Backcalculation of Asphalt Concrete–Overlaid Portland Cement Concrete Pavement Layer Moduli

KATHLEEN T. HALL AND ALAEDDIN MOHSENI

The United States currently has a large and growing mileage of portland cement concrete (PCC) highway pavement overlaid with asphalt concrete (AC). Evaluation of existing AC/PCC pavements and selection of second rehabilitation strategies are thus becoming increasingly pressing concerns of state highway agencies. Use of deflection test data to interpret the condition of the underlying PCC is crucial to a structural evaluation and second overlay design for this type of pavement. However, interpretation of deflection measurements is perhaps more difficult for AC/PCC pavement than for any other pavement type. Many of the available tools for backcalculation of pavement layer moduli are limited in their ability to successfully analyze AC/PCC pavement. A simple and straightforward procedure for backcalculation of AC/PCC pavement layer moduli is described. The approach is built on available closed-form solutions to backcalculation for bare PCC pavement, with adjustments made to measured deflections to account for the influence of the AC layer. An example using deflection data collected on an AC-overlaid PCC Interstate highway section indicates that the backcalculation procedure produces reasonable results that are consistent with those obtained from other backcalculation methods and with the known condition of the pavement.

The most widely used rehabilitation technique for portland cement concrete (PCC) pavements is resurfacing with asphalt concrete (AC). Many states have already overlaid substantial portions of their PCC highway pavement mileage with AC and plan to overlay more in the near future. Thus, the mileage of AC-overlaid PCC is growing. Evaluation and rehabilitation of AC/PCC pavements are becoming increasingly prominent and pressing concerns of state highway agencies.

Much of the distress seen in AC/PCC pavements is reflected from deterioration in the underlying PCC slab. The PCC distresses that are most responsible for AC overlay deterioration are slab cracking, punchouts, joint deterioration, deterioration resulting from poor PCC durability ("D" cracking and reactive aggregate distress), and deterioration of PCC and AC patches. The deterioration will also reflect through a second AC overlay unless it is identified and corrected. This requires a coordinated effort of distress surveying, nondestructive deflection testing (NDT), and coring for materials samples. The information obtained is valuable in establishing a profile of condition along the length of the project, which may then be used to identify areas requiring repair and to determine second rehabilitation options.

Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Ill.

Analysis of deflections measured at locations where the underlying PCC is severely deteriorated, as in the case of "D" cracking, will invariably produce extremely low backcalculated PCC modulus values. They should not be interpreted as the true stress-strain response of the PCC as a homogeneous elastic layer, but rather as an indication of the extent to which its behavior departs from that of a sound slab (i.e., the extent of the PCC's deterioration). The ability to diagnose the condition of the PCC from deflection measurements is particularly valuable in evaluation of AC/PCC pavements, because the extent of the deterioration of the PCC is often not fully evident from visible distress. In some cases, the deterioration of the PCC may be so severe and widespread that the only feasible rehabilitation alternatives are substantial structural improvements, such as a very thick AC overlay, an unbonded PCC overlay, or reconstruction.

Structural evaluation using NDT data is perhaps more difficult for AC/PCC pavements than for all other pavement types. The available computer programs for backcalculation of pavement layer moduli possess a variety of theoretical and practical limitations, which hinder their usefulness in AC/PCC pavement analysis. Valid and repeatable results are typically only obtained from even the best of these tools by knowledgeable pavement engineers with considerable experience in backcalculation.

Previous research (*1*,*2*) has demonstrated that a closed-form solution exists for backcalculation of PCC and subgrade moduli for slab-on-grade systems. One of the advantages of this direct approach to determination of pavement layer properties is its efficiency in processing deflection data. However, the direct approach applies only to two-layer systems in which the top layer behaves like a plate (e.g., a PCC slab). This approach is not directly applicable to analysis of AC-overlaid PCC pavements, because it does not account for the influence of the AC overlay on deflections. The adaptations to the closed-form approach that are required for backcalculation of AC/PCC pavement layer moduli are described in this paper.

LIMITATIONS OF AVAILABLE BACKCALCULATION TOOLS

Most of the tools currently used for backcalculation of pavement moduli are computer programs based on multilayer elastic theory. The programs determine the elastic moduli of pavement layers by matching deflection basin measurements to deflections predicted by multilayer elastic theory, given the layer thicknesses and Poisson's ratios and the magnitude and area of the applied load. A few backcalculation programs exist that use the equivalent thickness concept (i.e., reduction of a multilayer elastic system to an equivalent system of fewer layers for which a solution is more easily obtainable). Backcalculation may also be done using plate theory [i.e., two-layer elastic theory for the special case of a rigid upper layer that exhibits pure bending (without shear deformation) in response to load].

In backcalculation programs based on multilayer elastic theory, actual deflections are matched to predicted deflections in one of two ways: by iterative numeric integration of elastic layer equations or by searching a data base of deflection basins that have been generated for ranges of layer thicknesses and moduli. Backcalculation by the equivalent thickness method may also be done by iteration or by data base search. Iteration was used in the first plate theory backcalculation routines, but has since been replaced by direct solution of closed-form equations.

Iterative Backcalculation Programs

BISDEF (*1*), CHEVDEF (*2*), WESDEF (*3*), and ELSDEF are examples of iterative backcalculation programs that make repetitive calls to an elastic layer analysis subroutine [e.g., BISAR (*4*) for BISDEF] in order to match measured deflections to deflections predicted for program-selected layer moduli. The process stops when the measured and predicted deflections match within tolerance levels set by the user or when the maximum number of iterations set by the user is reached. A detailed description of the solution algorithm used in these programs is given by Anderson (*5*).

One limitation of iterative elastic layer backcalculation programs is that they require the user to enter starting values and ranges for the layer moduli. Unless appropriate starting values are selected, the program may never converge to a solution within the selected ranges. Some researchers have noted that there is no unique solution to the set of moduli that will produce a given deflection basin. Rather, there are as many solutions as there are layers in the pavement structure (*6-8*). As a result, the solution toward which the program converges depends on the initial or "seed" modulus values selected. The boundary values must also be selected judiciously. Limits that are too narrow may prevent the program from converging to the correct solution. Limits that are too broad may allow the program to converge to an incorrect solution, particularly if inappropriate seed moduli are selected. Success with these programs thus requires not only a good knowledge of pavements but also experience in backcalculation for the specific pavement type in question. It has even been suggested that iterative elastic layer backcalculation can never be truly automated until an expert system is developed to guide decisions such as selection of seed moduli (*6,9*).

A second limitation of iterative elastic layer backcalculation is that it is time-consuming, increasingly so for increasing number of layers. Convergence to a solution may require several iterations for a pavement system of three or more layers. The iterative backcalculation programs available today cannot process deflection data at a rate even close to that at which deflection data may be collected in the field.

In general, the iterative elastic layer backcalculation programs available do not perform well in analyzing AC/PCC pavements, for both of the reasons cited above. Frequently they are unable to match predicted and actual deflection basins within reasonable tolerance levels even when given broad ranges of moduli and permitted to run several iterations. Their tendency is to underpredict the modulus of the AC surface, often going to the lower limit of the AC modulus range allowed by the user, and consequently overpredicting the modulus of the PCC slab. As a result, it is necessary to confine the AC modulus to a narrow range bracketing an appropriate value [determined by independent means (e.g., as a function of AC mix temperature)] to obtain meaningful backcalculated modulus values for the PCC layer. The long execution time required for backcalculation of AC/PCC pavement layer moduli is also a significant limitation. Analysis of several dozen AC/PCC pavement deflection basins, such as might be measured on a highway section a few miles in length, may require several hours of program execution even on a high-end personal computer.

BOUSDEF (*10*) is an iterative backcalculation program similar to BISDEF, except that deflections for trial layer moduli combinations are computed not by an elastic layer subroutine but rather an equivalent thickness subroutine. This dramatically reduces execution time, which is BOUSDEF's major advantage over the BISDEF class of programs. However, the appropriateness of BOUSDEF for backcalculation of AC/PCC pavement layer moduli is questionable because of violation of assumptions of the equivalent thickness method. These include the assumptions that the pavement layers above the subgrade exhibit pure bending behavior, that all layers are fully bonded at their interfaces, that the layer moduli decrease with depth, and that the equivalent thickness of any layer (with respect to the layer below) is larger than the radius of the applied load.

Data Base Backcalculation Programs

Data base backcalculation programs run much more quickly than iterative programs but require a large amount of computer storage. Furthermore, a data base backcalculation program can only be applied to situations comparable with that for which the data base was generated (i.e., number of layers, material types, ranges of thicknesses and elastic moduli, interface bonding conditions, magnitude and geometry of loading, and number and spacing of sensors).

Of the backcalculation programs currently available, the data base–type program COMDEF (*11*) is the only one developed specifically for AC/PCC pavements. COMDEF's data base of deflection basins contains the results of more than 40,000 elastic layer program (BISAR) runs. As a result, the complete COMDEF data base occupies more than 4 megabytes of hard disk space on a personal computer. It is possible to load portions of the data base corresponding to the specific cross sections of interest to conserve hard disk space. A second and more serious limitation of COMDEF is that it requires deflections for seven sensors at 12-in. spacings; it cannot accommodate fewer sensors or other spacings. COMDEF does not permit the user to choose whether to model the AC/PCC interface condition as bonded or unbonded, and the program's documentation does not indicate which interface condition (presumably bonded) was used in the development of the data base.

MODULUS (*12*) is a data base backcalculation program in which the deflection basin data base is produced by a factorial of elastic layer program (CHEVRON) runs. MODULUS was developed for analysis of flexible pavements, but it may be used to analyze AC/PCC pavements. This process may take 15 min to 1 hr, depending on the pavement structure and the capabilities of the computer used, and must be repeated for every cross section of interest. At least 1 megabyte of hard disk space must be available to store the generated data base. Once the data base is generated, analysis of deflection data proceeds quickly.

Closed-Form Backcalculation

ILLIBACK (*13,14*) is a backcalculation program based on closed-form solution of plate theory equations, intended for use in analysis of bare PCC pavements. ILLIBACK executes more quickly than any other available backcalculation program and could conceivably be used for real-time analysis of deflection data in the field. It is the only available backcalculation program that determines a modulus of subgrade reaction (*k* value, psi/in.) as well as an elastic modulus for the subgrade. However, the current version of ILLIBACK can only be used for bare PCC pavements. Work is under way to modify ILLIBACK to address two-layer plate systems, for example, a PCC pavement with a bonded or unbonded PCC overlay, or a PCC pavement with a stabilized base.

Even with these modifications, however, ILLIBACK would not be an appropriate tool for analysis of AC/PCC pavement, because modeling the AC as a plate would fail to account for the significant compression that occurs in an AC overlay of a PCC slab. Nonetheless, for the purposes of AC/PCC pavement backcalculation, the efficiency and repeatability of the closed-form approach to backcalculation make it the most appealing of the available backcalculation schemes, if it can be modified to account for the behavior of the AC surface.

CLOSED-FORM BACKCALCULATION FOR BARE PCC PAVEMENT

For a bare PCC pavement, the PCC slab's elastic modulus (E_{pcc}) and the subgrade *k* value or elastic modulus (E_s) may both be backcalculated from the maximum deflection d_0 and the *AREA* of the deflection basin as defined by the following equation:

$$AREA = 6 * \left[1 + 2\left(\frac{d_{12}}{d_0}\right) + 2\left(\frac{d_{24}}{d_0}\right) + \left(\frac{d_{36}}{d_0}\right)\right] \quad (1)$$

where d_0 is the maximum deflection at the center of the load plate in inches and d_{12}, d_{24}, and d_{36} are the deflections at 12, 24, and 36 in. from the plate center, respectively, in inches.

AREA has units of length, rather than area, because each of the deflections is normalized with respect to d_0 in order to remove the effect of different load levels and to restrict the range of values obtained. *AREA* and d_0 are thus independent parameters from which the two unknown values E_{pcc} and *k* or E_s may be determined for a known slab thickness. This approach to direct backcalculation of slab and subgrade properties was first proposed by Hoffman and Thompson (*15*) and further validated by ERES (*16*) and Foxworthy (*17*). Further investigation of this concept by Ioannides (*13,14*) has produced a closed-form solution procedure to replace the iterative and graphical procedures used previously, as well as the computer program ILLIBACK for rapid analysis of deflection basin data for slab-on-grade pavement systems.

AREA Versus ℓ

Research by Ioannides (*13,14*) has demonstrated that for a given load radius and sensor arrangement, a unique relationship exists between *AREA* and the "dense liquid" radius of relative stiffness of the pavement, in which the subgrade is characterized by a *k* value (*18*):

$$\ell_K = \left[\frac{E_{pcc}\,D^3_{pcc}}{12(1 - \mu^2_{pcc})\,k}\right]^{1/4} \quad (2)$$

where

ℓ_k = dense liquid radius of relative stiffness (in.),
E_{pcc} = PCC elastic modulus (psi),
D_{pcc} = PCC thickness (in.),
μ_{pcc} = PCC Poisson's ratio, and
k = k value (psi/in.).

A separate unique relationship exists between *AREA* and the "elastic solid" radius of relative stiffness of the pavement, in which the subgrade is characterized by an elastic modulus and a Poisson's ratio (*19*):

$$\ell_e = \left[\frac{E_{pcc}\,D^3_{pcc}\,(1 - \mu^2_s)}{6(1 - \mu^2_{pcc})\,E_s}\right]^{1/3} \quad (3)$$

where

ℓ_e = elastic solid radius of relative stiffness (in.),
μ_s = subgrade Poisson's ratio, and
E_s = subgrade elastic modulus (psi).

The equations for deflection of a PCC slab resting on a dense liquid foundation or an elastic solid foundation have been summarized by Ioannides (*13*). For this study, these equations were solved for radial distances of 0, 12, 24, and 36 in. and for ℓ_k and ℓ_e values from 15 to 80 using the IMSL (*20,21*) library of functions available on the Apollo network of UNIX workstations at the University of Illinois. The deflections computed were used to obtain an *AREA* corresponding to each value of ℓ_k and ℓ_e. The results are shown in Figure 1.

Because the curves asymptotically approach an *AREA* value of 36 in., an appropriate and meaningful equation form for modeling the relationship of *AREA* to ℓ is that of an asymptotic regression model, also called a monomolecular growth model (*22*). Such a model has the following general form:

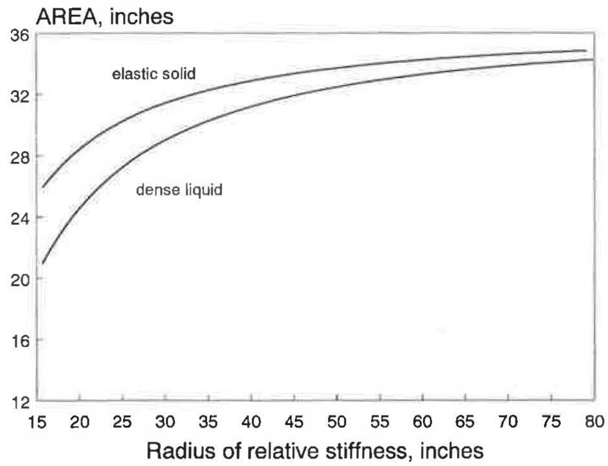

FIGURE 1 Relationship of *AREA* to radius of relative stiffness ℓ_k and ℓ_e for load radius a = 5.9 in.

$$AREA = k_1 - k_2\, e^{-k_3 \ell_k^{k_4}} \tag{4}$$

where

k_1 = the asymptotic y value,
k_2 = parameter for the range of *AREA* values, and
k_3, k_4 = scale parameters that govern the rate of growth.

The model must be rearranged to predict ℓ_k or ℓ_e as a function of *AREA*. The SAS statistical analysis software (*23*) was used to determine the parameters for each model by nonlinear regression.

$$\ell_k = \left[\frac{\ln\left(\dfrac{36 - AREA}{1812.279}\right)}{-2.559}\right]^{\frac{1}{0.228}} \tag{5}$$

[residual R^2 = 99.99 percent (predicted versus actual values), σ_Y = 0.097 in., n = 63, and residual range = 0.996 to 1.018].

$$\ell_e = \left[\frac{\ln\left(\dfrac{36 - AREA}{4521.676}\right)}{-3.645}\right]^{\frac{1}{0.187}} \tag{6}$$

[residual R^2 = 99.99 percent (predicted versus actual values), σ_Y = 0.118 in., n = 83, and residual range = 0.996 to 1.023].

Subgrade k or E_s

With *AREA* calculated from measured deflections, ℓ_k or ℓ_e may be obtained from Equations 5 or 6 or from Figure 1. The k value may then be obtained from Westergaard's (*18*) deflection equation:

$$k = \left(\frac{P}{8 d_0 \ell_k^2}\right) \times \left\{1 + \left(\frac{1}{2\pi}\right)\left[\ln\left(\frac{a}{2\ell_k}\right) + \gamma - 1.25\right]\left(\frac{a}{\ell_k}\right)^2\right\} \tag{7}$$

where

P = applied load (lb),
d_0 = maximum deflection at center of load (in.),
a = load radius, and
γ = Euler's constant, 0.57721566490.

Figure 2 was developed from Equations 5 and 7 for load P = 9,000 lb and load radius a = 5.9 in. For loads within about 2,000 lb of this value, the deflections d_0, d_{12}, d_{24}, and d_{36} may be scaled linearly to 9,000-lb deflections.

The elastic modulus of the subgrade (E_s) may be obtained from Losberg's (*19*) deflection equation:

$$E_s = \left[\frac{2P(1 - \mu_s^2)}{d_0\, \ell_e}\right]\left[0.19245 + 0.0272 \times \left(\frac{a}{\ell_e}\right)^2 + 0.0199\left(\frac{a}{\ell_e}\right)^2 \ln\left(\frac{a}{\ell_e}\right)\right] \tag{8}$$

Figure 3 was developed from Equations 6 and 8 for load P = 9,000 lb, load radius a = 5.9 in., and subgrade Poisson's ratio μ_s = 0.50. For loads within about 2,000 lb of this value, the deflections d_0, d_{12}, d_{24}, and d_{36} may be scaled linearly to 9,000-lb deflections.

PCC Elastic Modulus

Once the k value or elastic modulus of the subgrade is known, the elastic modulus of the PCC slab may be determined using the appropriate (dense liquid or elastic solid) definition of the radius of relative stiffness. Figure 4 was developed from Equations 2 and 5 for PCC Poisson's ratio μ_{pcc} = 0.15 and load radius a = 5.9 in. Figure 5 was developed from Equations 3 and 6 for PCC Poisson's ratio μ_{pcc} = 0.15, subgrade Poisson's ratio μ_s = 0.5, and load radius a = 5.9 in. For either support characterization, the PCC elastic modulus E_{pcc} may be determined for a known value of slab thickness, D_{pcc}.

BACKCALCULATION FOR AC/PCC PAVEMENT

AC Elastic Modulus

To remove the effect of the AC surface from the NDT data, the elastic modulus of the AC layer must be determined. The recommended method for determining E_{ac} is to monitor the temperature of the AC mix during deflection testing and to use a relationship between E_{ac} and temperature. The AC mix temperature may be measured directly or estimated from surface or air temperatures using procedures developed by Southgate (*26*), Shell (*27*), the Asphalt Institute (*28*), or Hoffman and Thompson (*15*). Air temperature data may be recorded during deflection testing or obtained from a local weather station.

The relationship between AC modulus and temperature is shown in Figure 6, developed by Thompson and Cation (*29*) for typical Illinois Department of Transportation mixes. The curves shown in Figure 6 apply to new AC mixes. AC that has been in service for some years may have a different modulus for any given temperature. The third line in Figure 6 is drawn for the AC cores used in the example described later.

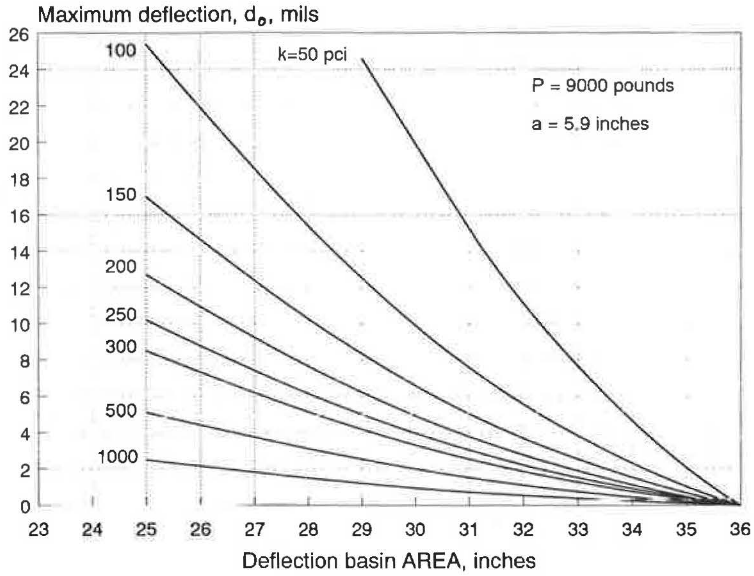

FIGURE 2 Effective *k* value determination from d_0 and *AREA*.

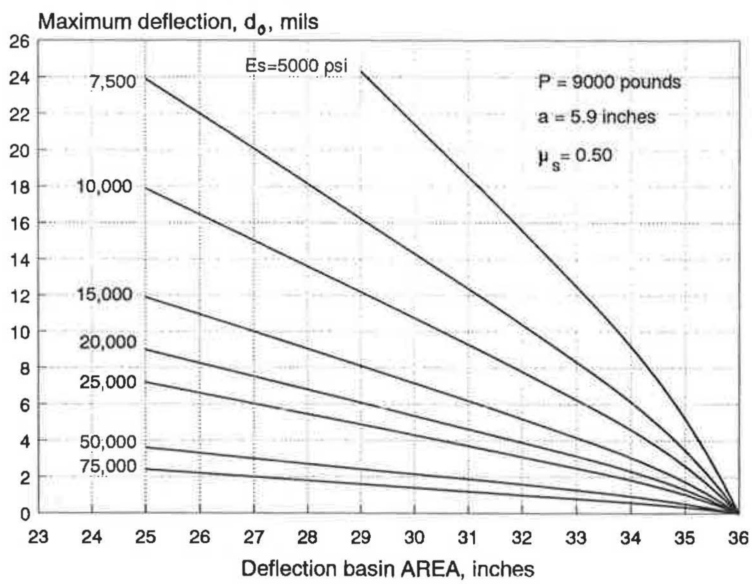

FIGURE 3 E_s determination from d_0 and *AREA*.

Diametral resilient modulus testing (ASTM D 4123) may be conducted at one or more temperatures on AC cores taken from the pavement in order to establish points for a curve for the E_{ac} versus temperature. However, because it may not be feasible to conduct this type of testing, correlations may be established between AC resilient modulus and indirect tensile strength, which may be more readily determined. Equation 13, developed by Carpenter and VanDam (*30*) for 4-in.-diameter samples of AC mixes at 72°F with typical Illinois Department of Transportation gradations and ranges of asphalt contents, asphalt stiffnesses, and compaction efforts, is an example of such a correlation:

$$M_R = 35{,}632 + 4{,}446\ (S_{IT}) \qquad (9)$$

(R^2 = 85 percent and n = 56) where M_R is AC resilient modulus (psi) and S_{IT} is AC indirect tensile strength (psi). This particular relationship is specific to the AC mixes tested. Similar relationships could be developed for other AC mixes.

d_0 of PCC Layer

The elastic layer program BISAR was used to model AC/PCC pavement structures over a broad range of parameters:

Parameter	*Values*
AC thickness	2, 4, and 6 in.
AC modulus	100, 500, and 1,000 ksi
PCC thickness	6, 8, and 12 in.
PCC modulus	3 million and 7 million psi
Subgrade modulus	6, 24, and 42 ksi
AC/PCC interface	bonded and unbonded

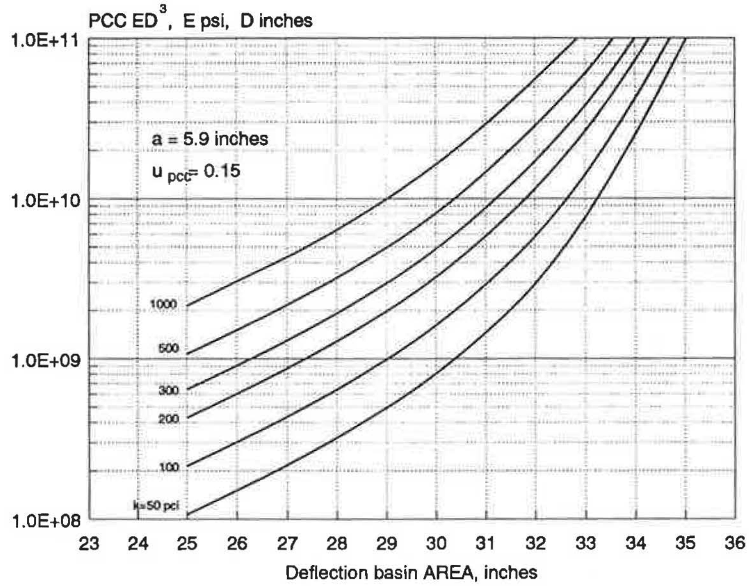

FIGURE 4 PCC elastic modulus determination from *k* value, *AREA*, and slab thickness.

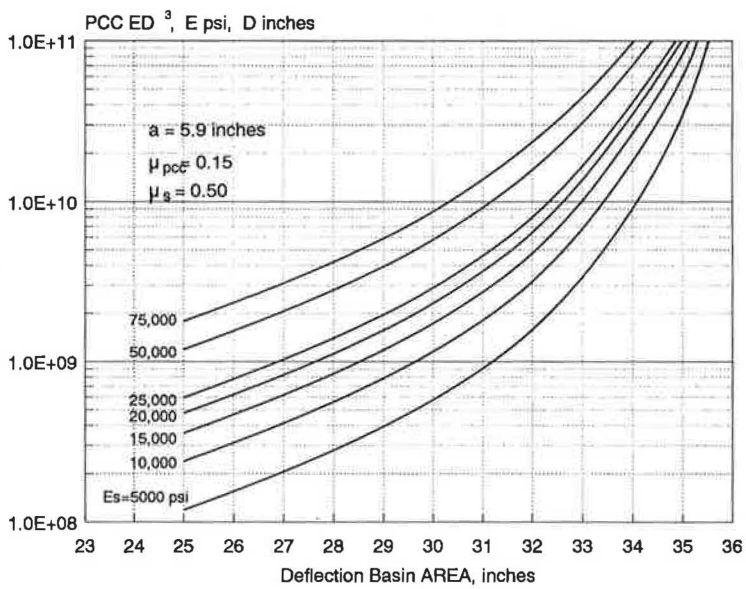

FIGURE 5 PCC elastic modulus determination from E_s, *AREA*, and slab thickness.

A load magnitude of 9,000 lb and a load radius of 5.9 in. were used. Poisson's ratio values used for the AC, PCC, and subgrade were 0.35, 0.15, and 0.5, respectively. The PCC/subgrade interface was modeled as unbonded.

Deflections were computed at the surface of the AC and the surface of the PCC at radial offsets of 0, 12, 24, and 36 in. Compression in the AC layer, as indicated by the change in d_0 between the AC and PCC surfaces, often accounted for a significant portion of the total deflection, depending primarily on the thickness and modulus of the AC and the stiffness of the subgrade, and to a lesser extent on the interface condition and the thickness and stiffness of the PCC slab. For example, in systems with a stiff subgrade (42 ksi), low AC modulus (100 ksi), and thick AC layer (6 in.), more than 50 percent of the total deflection in the pavement occurred in the AC layer.

The change in d_0 is significantly greater when the AC is not bonded to the PCC than when it is bonded. For each interface bonding condition, it was found that the change in d_0 could be predicted reliably as a function of the ratio of the AC thickness to AC modulus (D_{ac}/E_{ac}). These relationships were found to be insensitive to the ranges of other parameters

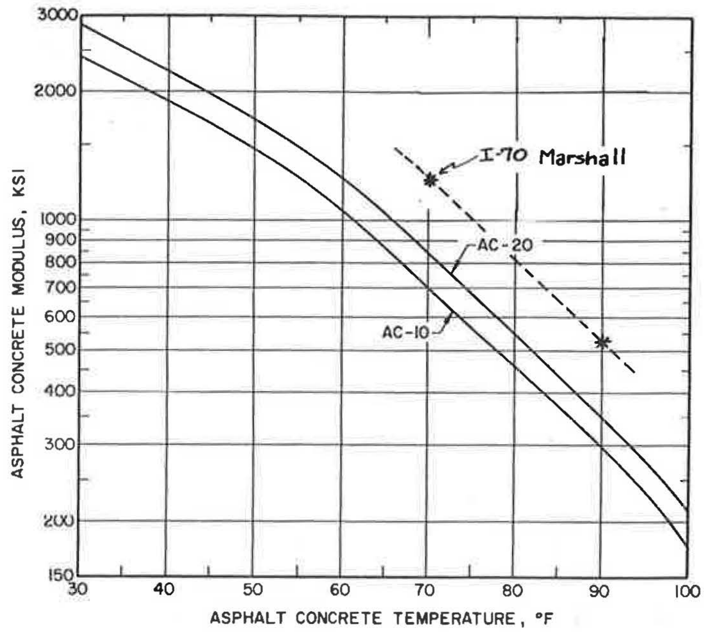

FIGURE 6 Asphalt concrete modulus–temperature relations for typical Illinois Department of Transportation Class I mixtures (*29*).

investigated. Equation 10 was obtained for AC/PCC bonded, and Equation 11 was obtained for AC/PCC unbonded:

$$d_{0\ \text{compress}} = -0.04524 + 63269.74 \left(\frac{D_{ac}}{E_{ac}}\right)^{1.02138} \quad (10)$$

(residual $R^2 = 99.94$ percent, $\sigma_Y = 0.047$ mils, and $n = 225$)

$$d_{0\ \text{compress}} = -0.02149 + 27058.01 \left(\frac{D_{ac}}{E_{ac}}\right)^{0.91878} \quad (11)$$

(residual $R^2 = 99.89$ percent, $\sigma_Y = 0.074$ mils, and $n = 225$)

where

$d_{0\ \text{compress}}$ = AC compression at center of load (mils),
D_{ac} = AC thickness (in.), and
E_{ac} = AC elastic modulus (psi).

The d_0 of the PCC slab in the AC/PCC pavement may be determined by subtracting the compression occurring in the AC surface from the d_0 measured at the AC surface.

The interface condition is a significant unknown in the backcalculation problem. The AC/PCC interface is assumed to be fully bonded when the AC layer is first placed, but how well that bond is retained is not known. Examination of cores taken at a later time may show that the bond has been reduced or completely lost. This is particularly likely if stripping occurs at the AC/PCC interface. Because in most cases the true interface bonding condition is not known, it is recommended that the change in d_0 be determined for both conditions.

AREA of PCC

In the elastic layer analyses conducted, only d_0 was found to change significantly between the AC and PCC layers; differences in d_{12}, d_{24}, and d_{36} were very close to zero over the entire range of parameters. Therefore, the *AREA* of the PCC slab may be computed from Equation 1 using the d_0 of the PCC slab determined as described above and d_{12}, d_{24}, and d_{36} measured at the AC surface. This computed *AREA* of the PCC will always be larger than the *AREA* of the AC surface's deflection basin. This is due to the form of Equation 1, in which *AREA* is normalized by dividing all of the deflections by d_0. If the denominator of each term decreases while the numerators remain unchanged, a larger *AREA* value will be computed.

Correction to d_0 and *AREA* of PCC

The computed d_0 and *AREA* of the PCC slab's deflection basin in the AC/PCC pavement are not the same d_0 and *AREA* that would be obtained if the AC layer were not present and deflections were measured on the bare PCC surface. To determine the PCC elastic modulus and the subgrade k value or elastic modulus independent of the AC overlay, the computed d_0 and *AREA* of the PCC slab must each be corrected to represent the bare PCC pavement condition. Furthermore, different corrections must be applied depending on the subgrade characterization (dense liquid or elastic solid) assumed in the backcalculation. This is because the different characterizations produce different deflection basins for the same input modulus values or, conversely, different backcalculated modulus values for the same input deflection basin.

Deflections were calculated for a factorial of bare PCC slabs on grade using the Apollo computer system to solve the Westergaard and Losberg equations for the dense liquid and elastic solid characterizations. The PCC slabs ranged from 6 to 12 in. in thickness and 3 million to 7 million psi in elastic modulus. The subgrade modulus or k value was held to a constant value to produce a wide range of ℓ_k or ℓ_e values.

The PCC slabs were then modeled in BISAR with AC overlays from 1 to 9 in. and E_{ac} values from 250 ksi to 1.25 million psi. The bare PCC deflection basins were compared with the deflection basins of the overlaid PCC slabs, and the needed correction equations were obtained. The general form used for all of the models is given in Equation 12. The values of the coefficients are given in Table 1. There are a total of eight models: a d_0 correction and an *AREA* correction for each of two AC/PCC bonding conditions and two subgrade characterizations. The corrections obtained are applied to the PCC d_0 and *AREA*, as shown in Equations 13 and 14.

$$\text{correction} = g + h * [D_{ac}^{a} * E_{ac}^{b} * D_{pcc}^{c} * d_{0\,pcc}^{d} * AREA_{pcc}^{e} * 10^{f}]^{i} \quad (12)$$

$$d_{0\,\text{bare}} = d_{0\,\text{pcc}} + d_0 \text{ correction} \quad (13)$$

$$AREA_{\text{bare}} = AREA_{\text{pcc}} + AREA \text{ correction} \quad (14)$$

The bare PCC d_0 and *AREA*, determined as described above, are the appropriate values to use to determine the PCC elastic modulus and dynamic k value or elastic modulus. It must be emphasized that the moduli determined in this manner (i.e., as if the AC surface were not present) are not the same moduli that the PCC and foundation layers exhibit in the actual AC/PCC pavement structure. The slab E and subgrade k and E are not intrinsic properties of either layer, but rather are influenced by the entire pavement structure's response to load. The purpose of this correction is to remove the effect of different AC overlay thicknesses and stiffnesses so that backcalculated PCC modulus values can be correlated to the extent of deterioration.

Sensitivity to Rigid Layer Beneath Foundation

This backcalculation method is based on an assumption of an infinite subgrade depth. Other researchers (*31,32*) have noted the sensitivity of various backcalculation procedures to the depth and stiffness of a rigid foundation layer. The sensitivity of this procedure to a rigid foundation layer was investigated by taking one of the weakest cross sections previously studied (2-in. AC, E_{ac} = 100,000 psi; 6-in. PCC, E_{pcc} = 3 million psi; and subgrade E_s = 6,000 psi) and determining the effect of BISAR-computed deflections at the AC and PCC surfaces with a rigid layer (modulus 250,000 psi) at depths of 5 to 20 ft. The rigid layer had no effect on the change in d_0 between the AC and PCC and only a slight effect on the change in *AREA*. The depth to a rigid layer was therefore judged to be not sufficiently significant to AC/PCC pavement analysis to require an additional correction.

EXAMPLE OF AC/PCC BACKCALCULATION PROCEDURE

Project Description

Deflection testing was conducted in September 1989 on a 9-mi section of I-70 near Marshall, Illinois, on an 8-in. CRCP pavement with a 4.5-in. AC overlay. The CRCP was constructed in 1968 and carried more than three times its design traffic by the time it was overlaid in 1980. Because of the heavy traffic and "D"-cracking aggregate used in the PCC, the pavement was severely deteriorated when it was rehabilitated.

The original pavement had a 4-in. bituminous-aggregate mixture base, but coring showed that the base was largely disintegrated and permeated by subgrade (silty clay) fines. Modeling the base and subgrade as a single layer thus appeared to reasonably represent the foundation conditions.

The first four basins were measured 10 ft apart in an eastbound section of the project that was rated in good condition on the basis of ride quality and visible distress. The second four, also 10 ft apart, were measured westbound at the same milepost, in a section of the project that was rated in fair to poor condition.

TABLE 1 COEFFICIENTS FOR d_0 AND *AREA* CORRECTION MODELS

	a	b	c	d	e	f	g	h	i	Obs	SEE	R^2
BDLD0 *	7.7888	3.6934	0.8548	14.9214	-10.7881	-2.2577	-1.5648	2.5484	0.2707	135	0.0547	0.9950
BDLAREA	1.1524	0.5378	-0.2374	2.0897	2.5639	9.4702	-0.5021	1.7250	1.3439	180	0.0138	0.9949
BESD0	2.3693	1.1245	0.4104	3.3122	-4.0414	-5.0151	-0.0477	0.7400	0.9850	180	0.0056	0.9990
BESAREA	2.8670	1.3189	-0.7492	3.4096	-5.8091	7.0101	0.5569	184.5114	0.5698	180	0.0145	0.9948
UDLD0	12.9885	4.3260	-17.4702	29.6353	-70.8581	51.6622	-1.8480	3.0444	0.0675	135	0.0538	0.9940
UDLAREA	1.7455	0.5138	-2.5830	0.7585	1.5610	4.9433	-0.3607	0.3118	0.8434	180	0.0202	0.9924
UESD0	2.2074	1.0511	-0.5542	2.0054	-1.5275	-7.7880	-0.2292	2.7547	1.2127	180	0.0070	0.9988
UESAREA	3.4949	1.4440	-1.4457	3.8288	-5.7058	8.9962	0.6607	35.0914	0.4809	180	0.0275	0.9902

* For BDLD0 Eac, in million psi

AC Elastic Modulus

The AC mix temperature was monitored during deflection testing by drilling holes to the middepth of the overlay, inserting liquid and a temperature probe, and allowing the temperature to stabilize before reading. The mix temperature varied from 66°F at 9 a.m. to 90°F at 3 p.m., as shown in Figure 7. Resilient modulus testing done later on cores from the AC surface indicated modulus values of about 1.2 million psi at 70°F and 520,000 psi at 90°F. The temperature-modulus relationship shown in Figure 6 was used to assign a modulus of 670,000 psi (at 84°F) to the first four basins and 615,000 psi (at 86°F) to the second four basins.

Backcalculation of PCC and Foundation Moduli

Table 2 gives the backcalculation results for the eight deflection basins (with all deflections scaled to a 9,000-lb load).

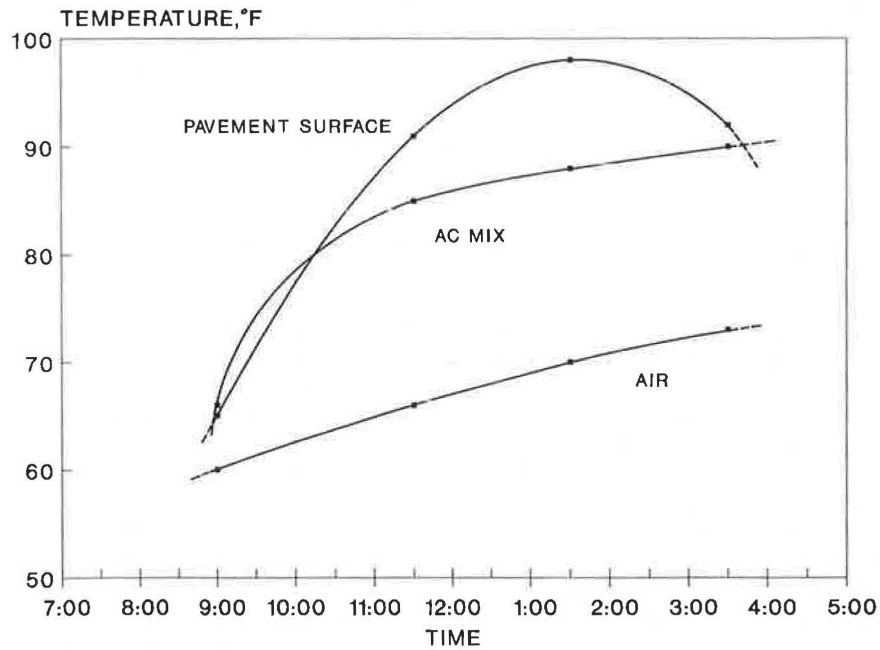

FIGURE 7 Variation in air, surface, and AC mix temperature during deflection testing for I-70 example.

TABLE 2 BACKCALCULATION RESULTS FOR I-70 EXAMPLE

MP & DIR	AC/PCC	AC d0 (mils)	AC AREA (in)	change in d0 (mils)	PCC d0 (mils)	PCC AREA (in)	DENSE LIQUID CORRECTED PCC d0 (mils)	DENSE LIQUID CORRECTED PCC AREA (in)	DENSE LIQUID lk (in)	ELASTIC SOLID CORRECTED PCC d0 (mils)	ELASTIC SOLID CORRECTED PCC AREA (in)	ELASTIC SOLID le (in)	DENSE LIQUID Epcc (M psi)	DENSE LIQUID k (pci)	ELASTIC SOLID Epcc (M psi)	ELASTIC SOLID Es (psi)
154 E	BONDED	4.54	27.16	0.28	4.26	28.57	3.00	28.24	27.62	4.55	29.67	23.18	6.40	480	4.69	24661
		4.98	27.96	0.28	4.70	29.29	3.56	29.03	30.10	5.07	30.45	25.77	6.43	342	5.20	19872
		5.88	28.24	0.28	5.60	29.37	4.90	29.27	30.94	6.29	30.77	27.01	4.94	235	4.60	15287
		5.82	28.40	0.28	5.54	29.55	4.79	29.45	31.58	6.18	30.92	27.61	5.27	231	4.89	15201
154 E	UNBONDED	4.54	27.16	0.46	4.08	29.52	2.47	29.31	31.08	3.88	30.25	25.05	9.91	463	6.42	26753
		4.98	27.96	0.46	4.52	30.18	2.93	29.98	33.74	4.32	30.92	27.61	9.85	332	7.00	21759
		5.88	28.24	0.46	5.42	30.12	3.95	29.94	33.55	5.23	30.89	27.48	7.23	249	5.72	18048
		5.82	28.40	0.46	5.36	30.31	3.87	30.13	34.39	5.17	31.07	28.29	7.76	242	6.13	17734
154 W	BONDED	7.58	22.97	0.31	7.27	23.71	10.01	23.58	18.59	10.92	26.93	17.16	0.85	312	1.07	13919
		7.51	21.79	0.31	7.20	22.48	10.47	22.28	17.02	11.58	26.16	15.99	0.68	354	0.88	14109
		8.78	22.65	0.31	8.47	23.27	15.33	23.31	18.25	14.97	27.65	18.41	0.54	211	0.90	9450
		7.39	23.94	0.31	7.08	24.74	8.93	24.64	20.10	9.89	27.50	18.14	1.13	301	1.32	14525
154 W	UNBONDED	7.58	22.97	0.50	7.08	24.16	7.03	23.95	19.10	6.96	25.12	14.65	1.29	421	1.23	25681
		7.51	21.79	0.50	7.01	22.90	7.44	22.69	17.49	6.90	23.91	13.33	1.01	472	1.03	28578
		8.78	22.65	0.50	8.28	23.65	9.16	23.46	18.44	8.22	24.74	14.20	0.92	347	0.98	22460
		7.39	23.94	0.50	6.89	25.23	6.43	25.03	20.73	6.76	26.15	15.98	1.66	394	1.51	24192

Because the AC and PCC were debonded in 15 of the 16 cores taken on this project, the backcalculated values corresponding to the unbonded interface assumption are, in this case, considered to be more realistic.

It is evident that the PCC in the eastbound section is in much better condition than in the westbound section. The eastbound CRCP modulus values are about 5.5 million to 8.5 million psi, whereas the westbound CRCP modulus values are all less than 1.5 million psi. Obviously, such low modulus values are unreasonable for sound PCC, and they suggest that the PCC is severely deteriorated because of "D" cracking. Although this entire mile of the project was rated in fair condition on the basis of ride quality and distress observations, the deflections shown in Table 2 were measured at locations where the AC overlay was uncracked. This is consistent with the results of the subsequent coring operation: at locations where exceptionally high deflections were measured, the underlying PCC was invariably deteriorated. This was true even at locations with little or no distress visible at the AC surface.

Comparison with Other Backcalculation Results

Table 3 gives the backcalculation results obtained for the eight deflection basins using MODULUS, a program recently developed at the Texas Transportation Institute under NCHRP Project 10-27 (*12*), which generates a matrix of solutions for ranges of layer moduli and selects the combination that produces deflections most closely matching the measured deflections.

The AC modulus was restricted in MODULUS to a fairly narrow range of 600 to 700 ksi, which encompasses the values used before: 670 ksi for the first four deflection basins and 615 ksi for the second four basins. The version of MODULUS used to analyze these data assumed full bond between the AC and PCC layers.

MODULUS consistently assigned the minimum allowable value of 600 ksi to theAC layer. The values obtained for the PCC are similar to those obtained before when the AC and PCC were assumed bonded: about 2 million to 4 million psi for the eastbound basins, and less than 1 million psi for the westbound basins. These values are of interest for comparison with those obtained by the new procedure, but the higher PCC modulus values backcalculated under the assumption that the AC and PCC are not bonded are considered to be more realistic.

An attempt to allow MODULUS to backcalculate the AC modulus within a broader range produced significantly lower moduli for the AC (about 450 ksi for the first four basins and 125 ksi for the second four basins) and correspondingly higher PCC moduli (in excess of the selected maximum of 4 million psi for several basins). The 325-ksi drop in modulus attributed to the AC by the MODULUS program was not considered reasonable considering (*a*) the rise of only 2°F in measured AC mix temperature that occurred during the time that the deflections were measured and (*b*) the modulus values obtained for the same temperature range from laboratory tests on the AC cores.

TABLE 3 BACKCALCULATION RESULTS FROM MODULUS FOR I-70 EXAMPLE

AC/PCC	mp	dir	no	Eac (psi)	Epcc (million psi)	Esub (psi)
Bonded	154.0	E	1	600,000	2.9	27,200
			2	600,000	4.2	21,500
			3	600,000	3.2	17,800
			4	600,000	2.6	18,700
Bonded	154.0	W	1	600,000	0.51	22,900
			2	600,000	0.60	24,300
			3	600,000	0.39	20,100
			4	600,000	0.81	20,800

Assumptions in Backcalculation

The results of backcalculation by any method should be viewed in the light of the inherent assumptions concerning the pavement layers. For the AC/PCC backcalculation procedure described here, the assumptions include characterization of the AC as an elastic layer, the PCC as a plate (an elastic layer that exhibits pure bending without shear deformation), and the foundation as either a bed of springs or an elastic solid. These are certainly simplifications of the true nature of the layer properties. The most obvious violation of these assumptions is the attribution of plate bending behavior to severely "D" cracked PCC, which may have more in common with a granular base than with a sound PCC slab. The extremely low backcalculated values that result should not be interpreted as the true stress-strain response of the PCC as a homogeneous elastic layer, but rather as an indication of the extent to which its behavior departs from that of a sound slab (i.e., the extent of the PCC's deterioration). The ability to diagnose the condition of the PCC from deflection measurements is particularly valuable in evaluation of AC/PCC pavements, because the extent of the deterioration of the PCC is often not fully evident from visible distress.

SUMMARY AND CONCLUSIONS

The development of a simple and straightforward procedure for backcalculation of AC/PCC pavement layer moduli was described. The procedure relies on knowledge of the AC surface modulus based on AC mix temperature at the time of deflection testing. Adjustments to the deflection basin measured at the AC surface are made to determine the deflection basin induced in the PCC layer. The PCC deflection basin may then be used to predict the deflection basin that would be measured without the AC layer present. The backcalculated PCC modulus determined in this manner, independent of the effect of the AC overlay, may then be used as an indicator of the extent of deterioration in the PCC.

Assignment of the AC modulus on the basis of mix temperature at the time of deflection testing is necessary to avoid backcalculating incorrect values for the PCC modulus and thus misinterpreting the condition of the PCC. Other researchers have noted that the solutions to multilayer backcalculation problems are not unique. Thus, it is possible to obtain good matches between measured and predicted deflections for AC modulus values that are clearly inconsistent with the conditions existing at the time of deflection testing.

The example presented indicates that the AC/PCC backcalculation procedure described produces reasonable results that are consistent with those obtained using another backcalculation routine considered to be reliable.

An important feature of the AC/PCC pavement backcalculation procedure described here is its ability to identify areas in which the underlying PCC is deteriorated. This information is crucial to decisions that must be made for second rehabilitation, including division of the project into uniform sections, identification of areas requiring repair, selection of an overlay type or other rehabilitation alternative, and second overlay design.

ACKNOWLEDGMENTS

This paper is based on the results of Project IHR-517, "Development and Field Testing of an Illinois Pavement Feedback System." IHR-517 was sponsored by the Illinois Department of Transportation (Division of Highways) and the U.S. Department of Transportation (FHWA). The authors are grateful for the encouragement and direction of Michael Darter and the generous input of many other individuals, including Robert Elliott, Sam Carpenter, Barry Dempsey, Marshall Thompson, and Anastasios Ioannides. The cooperation and assistance of Max Rexroad of the University of Illinois, as well as personnel in the Illinois Department of Transportation's Bureau of Materials and Physical Research and in District 5, are also gratefully acknowledged.

REFERENCES

1. A. J. Bush III. *Computer Program BISDEF.* U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1985.
2. A. J. Bush III. *Nondestructive Testing for Light Aircraft Pavements, Phase II: Development of the Nondestructive Evaluation Methodology.* Report FAA-RD-80-9-II. Federal Aviation Administration, U.S. Department of Transportation, 1980.
3. F. J. Van Cauwelaert, D. R. Alexander, T. D. White, and W. R. Barker. Multilayer Elastic Program for Backcalculating Layer Moduli in Pavement Evaluation. In *Nondestructive Testing of Pavements and Backcalculation of Moduli* (A. J. Bush III and G. Y. Baladi, eds.). ASTM STP 1026. ASTM, Philadelphia, Pa., 1989.
4. D. L. DeJong, M. G. F. Peutz, and A. R. Korswagen. *Computer Program BISAR.* Koninklijke/Shell-Laboratorium, Amsterdam, the Netherlands, 1973.
5. M. Anderson. *Evaluation of Models for Backcalculation of Pavement Layer Moduli.* Applied Research Associates, Inc., Nov. 1990.
6. R. L. Lytton. Backcalculation of Layer Moduli. In *Nondestructive Testing of Pavements and Backcalculation of Moduli* (A. J. Bush III and G. Y. Baladi, eds.). ASTM STP 1026. ASTM, Philadelphia, Pa., 1989.
7. F. H. Scrivner, C. H. Michalak, and W. M. Moore. Calculation of the Elastic Moduli of a Two-Layer Pavement System from Measured Surface Deflections. In *Highway Research Record 431*, HRB, National Research Council, Washington, D.C., 1973.
8. T. Y. Hou. *Evaluation of Layered Material Properties from Measured Surface Deflections.* Ph.D. dissertation. University of Utah, Salt Lake City, 1977.
9. Y. J. Chou, J. Uzan, and R. L. Lytton. Backcalculation of Layer Moduli from Nondestructive Pavement Deflection Data Using the Expert System Approach. In *Nondestructive Testing of Pavements and Backcalculation of Moduli* (A. J. Bush III and G. Y. Baladi, eds.). ASTM STP 1026. ASTM, Philadelphia, Pa., 1989.
10. H. Zhou, R. G. Hicks, and C. A. Bell. BOUSDEF: A Backcalculation Program for Determining Moduli of a Pavement Structure. In *Transportation Research Record 1260*, TRB, National Research Council, Washington, D.C., 1990, pp. 166–179.
11. M. Anderson. A Data Base Method for Backcalculation of Composite Pavement Layer Moduli. In *Nondestructive Testing of Pavements and Backcalculation of Moduli* (A. J. Bush III and G. Y. Baladi, eds.). ASTM STP 1026. ASTM, Philadelphia, Pa., 1989.
12. R. L. Lytton, F. P. Germann, Y. J. Chou, and S. M. Stoffels. *NCHRP Report 327: Determining Asphaltic Concrete Pavement Structural Properties by Nondestructive Testing.* TRB, National Research Council, Washington, D.C., 1990.
13. A. M. Ioannides. Dimensional Analysis in NDT Rigid Pavement Evaluation. *Transportation Engineering Journal*, ASCE, Vol. 116, No. TE1, 1990.
14. A. M. Ioannides, E. J. Barenberg, and J. A. Lary. Interpretation of Falling Weight Deflectometer Results Using Principles of Dimensional Analysis. *Proc., Fourth International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, West Lafayette, Ind., 1989.
15. M. S. Hoffman and M. R. Thompson. *Mechanistic Interpretation of Nondestructive Pavement Testing Deflections.* Transportation Engineering Series No. 32, Illinois Cooperative Highway and Transportation Research Series No. 190. University of Illinois at Urbana-Champaign, Urbana, 1981.
16. *Nondestructive Structural Evaluation of Airfield Pavements.* ERES Consultants, Inc., 1982.
17. P. T. Foxworthy. *Concepts for the Development of a Nondestructive Testing and Evaluation System for Rigid Airfield Pavements.* Ph.D. thesis. University of Illinois at Urbana-Champaign, Urbana, 1985.
18. H. M. Westergaard. Stresses in Concrete Runways of Airports. *HRB Proc.*, Vol. 19, 1939.
19. A. Losberg. *Structurally Reinforced Concrete Pavements.* Doktorsavhandlingar Vid Chalmers Tekniska Högskola, Göteborg, Sweden, 1960.
20. *IMSL SFUN/LIBRARY User's Manual.* Version 2.1. IMSL, Inc., 1989.
21. *IMSL MATH/LIBRARY User's Manual.* Version 1.1. IMSL, Inc., 1989.
22. G. A. F. Seber and C. J. Wild. *Nonlinear Regression.* John Wiley and Sons, Inc., New York, 1989.
23. *SAS User's Guide: Statistics.* Version 5 edition. SAS Institute, Inc., Cary, N.C., 1985.
24. D. M. Burmister. The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways. *HRB Proc.*, Vol. 23, 1943.
25. D. M. Burmister. The General Theory of Stresses and Displacements in Layered Systems. Parts I, II, and III. *Journal of Applied Physics*, Vol. 16, 1945.
26. H. F. Southgate. *An Evaluation of Temperature Distribution Within Asphalt Pavements and Its Relationship to Pavement Deflection.* Research Report KYHPR-64-20. Kentucky Department of Highways, 1968.
27. *Pavement Design Manual.* Shell International Petroleum Company, London, England, 1978.
28. *Research and Development of the Asphalt Institute's Thickness Design Manual (MS-1) Ninth Edition.* Research Report 82-2. Asphalt Institute, College Park, Md.,1982.
29. M. R. Thompson and K. A. Cation. *A Proposed Full-Depth Asphalt Concrete Thickness Design Procedure.* Transportation Engineering Series No. 45, Illinois Cooperative Highway and Transportation Program Series No. 213. University of Illinois at Urbana-Champaign, Urbana, 1986.

30. S. H. Carpenter and T. VanDam. Laboratory Performance Comparisons of Polymer-Modified and Unmodified Asphalt Concrete Mixtures. In *Transportation Research Record 1115*, TRB, National Research Council, Washington, D.C., 1987.
31. T. Rwebangira, R. G. Hicks, and M. Truebe. Sensitivity Analysis of Selected Backcalculation Procedures. In *Transportation Research Record 1117*, TRB, National Research Council, Washington, D.C., 1987.
32. R. C. Briggs and S. Nazarian. Effects of Unknown Rigid Subgrade Layers on Backcalculation of Pavement Moduli and Projections of Pavement Performance. In *Transportation Research Record 1227*, TRB, National Research Council, Washington, D.C., 1989.

The contents of this paper reflect the opinions of the authors, who are responsible for 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 paper does not constitute a standard, specification, or regulation.