Comparison of Pavement Deflection Analysis Methods Using Overlay Design

JOSEPH M. MAESTAS AND MICHAEL S. MAMLOUK

Four pavement deflection analysis methods, in the form of personal computer software programs, were evaluated and compared from the practitioner's perspective on the basis of calculated overlay design thickness, common characteristics, and performance. These programs are ELSDEF, MODCOMP2, MODULUS4, and ISSEM4. Each program applies the concept of backcalculation, which is the determination of in situ material properties of a pavement structure from its response to dynamic surface loading. A total of 29 in-service, flexible pavement sections, requiring significant rehabilitation, were selected from areas of various environmental conditions, traffic loading, and subgrade soil types in Arizona. Through backcalculation, actual falling weight deflectometer field deflections were used to estimate layer moduli of all pavement sections. The moduli results were then used in the overlay design of each section in accordance with the 1986 AASHTO *Guide for Design of Pavement Structures*. Although the four backcalculation programs are characteristically different, neither layer modulus nor overlay thickness results were statistically different in most cases. However, from a practical perspective, backcalculation, as represented by these programs, is not adequate for use by the practitioner. Additional research is needed to refine the backcalculation process.

The need to standardize and adopt a mechanistic overlay design procedure for flexible pavement has led to the proliferation of PC-compatible backcalculation software programs used for pavement structure evaluation and, potentially, for mechanistic overlay design. These programs require data from common, dynamic nondestructive (NDT) testing devices. Generally, a falling weight deflectometer (FWD) is preferred. Although NDT applications show much promise in pavement evaluation, more research is needed in the areas of backcalculation and overlay design.

Some general similarities among backcalculation programs are that they are iterative in nature, require essentially the same input parameters, and produce the elastic modulus for each pavement layer by equating measured NDT deflections with those calculated. Several recent studies have been conducted on various backcalculation programs. These studies address sources and effects of backcalculation error and performance comparisons of backcalculation programs. They have specifically evaluated the source, degree, and effect of error attributed to deflection measurement, the NDT device used, program user expertise, and the accuracy of program input data (i.e., depth to rigid layer, "seed moduli," moduli limits, etc.) (*1–4*). Many studies have compared certain backcalculation programs on the basis of moduli results [see, for example, Ali and Khosla (*5*)]. However, a limited number of studies have evaluated the effect and comparison of various backcalculation programs on the basis of overlay design. Mahoney et al. (*6*) compared certain backcalculation programs by overlay design using an assumed fixed traffic level and applying the asphalt strain criterion.

If various backcalculation programs result in the same practical overlay design for a particular pavement section, it may mean that we have reached the ultimate level of backcalculation needed for the current highway practice. However, if various overlay designs are the result, caution should be exercised when backcalculation is performed. Additional work would be needed to refine the backcalculation methodology. This paper serves to evaluate the backcalculation effect among various programs through the application of the AASHTO overlay design procedure using actual field data. This paper also provides an in-depth look into each program's relative capabilities and performance. The backcalculation programs used in this study were selected on the basis of their availability to the authors, adequate cross section of common programs, and compatibility with an IBM PC or equivalent.

BACKGROUND

Backcalculation

Backcalculation, the "inverse" problem of determining material properties of a flexible pavement structure from its response to surface loading, has not been fully resolved. No direct, closed-form solution is currently available to determine the layer moduli of a multilayered system given the surface deflections and layer thicknesses. Therefore, it is currently necessary to employ iteration or optimization schemes to calculate theoretical deflections by varying the material properties (i.e., layer moduli) until a tolerable "match" of measured deflections is made. Because Poisson's ratios of pavement layers do not significantly affect calculated deflections, they are not iteratively modified like the layer moduli.

Several backcalculation computer programs are available and used by various highway agencies. Initial or "seed" layer moduli values are either assumed by the user or estimated by the program, and the corresponding deflections are computed by a particular analysis (multilayer elastic or finite element) subroutine in the program. The layer moduli are then adjusted using an iterative or optimization process until the computed deflections match the measured deflections within a certain tolerance. This is the extent of similarities among the programs whose unique characteristics create many differences.

J. M. Maestas, Office of Engineering, FHWA, Room 3118, HNG-42, 400 Seventh St., S.W., Washington, D.C. 20590. M.S. Mamlouk, Department of Civil Engineering, Arizona State University, Tempe, Ariz. 85287.

Some differences involve (a) iteration convergence methodologies, (b) consideration of nonlinear material behavior, (c) the need for and affect of seed moduli, (d) predesignated, allowable ranges of calculated layer elastic moduli, (e) a variety of input parameters and assumptions, and (f) the depth to bedrock.

Backcalculation is an ill-posed process in which minor deviations between measured and computed deflections usually result in significantly different moduli. In many cases, self-compensation of moduli results in obtaining various combinations of moduli producing essentially the same deflection basin. Compensation between depth to bedrock and subgrade modulus can also occur.

Overlay Design

Current overlay design methods range from engineering judgment to mechanistic (or mechanistic-empirical) approaches. Evaluating the material properties of existing pavement layers is a prerequisite for any rational overlay design process.

One of the most commonly used methods of overlay design is the AASHTO procedure. The 1986 AASHTO guide (*7*) recommends the use of layer moduli as a basis for material characterization. Layer moduli can be obtained by either laboratory testing or, where the latter is more practical, backcalculation. The AASHTO guide has recognized the improved accuracy of NDT in structurally evaluating existing pavement systems by allowing a method that uses a backcalculation technique that applies the "multielastic theory" to calculate layer moduli. Since the backcalculation problem has not been fully resolved, errors in backcalculation might result in different overlay thickness designs for the same pavement structure. This uncertainty in overlay thickness might result in millions of dollars in material costs as a result of over- or underdesign of the pavement.

Although the 1986 AASHTO guide emphasizes the use of a resilient modulus as a basis for material characterization, the procedure recommends the use of correlations of questionable accuracy between the modulus and the structural layer coefficients (a_i). Also, the AASHTO overlay procedure does not consider the depth to bedrock. Thus, if there is a compensation between the subgrade modulus and depth to bedrock, inconsistent overlay thicknesses will result.

RESEARCH METHODOLOGY

Selection of Test Sites

To adequately compare backcalculation programs on the basis of AASHTO overlay thickness, actual NDT data would be required from typical flexible pavement structural sections that require significant rehabilitation. To accomplish this, 29 in-service test sites were selected from the Arizona Department of Transportation (ADOT) construction schedule of pavement rehabilitation projects. These sites are located in areas with various traffic loading, environmental conditions, and subgrade soil types within the state (Figure 1). Preliminary information regarding these sites, shown in Table 1, was obtained from existing ADOT materials pavement design

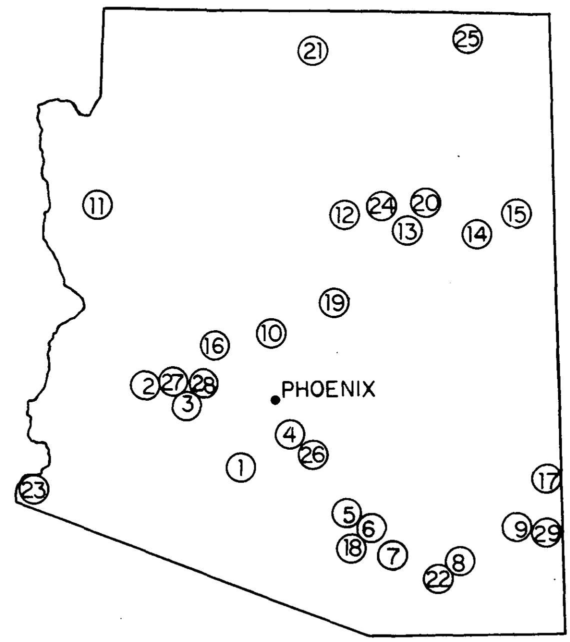

FIGURE 1 Location of test sites.

memorandums. These sites are specific locations within the limits of projects scheduled for pavement rehabilitation between late 1989 and the present. They are located only on Interstate and primary highways (United States and Arizona state routes).

Test sites within the project limits were selected on the basis of the extent of rehabilitation, which included either mill and overlay or just overlay. After selecting test sites, required information for each site was obtained from ADOT's Pavement Management System, Project History, Subgrade *R*-value, and NDT deflection data bases. Specific site locations coincide with locations of actual deflection measurement data selected for backcalculation analysis. Cumulative, 10-year, 18-kip equivalent single axle load (ESAL) in the design lane for each site was obtained from the NDT deflection data base. Deflection and pavement data including the Arizona seasonal variation factor (SVF), percent pavement surface cracking, and pavement surface temperature during NDT were also obtained from the NDT deflection data base. The SVF is an Arizona climate-based, regional factor used to determine percent of time of saturation exposure and ultimately used to select the AASHTO layer drainage coefficients. Layer thicknesses and material types of each site are shown in Table 2. Thicknesses of all surface layers were obtained from pavement coring results, whereas those of all other layers were of "plan" thicknesses obtained from the Project History data base. The AASHTO soil classification of subgrade material at each site was obtained from the subgrade *R*-value data base.

FWD Deflection Testing

ADOT routinely performs project-level FWD deflection testing. All FWD deflection data are collected and maintained in a computer data base. Currently, five deflection tests are performed per mile for each lane. A set of seven deflections,

TABLE 1 Location and Characteristics of Test Sites

Site No.	Route/ Direction	Milepost	SVF[1]	1990		Surface Temperature @NDT (°F)	Cumulative ESAL[3] (1000)
				Cracking (%)	Roughness[2]		
1	I-8/EB	135.0	1.2	1	76	72	6,840
2	I-10/EB	71.0	0.8	1	121	118	19,364
3	I-10/WB	91.4	1.0	25	100	80	21,758
4	I-10/WB	170.0	1.0	2	144	58	15,202
5	I-10/EB	240.6	1.6	2	125	100	28,439
6	I-10/WB	250.7	1.6	0	134	102	21,654
7	I-10/EB	273.1	1.7	0	109	77	17,118
8	I-10/WB	315.7	1.9	8	153	60	14,179
9	I-10/EB	368.6	1.7	8	141	107	10,689
10	I-17/SB	247.6	2.5	6	104	88	9,709
11	I-40/WB	51.6	1.7	4	183	82	21,072
12	I-40/WB	213.0	2.9	0	90	76	12,539
13	I-40/WB	255.6	1.7	0	99	100	14,119
14	I-40/WB	307.6	1.8	1	204	108	18,108
15	I-40/WB	333.3	2.0	0	224	106	16,849
16	US60/WB	109.6	1.5	15	268	113	1,321
17	SR75/NB	380.6	1.7	20	264	99	98
18	SR86/WB	168.2	1.7	20	157	59	2,280
19	SR87/NB	265.0	3.8	2	190	58	2,488
20	SR87/NB	363.0	1.8	4	263	70	177
21	US89A/NB	531.6	1.7	4	145	50	258
22	SR90/EB	315.8	2.2	0	138	54	254
23	US95/NB	11.6	0.4	3	201	99	1,156
24	SR99/NB	60.3	1.6	30	372	110	224
25	US160/EB	409.6	1.8	15	341	100	868
26	SR387/NB	4.2	1.3	8	113	70	3,948
27	I-10/WB	78.0	0.8	2	95	100	19,364
28	I-10/EB	92.6	1.0	30	173	94	21,758
29	I-10/EB	376.0	1.7	6	243	107	10,689

Notes: 1. Arizona seasonal variation factor
2. Mays roughness meter reading
3. Projected 10-year equivalent single axle loads in the design lane

which comprise a single deflection "bowl" or basin, are measured by sensors placed at 1-ft spacings. Multiple load drops are made at various load heights during FWD testing at a single location providing a wide range of load levels. The particular deflection basins used in this study have already been "normalized" to 9 kips by ADOT. This normalized deflection basin is an actual basin measured at the load level nearest to 9 kips and proportionally modified to coincide with a deflection basin produced at a load level of exactly 9 kips.

Because specific test sites were selected from within actual pavement sections scheduled for rehabilitation, FWD deflection data were readily available. In an effort to select a representative deflection basin of the pavement section, a single basin similar to the average basin for that particular pavement section was selected. A single deflection basin was selected for analysis instead of an average because the authors believe the average does not adequately represent an actual basin. Another consideration in selecting a particular deflection basin was the extent of cracking at the NDT location. Nearly every deflection basin selected to represent an individual test site was measured on pavement surface areas having 10 percent cracking or less. This was done in an effort to minimize errors associated with deflection testing of cracked pavements. The selected deflection basins were then used for the backcalculation of layer moduli.

Backcalculation

Unique Characteristics and Observations of Programs

The following common PC software programs were evaluated in this research: ELSDEF, MODCOMP2, MODULUS4, and ISSEM4. Table 3 includes a comparison of common characteristics of these backcalculation programs. To supplement Table 3, the following sections are included to briefly address some general information, unique characteristics, and observations regarding the use of each program.

ELSDEF The ELSDEF program, developed by Bush (*8*), incorporates ELSYM5 as a subprogram to calculate stresses, strains, and deformations in the pavement structure. This technique is explicitly a linear elastic analysis procedure. Subgrade thickness can be assumed as semi-infinite or given a certain thickness by the user. The program iteratively adjusts the layer moduli until the calculated deflections match the measured deflections within a certain error tolerance (see Table 3). To assist the user in satisfactory convergence, each set of iteration results offers layer moduli with and without consideration of designated moduli limits. In the sole case of this program, it may not be extremely important to use core

TABLE 2 Layer Thicknesses and Material Types

Site No.	Pavement Layer Number: Material Type/Thickness (in.) 1	2	3	AASHTO Subgrade Soil Classification
1	AC/8.0	AB/4.0	SM/8.0	A-1-b(o)
2	AC/6.4	AB/4.0	SM/15.0	NA
3	AC/8.1	AB/4.0	SM/8.3	A-2-7(o)
4	AC/6.0	AB/4.0	SM/15.0	A-6(2)
5*	AC/8.0	AB/4.0	CB/6.0	A-4(o)
6*	AC/8.0	AB/4.0	CB/6.0	A-6(5)
7	AC/5.5	AB/3.0	SM/6.0	A-1-a(o)
8	AC/5.3	AB/4.0	SM/24.0	A-1-b(o)
9	AC/8.0	AB/4.0	SM/15.0	A-2-4(o)
10*	AC/11.5	AB/4.0	SM/11.0	A-2-7(o)
11	AC/9.7	SM/3.0	--	A-1-b(o)
12	AC/6.6	AB/2.0	SM/12.0	A-2-4(o)
13	AC/13.5	SM/6.0	--	A-1-b(o)
14	AC/6.6	BB/5.0	SM/4.0	A-2-4(o)
15	AC/8.8	CB/10.0	SM/8.0	A-2-4(o)
16	AC/4.5	--	--	NA
17	AC/5.0	AB/4.0	SM/9.0	NA
18	AC/4.0	AB/4.0	SM/15.0	A-2-7(o)
19	AC/3.5	--	--	A-4(o)
20	AC/2.0	AB/4.0	SM/15.0	NA
21	AC/2.8	SM/6.0	--	NA
22	AC/4.6	AB/4.0	SM/12.0	A-2-4(o)
23	AC/4.7	CB/7.0	SM/14.0	A-7-6(31)
24	AC/3.0	--	--	NA
25	AC/4.0	--	--	A-3(o)
26	AC/4.5	AB/6.0	SM/20.0	A-1-b(1)
27	AC/10.0	AB/4.0	SM/10.0	NA
28	AC/7.5	AB/4.0	SM/13.3	A-2-4(o)
29	AC/7.5	AB/6.0	SM/21.0	NA

Legend: AC - Asphalt Concrete, AB-Aggregate Base
BB - Bituminous Treated Base,CB-Cement Treated Base
SM - Select Material (Granular Subbase)
NA - Not available to authors
*Two layers were combined during backcalculation in order to change the 5-layer system to a 4-layer system which were combined

thicknesses for the surface or any other layers because input values are rounded to the nearest inch. ELSDEF is the only program of the four evaluated that allows the user to estimate the subgrade layer thickness between the range of 0 and 999 in. and its moduli limits. For the purposes of this study, the following typical trial subgrade thicknesses of 999 in. representing a semi-infinite layer, 240 in., and 120 in. were used to obtain the optimum (minimal deflection match error) set of layer moduli. Also, a semi-infinite subgrade layer can be designated by simply entering zero as its thickness.

MODCOMP2 MODCOMP2, Version 2.4, originally developed by Irwin (*9*), was used for this research. This backcalculation program also uses an iterative approach to compute a final set of layer moduli. In each iteration, the difference between each measured and calculated deflection expressed as a percentage of the measured deflection is compared with a specified tolerance (see Table 3). The program allows the use of up to eight layers and applies the root mean square (RMS) as the error criterion. It incorporates the Chevron elastic layer analysis as a subprogram to compute stresses, strains, and deformations in the pavement structure. No subroutine exists explicitly for data entry. Input data required must be structured in accordance with a prescribed format. The program will terminate if the error tolerance is met or if the prespecified maximum number of iterations is reached.

MODULUS4 MODULUS, Version 4.0, is a backcalculation program developed by the Texas Transportation Institute (*10*). Its methodology applies a pattern search algorithm to minimize the sum of squares for error between measured and calculated deflections. This method replaces direct deflection computation with an interpolation process that guarantees convergence. It detects nonlinearity in the subgrade and automatically selects the optimum number of sensors for backcalculation use. It incorporates the U.S. Army Corps of Engineers WES5 linear elastic program to compute stresses, strains, and deformations in the pavement system. As shown in Table 3, MODULUS4 is the only program evaluated that does not require user-designated "seed" moduli or maximum number of iterations per basin evaluation. It is also the only program that automatically calculates the subgrade depth on the basis of measured deflections and offers default values for load plate radius, number of deflections, and deflection sensor spacing. Not indicated in Table 3 is the fact that this program provides all measured and calculated deflections only for final

TABLE 3 Comparison of Common Characteristics Among Backcalculation Programs

Program Characteristic	Backcalculation Program			
	ELSDEF	MODCOMP2	MODULUS4	ISSEM4
***INPUT*:**				
Error Tolerance*	(10%)	√	X	X
Max No. of Iterations	(3)	√	X	(6)
No. of Load Levels	≯5	≯6	X	X
Load Magnitude	√	√	√	X
Load Plate Radius	X	X	(5.91 in.)	√
Load Pressure	√	√	X	√
No. of Deflections	≯10	≯8	(7)	≯7
Deflection Readings	√	√	√	√
Deflection Sensor Spacing	√	√	(12 in.)	√
No. of Layers	≯5	≯8	≯4	≯4
Pavement Layer:				
Thickness	√	√	√	√
Poisson's Ratio	√	√	√	√
Modulus Limits	√	X	√	X
Seed Modulus	√	√	X	√
Fixed/Variable Modulus	X	√	X	X
Linear/Nonlinear Response	X	√	√	X
Subgrade Thickness	≯999 in.	Semi -infinite	(Calculated)	Semi-infinite
Subgrade Modulus Limits	√	X	X	X
Subgrade Seed Modulus	√	√	√	√
***OUTPUT*:**				
(Per Iteration)				
Deflections:				
Measured	√	√	X	X
Calculated	√	√	X	X
Percent Difference*	√	√	X	X
Absolute Sum	√	X	√	X
Root Mean Square	X	√	X	X
Final Moduli:	√	√	√	√
Percent Difference Between Iterations	X	X	X	Pre-set @3.5

* - Cumulative absolute difference between each measured and calculated deflection expressed as a percentage of the measured deflection
( ) - Default values which can be overwritten by the user.
√ - Applicable
X - Not Applicable

moduli results, unlike some other programs that provide such data on a per-iteration basis.

ISSEM4 In situ stress-dependent elastic moduli, 4 (maximum layers) (ISSEM4) program was originally developed by Stubstad (*11*) with technical assistance from Florida and Arizona DOT engineers. It was originally designed to evaluate only deflection data of the Dynatest FWD. ISSEM4 is the only program that applies nonlinear relationships for "finite cylinders within conically-shaped volume of influence of the applied FWD load" as described in the user's guide. It iteratively backcalculates modulus values of a layered, nonlinear elastic system. Process algorithms are based on Boussinesq's equations and a version of the equivalent thickness method (*12*). ELSYM5 is used as a subroutine to adjust the subgrade moduli until a match of measured and calculated deflections is made. ISSEM4 provides various analysis options or "iteration mode identifiers" that include fixing the modulus of the surface layer and calculating the surface layer thickness.

The program analysis option selected for this research, considered the most typical, was one that assumed that input layer thicknesses are correct and that all layer modulus values are to be calculated. Multiple iterations are performed by the program until the percent difference between individual layer modulus values of two consecutive iterations is less than 3.5 percent if the designated maximum number of iterations are performed or if divergence persists. This convergence error criterion is unique because it does not involve matching calculated and measured deflections. The following are unique characteristics of ISSEM4:

1. ISSEM4 does not provide a comparison and analysis of measured and calculated deflections as part of intermediate or final results.
2. This program will not function if the evaluated pavement section does not have increasing layer thicknesses with depth. This lack of layers necessitated the consolidation of layers of like material, providing only two- and three-layer systems. This was a predominant problem because the typical test site pavement section had a 4-in.-thick base course layer (Layer 2) that was usually thinner than the surface layer.
3. Only five deflections, some NDT-measured and some interpolated by the program, are required for three- and four-

layer systems. Four deflections are required for two-layer systems.

4. Input data must be provided in metric units.

5. In this study, results were almost always obtained only when sites were treated as two- and three-layer pavement systems.

6. The program accepted seed modulus values of underlying layers that were less than those of overlying layers; this occurred despite the warning in the program user's manual that such circumstances could render results unreliable.

7. The program would not accept adjacent pavement layers that had identical seed modulus values.

Selection of Parameters

Common input layer moduli ranges, applicable only to ELSDEF and MODULUS4, and Poisson's ratios used in this study are shown in Table 4. For other backcalculation programs not requiring moduli limits, final moduli were selected with the lowest convergence error or best "goodness of fit" results despite the moduli values being outside the practical moduli input limits in Table 4. Also, selection of input values of Poisson's ratios for the asphaltic concrete and bituminous base were based on the pavement surface temperature at the time of NDT. Such temperatures ranged from 50°F to 118°F. Since backcalculation programs are not significantly sensitive to Poisson's ratio input values, the following general relationships for the bituminous-bound layers were applied with other values obtained by interpolation and extrapolation: Poisson's ratio = 0.30, 0.35, and 0.40 at 40°F, 70°F, and 100°F, respectively. Poisson's ratios used for all other layers were considered as commonly used values.

Analysis and Comparison of Results

A comparison of the overall average layer modulus results of each program is included in Figure 2. Figure 2 indicates that ELSDEF produced the lowest average modulus of the surface layer, whereas ISSEM4 produced the highest. Also, average modulus results of MODCOMP2 and MODULUS4 are similar for Layers 1 and 2. All four programs provided similar average modulus results of Layers 2 through 4. Figure 2 does not include ISSEM4 average modulus results of Layer 3; this layer was combined with Layer 2 or 4. Modulus results from iterations yielding these minimal covergence error results were used in the overlay design portion of this research.

Comparison of Program Error Criterion

Because the error criterion of each program is different, except for ELSDEF and MODULUS4, a valid comparison of programs on the basis of given convergence error results was not possible. However, the absolute sum (ABS) of MODCOMP2 and ISSEM4 convergence error can be calculated using final moduli results and an elastic layer program such as ELSYM5 and Chevron. These programs can calculate the theoretical deflections using pavement layer data (e.g., layer thickness, Poisson's ratio, moduli, etc.). The ABS of the differences between the theoretical and measured deflections can be obtained and could provide a complete comparison of the programs on the basis of convergence error results.

AASHTO Overlay Design

Moduli Corrections and Selection of Design Parameters

A PC-compatible AASHTO overlay design program, developed by Mamlouk (*13*), was used for this study. Overlay design was performed by using standard AASHTO layer coefficients from each program's final backcalculated layer moduli values of each site's pavement structural section. The only modulus correction applied involved only bituminous-bound layers. Using actual temperatures at NDT, this modulus correction simultaneously computes the average asphalt pavement layer temperature and adjusts the modulus for the standard temperature of 70°F. This temperature correction procedure, as outlined in the AASHTO guide, was applied, assuming that the asphalt pavement surface temperature at the time of NDT is equal to the mean air temperature of the 5 days before NDT. No modulus corrections were made on the predominant granular base and subbase layers to reflect variable stress states. Also, data required to estimate AASHTO's effective subgrade soil resilient modulus was not available to the authors. Instead, the actual backcalculated modulus value for the subgrade was directly used in each overlay design.

After correcting the bituminous-bound layer moduli for temperature, structural layer coefficients for each non-

TABLE 4 Backcalculation and AASHTO Overlay Design Parameters

Layer Material	Modulus (ksi)		Poisson's Ratio	Structural Coefficient	
	Min.	Max.	at 70°F	Min.	Max.
Asphaltic Concrete	50	1000	0.35	0.20	0.45
Base:					
bituminous	5	400	0.35	0.10	0.30
cement	90	1000	0.25	0.10	0.27
granular	3		0.35	0.05	0.17
Subbase:					
granular	3	110	0.35	0.05	0.15
Subgrade	5	40	0.40		

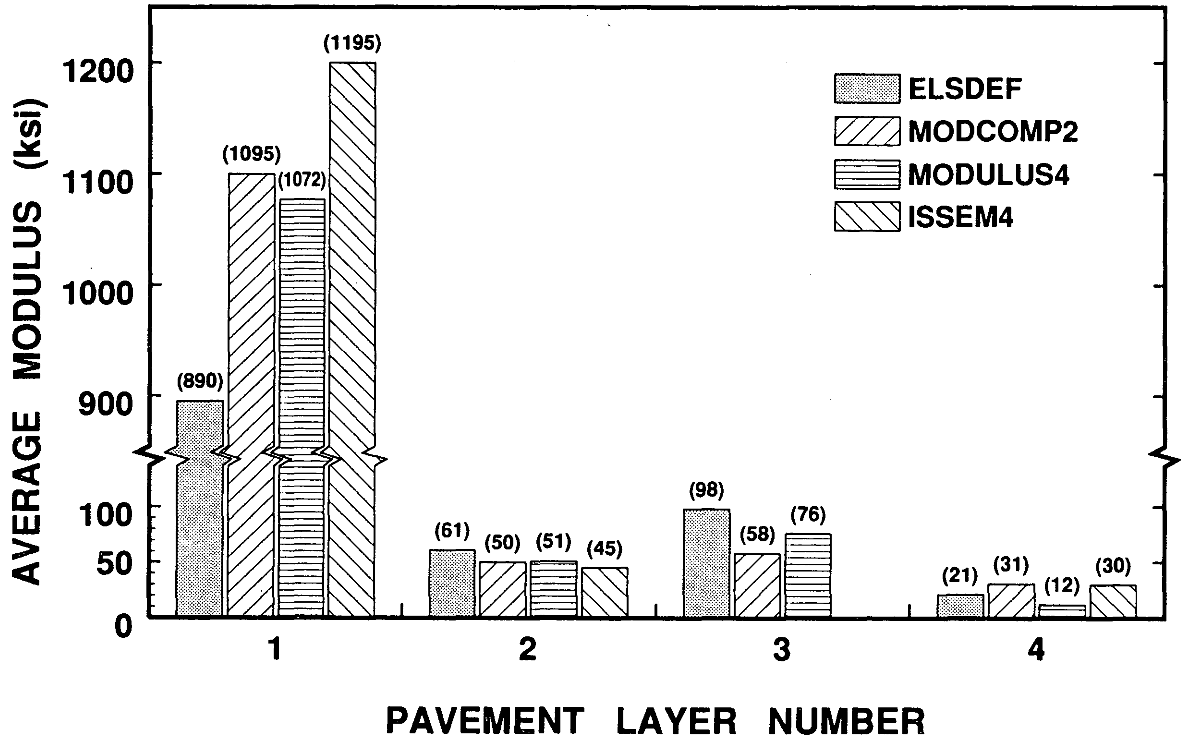

FIGURE 2 Comparison of pavement layer moduli among backcalculation programs.

subgrade layer were obtained using the AASHTO correlations given their backcalculated or corrected modulus values, or both, as shown in Table 4.

Using an empirical relationship developed by ADOT (*14*), base and subbase drainage coefficients were estimated as a function of drainage quality and the previously mentioned SVF. Drainage quality was assumed to be "fair" for all overlay designs. Because the primary objective is to compare backcalculation programs, the need to perform an exact overlay design to suit each site was not considered essential. Consequently, some required AASHTO overlay design parameters were assumed and used in each site's overlay design. These parameters are 99.9 percent reliability, 0.45 overall standard deviation, 4.5 overlay initial serviceability index, 3.0 overlay terminal serviceability index, and 0.45 structural layer coefficient of overlay. However, the design ESALs, SVF, layer thicknesses, moduli, and coefficients were parameters characteristic to each site and used for each overlay design.

Milling existing asphaltic concrete pavement prior to overlay was considered in the automated overlay design of applicable sites. Milling is a typical rehabilitation strategy employed by ADOT on most existing flexible pavements on the interstate highway system. In this study, milling 3 in. before overlay was assumed for these particular sites.

Results

Overlay thicknesses, rounded to the nearest ½ in., required for each test site are shown in Table 5. Table 5 also indicates whether milling was considered and includes the average overlay thickness of all test sites for each program.

A comparison of overlay thickness results by backcalculation program per site in Table 5 reveals significant differences between programs. Sites 1 through 3, 9, 11, 23, and 28 each have a maximum overlay thickness difference of over 3 in. From a practical perspective, these differences could translate into a significant amount of money on a large overlay construction project.

ANALYSIS OF RESULTS

An analysis of variance (ANOVA) was performed to test the null hypothesis that all programs are the same. A completely randomized design was applied where extraneous sources of variability were not controlled. Five ANOVAs were performed to individually consider the following factors: backcalculated modulus results of each layer and overlay thickness results. In considering a level of significance of 0.05 for this research, the results indicate that the backcalculation programs are significantly different on the basis of subgrade layer modulus (E_4) results. However, results also reveal that the backcalculation programs are not significantly different considering the other individual factors (modulus results of Layers 1 through 3 and overlay thickness).

Knowing only that the programs are significantly different on the basis of E_4, the procedure of multiple comparisons was further performed using Tukey's method as described in Ott (*15*) to determine how each program relatively differed on this basis. Multiple comparisons, using results of the ANOVA, determine the relative difference of the E_4 sample means of each program on the basis of a particular critical value. Results of the multiple comparisons indicate that MODULUS4 yields

TABLE 5 Summary of AASHTO Overlay Design by Backcalculation Program and Test Site

Site No.	Milled?	Overlay (in.) by Backcalculation Program			
		ELSDEF	MODCOMP2	MODULUS4	ISSEM4
1	YES	3.5	4.5	5.5	0
2	YES	2.5	3.0	6.5	2.5
3	YES	3.0	3.0	8.5	4.0
4	YES	6.5	6.5	8.0	6.0
5	YES	7.5	7.5	9.0	7.0
6	YES	5.5	5.0	7.0	4.0
7	YES	7.0	7.0	9.5	7.5
8	YES	3.5	3.5	5.0	3.5
9	YES	0	0.5	3.5	0.5
10	YES	0	0	0	0
11	YES	9.0	3.5	8.0	9.0
12	YES	7.5	4.5	7.5	4.5
13	YES	0.5	0	0.5	0
14	YES	8.0	7.5	7.5	8.5
15	YES	2.5	4.5	5.5	7.5
16	NO	5.5	5.5	6.0	5.5
17	NO	0.5	0.5	1.0	0.5
18	NO	2.5	1.5	2.0	1.0
19	NO	5.5	5.5	6.0	5.5
20	NO	0	2.5	3.0	2.5
21	NO	3.0	3.5	4.5	3.0
22	NO	0	0	0.5	0
23	NO	0	2.5	1.5	4.0
24	NO	4.5	5.0	5.5	4.0
25	NO	5.0	5.0	6.0	4.5
26	NO	0	0	3.0	1.5
27	YES	2.5	3.0	4.5	3.5
28	YES	3.5	2.0	7.0	2.0
29	YES	1.0	1.0	2.5	0
Average		3.45	3.38	4.98	3.52

subgrade layer modulus results significantly lower than those of the other programs.

In addition to the ANOVA, average overlay thickness results were evaluated and found to be not statistically different, considering an allowable level of significance of 0.05. However, in reality, the large differences in overlay thickness between programs per site are very serious.

MODULUS4 results contributed to overlay design thicknesses larger than those from other backcalculation programs, whereas ELSDEF resulted in smaller thicknesses, as shown in Table 5. The larger overlay thicknesses produced by MODULUS4 were attributed to its backcalculated subgrade moduli (E_4) results that were determined to be significantly lower than those of other programs. These results are because MODULUS4 automatically calculates a subgrade thickness that was usually not semi-infinite, as was assumed in the cases of MODCOMP2 and ISSEM4. This lower subgrade thickness estimation resulted in higher strains in the subgrade, consequently reducing the layer modulus. In the AASHTO overlay design procedure, the lower the modulus, the higher the required thickness. Because the AASHTO overlay design procedure does not consider the subgrade thickness or depth to rigid layer, excessive overlay thicknesses will result when using backcalculation programs such as MODULUS4.

SUMMARY AND CONCLUSIONS

Several backcalculation programs are currently available and used to evaluate the structural condition of existing pavements. Because pavement structural evaluation results significantly affect overlay design results, the main objective of this study was to evaluate the effect of backcalculation program differences on overlay thickness. Secondary objectives were to conduct a comprehensive comparison of program characteristics and performance and simulate the use of backcalculation programs by practitioners.

Four common, PC-compatible, backcalculation programs (ELSDEF, MODCOMP2, MODULUS4, and ISSEM4) were compared and used to backcalculate layer moduli from 29 typical, in-service, flexible pavement sites within projects that required significant rehabilitation. FWD field deflections from each test site were used to estimate layer moduli by backcalculation. The estimated moduli were used in the design of required overlays in accordance with the 1986 AASHTO design guide.

Although the various backcalculation programs produced various layer moduli, these differences were not statistically significant except for the subgrade. The overlay thickness results between programs were not statistically different. However, the variability of overlay thickness results per site were serious considering practical applications.

In summary, "state of the art" in backcalculation, as represented by the programs evaluated in this research, is not adequate for use by the practitioner. Despite favorable statistical results, reliable and realistic results will not be obtained using such programs in conjunction with the AASHTO overlay design method. Backcalculation programs must still be used with extreme caution.

Additional research is needed to further refine the backcalculation process to reduce the effects of extraneous sources of error and dependence on user experience. When all effects on moduli results are identified and quantified, perhaps a more intricate statistical analysis can be applied when similarly comparing programs to accurately account for the effects of extraneous sources of error. The method of considering the depth to rigid layer should be improved and standardized among programs. Also, the criteria for evaluating the degree of deflection match should be standardized among all programs. More research is needed to provide a more rational overlay design procedure that relates the elastic layer moduli to overlay thickness without the need to apply empirical structural layer coefficients. The correlation between AASHTO structural layer coefficients and layer moduli serves to "mask" or reduce the true differences between the programs evaluated on the basis of overlay design thickness results. The AASHTO procedure should be modified to compensate for the depth to the rigid layer in the overlay thickness design procedure.

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