mile post end	2.000
Project number	100
County	CARLTON
24-Hr temperature drop (°F)	22
Climatic region	2
Traffic (18-kip ESALs/day)	500
Thickness of the existing AC layer (in.)	6
Modulus of the existing AC layer (Psi)	457,000
Modulus of the support (Psi)	22,500
Thickness of the overlay (in.)	2.5
Modulus of overlay (mix stiffness) (Psi)	565,000
Slope of LOG mix stiffness vs. LOG time curve	0.653
Life of the overlay (yrs) for low damage	3.9
Life of the overlay (yrs) for medium damage	4.5
Life of the overlay (yrs) for high damage	5.7

Condition Evaluation (Distress)

Average Crack Spacing: 120 in. (304.8 cm)

The program requires the average crack spacing in order to perform calculations.

Table 2 provides a sample output of the program.

Sensitivity Analysis

A sensitivity analysis was conducted to demonstrate the reasonableness of the procedure and to identify the design inputs that influence the overlay thickness calculated. This analysis allows the user to prioritize the importance of design input for a particular overlay design procedure and allocate time and money to each input accordingly. The sensitivity analysis was conducted by individually varying the following major inputs: thickness of the overlay, modulus of the overlay, level of damages, climatic zones, traffic, service temperature, 24-hr temperature drop, and crack spacing.

During the sensitivity analysis, the following pavement parameters were used as the standard section AC/AC:

Existing asphalt concrete: 4 in. (10.16 cm)
Granular base: 7 in. (17.78 cm)
Crack spacing: 120 in. (304.8 cm)
Aggregate interlock: M (medium)
24-Hr temperature drop: 22.5°F (12.5°C)
Modulus-of-support layer: 25,000 psi (172,414 kPa)
Modulus of existing AC: 400,000 psi (2,758,621 kPa)

The pavement section that was selected as the base for the analysis of asphalt concrete overlays of existing portland cement concrete pavement surfaces is as follows:

Subgrade soil type: 3 (sands and gravel)
Existing PCC slab: 9 in. (22.86 cm)
Crack spacing: 360 in. (921.60 cm)
Aggregate interlock: M (Medium)
24-Hr temperature drop: 22.5°F (12.5°C)

Tables 3, 4, and 5 present a representative portion of the results of the sensitivity analysis. As expected, increasing the overlay thickness results in an increase in the life of the overlay for all damage levels in all regions. A dramatic increase in the life of the overlay is seen for the lower modulus value overlays. The climatic region has a large impact on time to failure of the overlay. Using the same parameters for traffic, thickness of overlay, and modulus of the overlay, very different results were obtained when the climatic region was changed.

Changes in service temperature, 24-hr temperature drop, and climatic region also have a major impact on the life of the overlay for all regions.

CONCLUSIONS AND RECOMMENDATIONS

The ODE program offers potential help for highway engineers to determine when reflective cracking will develop in an asphalt overlay on the basis of asphalt cement and mix properties. The equations used in this program were developed for six climatic regions for asphalt overlays of asphalt concrete pavements and for two regions for asphalt for asphalt overlays of portland cement concrete pavements.

The mechanistic-empirical approach provides an excellent means to develop design equations that are soundly based on mechanistically correct concepts with a limited amount of parameters. However, they will only be as good as the data used to calibrate them. Until accurate data are available, the resulting design equations may be less accurate than desired.

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TABLE 3 RESULTS OF SENSITIVITY ANALYSIS VARYING THICKNESS AND MODULUS OF OVERLAY FOR MEDIUM DAMAGE LEVEL (0.40) AC/AC PAVEMENT SECTION

Climatic Region	Damage Level	Traffic (18-kip ESAL/day)	Thickness of Overlay (in.)	Modulus of AC Overlay (Psi)	Time to Reach Medium-Level Reflective Cracking (yr)
1	.40	500	1.0	350,000	2.63
1	.40	500	2.0	350,000	9.23
1	.40	500	3.0	350,000	20.21
1	.40	500	4.0	350,000	19.73
1	.40	500	1.0	700,000	0.75
1	.40	500	2.0	700,000	2.83
1	.40	500	3.0	700,000	3.86
1	.40	500	4.0	700,000	4.02
2	.40	500	1.0	350,000	1.41
2	.40	500	2.0	350,000	4.97
2	.40	500	3.0	350,000	10.88
2	.40	500	4.0	350,000	12.95
2	.40	500	1.0	700,000	0.41
2	.40	500	2.0	700,000	1.52
2	.40	500	3.0	700,000	2.43
2	.40	500	4.0	700,000	3.25
3	.40	500	1.0	350,000	2.24
3	.40	500	2.0	350,000	7.88
3	.40	500	3.0	350,000	17.24
3	.40	500	4.0	350,000	30.48
3	.40	500	1.0	700,000	0.63
3	.40	500	2.0	700,000	2.36
3	.40	500	3.0	700,000	5.35
3	.40	500	4.0	700,000	9.80
4	.40	500	1.0	350,000	1.71
4	.40	500	2.0	350,000	6.00
4	.40	500	3.0	350,000	13.14
4	.40	500	4.0	350,000	11.34
4	.40	500	1.0	700,000	0.48
4	.40	500	2.0	700,000	1.83
4	.40	500	3.0	700,000	2.27
4	.40	500	4.0	700,000	1.92
5	.40	500	1.0	350,000	3.21
5	.40	500	2.0	350,000	11.29
5	.40	500	3.0	350,000	24.72
5	.40	500	4.0	350,000	41.57
5	.40	500	1.0	700,000	0.90
5	.40	500	2.0	700,000	3.40
5	.40	500	3.0	700,000	7.41
5	.40	500	4.0	700,000	13.24
6	.40	500	1.0	350,000	3.08
6	.40	500	2.0	350,000	10.87
6	.40	500	3.0	350,000	23.78
6	.40	500	4.0	350,000	33.16
6	.40	500	1.0	700,000	0.87
6	.40	500	2.0	700,000	3.26
6	.40	500	3.0	700,000	6.01
6	.40	500	4.0	700,000	9.38

NOTE: 1 inch = 2.54 cm, 1 Psi = 6.894 kilopascals, 1 kip = 4.448 kilonewtons

TABLE 4 RESULTS OF SENSITIVITY ANALYSIS VARYING THICKNESS AND MODULUS OF OVERLAY FOR HIGH DAMAGE LEVEL (0.50) IN AC/PCC PAVEMENT SECTIONS

Climatic Region	Damage Level	Traffic (18-kip ESAL/day)	Thickness of Overlay (in.)	Modulus of AC Overlay (Psi)	Time to Reach High-Level Reflective Cracking (yr)
2	0.50	500	1.5	350,000	0.99
2	0.50	500	2.0	350,000	2.08
2	0.50	500	3.0	350,000	5.87
2	0.50	500	4.0	350,000	12.27
2	0.50	500	5.0	350,000	21.74
2	0.50	500	1.5	700,000	0.34
2	0.50	500	2.0	700,000	0.72
2	0.50	500	3.0	700,000	2.09
2	0.50	500	4.0	700,000	4.43
2	0.50	500	5.0	700,000	7.93
3	0.50	500	1.5	50,000	9.52
3	0.50	500	2.0	350,000	19.90
3	0.50	500	3.0	350,000	56.24
3	0.50	500	1.5	700,000	3.30
3	0.50	500	2.0	700,000	7.00
3	0.50	500	3.0	700,000	20.20

NOTE: 1 inch = 2.54 cm, 1 Psi = 6.894 kilopascals, 1 kip = 4.448 kilonewtons

TABLE 5 RESULTS OF SENSITIVITY ANALYSIS VARYING SERVICE TEMPERATURE OF OVERLAY FOR LOW DAMAGE LEVEL (0.33) IN AC/AC PAVEMENT SECTION

Climatic Region	Damage Level	Service Temperature (°F)	Modulus of AC Overlay (Psi)	Time to Reach Low-Level Reflective Cracking (yr)
1	0.33	50	977,298	1.89
1	0.33	60	566,163	5.61
1	0.33	70	273,712	16.97
2	0.33	50	977,298	1.05
2	0.33	60	566,163	2.94
2	0.33	70	273,712	8.86
3	0.33	50	977,298	1.91
3	0.33	60	566,163	4.75
3	0.33	70	273,712	14.62
4	0.33	50	977,298	1.27
4	0.33	60	566,163	3.89
4	0.33	70	273,712	11.77
5	0.33	50	977,298	3.10
5	0.33	60	566,163	7.72
5	0.33	70	273,712	23.49
6	0.33	50	977,298	2.24
6	0.33	60	566,163	5.87
6	0.33	70	273,712	18.09

NOTE: °F = 5/9°C or Kelvins, 1 in. = 2.54 cm, 1 Psi = 6.894 kilopascals, 1 kip = 4.448 kilonewtons

REFERENCES

1. P. W. Jayawickrama, R. E. Smith, R. L. Lytton, and M. R. Tirado-Crovetti. *Development of Asphalt Concrete Overlay Design Equations*. Vol. I. Final Report No. DTFH61-84-C-00053. Washington, D.C., 1987.
2. P. L. Lytton and A. Garcia-Diaz. *Evaluation of AASHO Road Test Satellite and Environmental Studies* Final Report, NCHRP Project 20-7, Task 17, Texas Transportation Institute, Texas A&M University, College Station, 1983.
3. P. C. Paris and F. Erdogan. A Critical Analysis of Crack Propagation Laws. *Transactions of the ASME, Journal of Basic Engineering,* Ser. D, 85, No. 3, 1963.
4. C. W. Thornthwaite. An Approach Toward a Rational Classification of Climate. *Geographical Review,* Vol. 38, No. 1, 1948, pp. 55–94.
5. S. H. Carpenter, R. L. Lytton, and J. A. Epps. *Environmental Factors Relevant to Pavement Cracking in West Texas.* Research Report 18-1, Texas Transportation Institute, Texas A&M University, College Station, January 1974.

6. *Special Report 1: Frost Action in Roads and Airfields.* HRB, National Research Council, Washington, D.C., 1951, p. 123.
7. *Report on Frost Investigation, 1944–1945.* New England Division, U.S. Army Corps of Engineers, U.S. War Department, Boston, Mass., April 1947.
8. *Climatology of the United States No. 81 (by State) Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951–80.* National Climatic Center, Asheville, N.C.
9. C. Van der Poel. A General System Describing the Viscoelastic Properties of Bitumens and Its Relation to Routine Test Data. *Journal of Applied Chemistry,* Vol. 4, May 1954.
10. N. W. McLeod. Asphalt Cements: Pen-Vis Number and Its Application to Moduli Stiffness. *Journal of Testing and Evaluation,* Vol. 4, No. 4, 1976.
11. R. E. Smith and R. L. Lytton. *Synthesis Study of Nondestructive Testing Devices for Use in Overlay Thickness Design of Flexible Pavements.* Report No. DTFH61-82-C-00073. Washington, D.C., 1983.
12. M. R. Tirado-Crovetti, M. T. Darter, R. E. Smith, P. W. Jayawickrama, R. L. Lytton. *Development of Asphalt Concrete Overlay Design Equations*, Vol. II. Final Report No. DTFH61-84-C-00053. Washington, D.C., 1987.
13. R. L. Lytton and C. H. Michaleak. *Flexible Pavement Deflection Using Elastic Moduli and Field Measurements.* Research Report 207-7F, Texas Transportation Institute, Texas A&M University, College Station, August 1979.

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