Layer Moduli from Deflection Measurements: Software Selection and Development of Strategic Highway Research Program's Procedure for Flexible Pavements

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Deflection basin measurements on flexible pavements for the purpose of structural capacity evaluation are a key component of the Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance monitoring program. In the near term, SHRP will apply a backcalculation procedure to these deflection measurements to estimate the in situ elastic moduli of the pavement layer materials. Because a standard method for evaluating the structural capacity of flexible pavements from deflection data does not presently exist, SHRP has undertaken a study to develop a layer moduli backcalculation procedure for use in the initial analysis of the SHRP deflection data. This procedure covers not only the software but also the rules, guidelines, and criteria used in applying the program. The process SHRP has followed in selecting software and developing a backcalculation procedure for flexible pavements is discussed, and the outcome of the software evaluation portion of the study is presented.

Deflection measurements on flexible pavements for the purpose of structural capacity evaluation are a key component of the Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance (LTPP) monitoring program. Since the spring of 1988, SHRP has completed an initial round of deflection testing on hundreds of in-service pavement test sections and begun a second round. Like the rest of the LTPP data, the raw deflection data are being stored in SHRP's National Pavement Performance Data Base and ultimately will be available to all researchers to use as they see fit.

In the near term, SHRP will apply a backcalculation procedure to these data for the sole purpose of meeting the immediate needs of the initial analysis of the LTPP data. The layer moduli derived from this endeavor will supplement, not replace, the raw deflection data stored in SHRP's data base. This endeavor is undertaken with the full expectation that it will be the first analysis, but not by any means the last. Too much remains to be learned about the art and science of backcalculation for this analysis to be regarded as definitive.

Numerous methods for evaluating the structural capacity of flexible pavements from deflection basin data are available, but a standard procedure does not presently exist. This paper will discuss the process SHRP has followed in selecting software and developing a backcalculation procedure for flexible pavements, and presents the outcome of the software evaluation portion of the study. Development of a procedure for rigid pavements is currently in progress and thus is not discussed in this paper.

SHRP's selection of backcalculation software does not constitute an endorsement and does not imply that the particular program selected is, in any sense, the "best" program available. Indeed, given the present state of the art, it is probable that the best program for use in any given circumstance depends on a number of factors, including, but not limited to, the level of expertise of the user, the nature of the pavement being evaluated, and the intended use of the results.

Before embarking on a detailed discussion, it is important to clarify the authors' terminology. In using the term "backcalculation software," the authors mean just that—the computer programs used in backcalculation. However, it is the authors' contention that the manner in which a backcalculation program is used is as important and, in some cases, more important than which program is used. Hence, in referring to backcalculation procedures, the authors are referring to not only the software, but also the "rules" by which that software is applied.

DEVELOPMENT PROCESS

The objective of the SHRP study summarized in this paper was to develop a backcalculation procedure for flexible pavements, on the basis of existing backcalculation software, that will provide the most accurate, repeatable, and reliable results possible, given the present state of the art. It was anticipated that this procedure would involve the development of detailed guidelines and specifications for the application of that software.

With this objective in mind, the process by which SHRP has pursued the selection and development of a flexible pavement backcalculation procedure for use in the LTPP data analysis involves the following steps, which will be discussed in greater detail in the ensuing sections of this paper.

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1. Software identification,
2. Development of preliminary software selection criteria,
3. Preliminary software selection,
4. Software evaluation,
5. Compilation of evaluation results,
6. Final software selection, and
7. Procedure development and documentation.

To date, this process has been completed through the sixth step outlined above. The procedure development and documentation stage of the process currently is in progress and will be finalized after a review of the preliminary rules by the SHRP Expert Task Group (ETG) for Deflection Testing and Backcalculation.

Software Identification and Preliminary Software Selection

The first three steps in the process outlined earlier were quite straightforward. Software identification involved a review of the literature to identify a number of the programs available and their pertinent features. The second and third steps were accomplished through discussions at a meeting of SHRP's Deflection Testing and Backcalculation ETG in November 1990. The ETG recommended that software selected for detailed evaluation meet the following criteria:

- Use layered elastic theory;
- Allow variable slip conditions at layer interfaces;
- Have flexible plate boundary conditions;
- Require user input for seed moduli but program results independent of seed moduli;
- Report goodness of fit for each deflection measurement;
- Have capability for user-defined depth to rigid layer;
- Have nonlinear modeling capability for base and subgrade materials (desirable);
- Provide the capability for the user to fix a layer modulus;
- Be able to model at least five layers; and
- Have capability for applying a weighing function to the error tolerances (desirable, but not essential).

On the basis of the above criteria (which were relaxed in a few cases), four programs were selected for further evaluation. They are ISSEM4 (*1*), MODCOMP3 (*2*), MODULUS (*3*), and WESDEF (*4,5*).

Software Evaluation: The Plan

The purpose of SHRP's flexible pavement backcalculation software evaluation exercise was twofold: (a) to provide a basis for selecting a program for use in the SHRP backcalculation and (b) to provide a basis for development of the procedures to be used with that software. For this endeavor a group composed of ETG members, the software developers, and SHRP contractors was assembled. Each evaluator was requested to work independently of the others to run all of the backcalculation programs using the same data sets from a number of actual SHRP test sections.

By having a spectrum of users from "informed" to "expert" for each program, SHRP hoped to gain some insight into what was required in terms of user input and application rules to be successful with each program and thus obtain information for the development of the SHRP backcalculation procedure document. To judge the "success" of a program, several criteria were planned. First, the participants were to make informed estimates of the material moduli, on the basis of laboratory test results for the materials involved, for comparison with the backcalculation results. In addition, results were to be evaluated on the basis of reasonableness, robustness, stability, goodness of fit, and general suitability for SHRP's purposes.

Deflection data and other pertinent information from eight SHRP pavement test sections were extracted from the SHRP data base for use in this software evaluation exercise. A primary consideration in the selection of these data sets was coverage of the wide range of pavement structures that make up the SHRP experiments. Other considerations included the distribution of these sections by climatic region, SHRP region, and geographical location within the United States. Figure 1 shows the pavement structures, and Table 1 gives typical measured deflections for these pavements.

Software Evaluation: The Reality

The SHRP backcalculation software evaluation exercise did not progress entirely according to plan. The first problem encountered was related to data availability. Laboratory materials data on which the "informed estimates" of the layer moduli were to be based were not available until after completion of the study, and hence that basis for evaluation of analysis results was lost. Since these data would have also helped the evaluators determine appropriate seed moduli and other input values, their efforts were also hindered by the lack of laboratory materials data. The other significant deviation from the plan was that the evaluation process turned out to be sufficiently time consuming that several of the evaluators were not able to complete the evaluation of all of the software. However, enough of the work was completed to provide a basis for decision making and procedure development.

Evaluation Results

Overview of Evaluators' Comments and Recommendations

Before proceeding with the detailed evaluation, an overview of the comments and recommendations provided by the evaluators was undertaken to determine how they viewed each program. Although the ranking of the programs varied from one evaluator to another, MODCOMP3, MODULUS, and WESDEF were overwhelmingly ranked as the top three backcalculation programs. Program ISSEM4 was consistently given the lowest rating for the following reasons:

- Not able to achieve a reasonable solution for several of the sections analyzed,

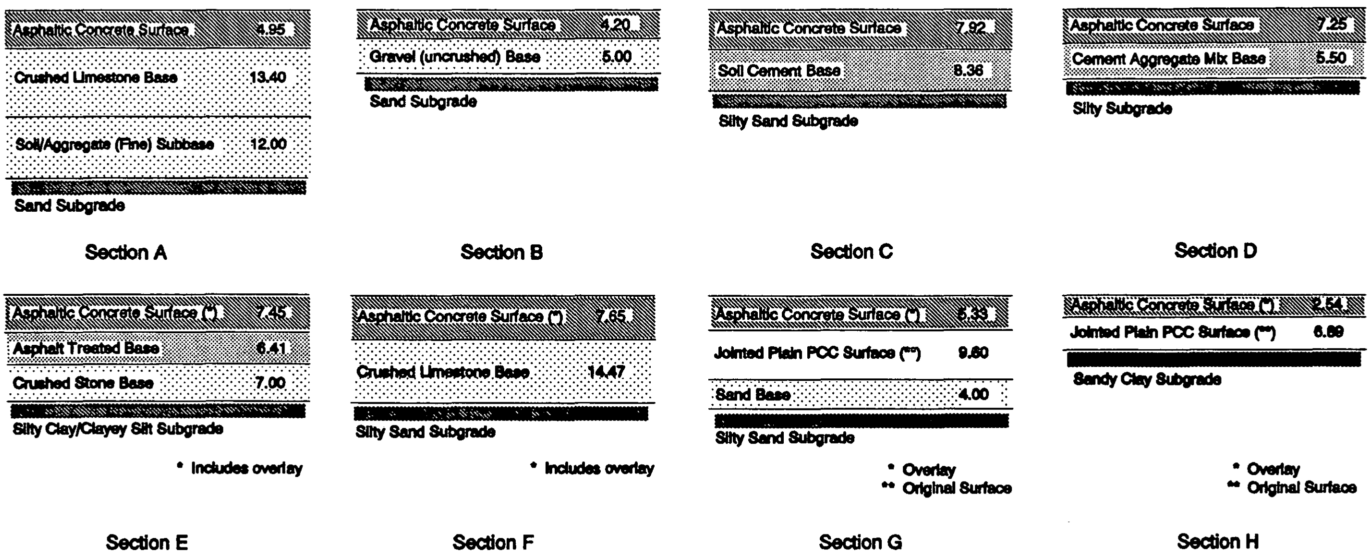

FIGURE 1 AC surfaced pavement structures.

TABLE 1 Typical Deflection Data

Section ID	Load (lbs)	Deflection (mils) @						
		r=0"	r=8"	r=12"	r=18"	r=24"	r=36"	r=60"
A	10006	9.47	7.43	6.31	4.90	3.82	2.48	1.24
B	9596	12.21	9.43	7.65	5.72	4.32	2.62	1.36
C	9522	4.87	3.89	3.40	2.95	2.57	2.03	1.31
D	9474	5.67	5.27	4.97	4.50	4.10	3.42	2.38
E	9752	3.67	2.88	2.60	2.23	1.95	1.29	0.65
F	9512	5.07	4.32	3.67	2.99	2.40	1.69	1.01
G	9398	2.81	2.41	2.33	2.24	2.14	1.90	1.40
H	9704	5.77	4.79	4.66	4.26	3.75	2.80	1.49

Note: Deflections shown correspond to a nominal 9,000 lb load. Deflection measurements were also taken at 3 additional load levels.

- Has convergence problems with several of the sections analyzed,
- Not capable of handling a rigid base layer, and
- Does not calculate deflections at the set sensors for comparison with the measured deflections.

Because a preliminary evaluation of the backcalculation results confirmed the evaluator's findings, ISSEM4 was eliminated from further study. Thus, the remainder of the software evaluation focused on MODCOMP3, MODULUS, and WESDEF.

Program-to-Program Comparison

Several analyses were conducted to aid in the selection of software for use by SHRP. First, a very broad program-to-program comparison of the backcalculated moduli was conducted. Figure 2 illustrates the results of this analysis for MODCOMP3 versus MODULUS. Although there was considerable variation, it was also apparent that an excellent correlation exists between these programs. The best agreement exists between MODULUS and WESDEF (R^2 = 0.89), followed by MODCOMP3 and MODULUS (R^2 = 0.85), and MODCOMP3 and WESDEF (R^2 = 0.83).

The data also showed that MODCOMP3 tends to predict higher subgrade moduli but lower base/subbase moduli. Although several reasons can be offered to explain these global differences, it is postulated that they were primarily related to the inclusion or omission of a rigid base layer in the analysis. MODULUS computes a hypothetical depth to a rigid layer and WESDEF uses a default depth of 20 ft—in each case, the user can override the program value, but this was not done by most of the evaluators. Since MODCOMP3 allows for up to 15 layers, the user can easily specify a rigid base layer having fixed modulus. However, boring data for each

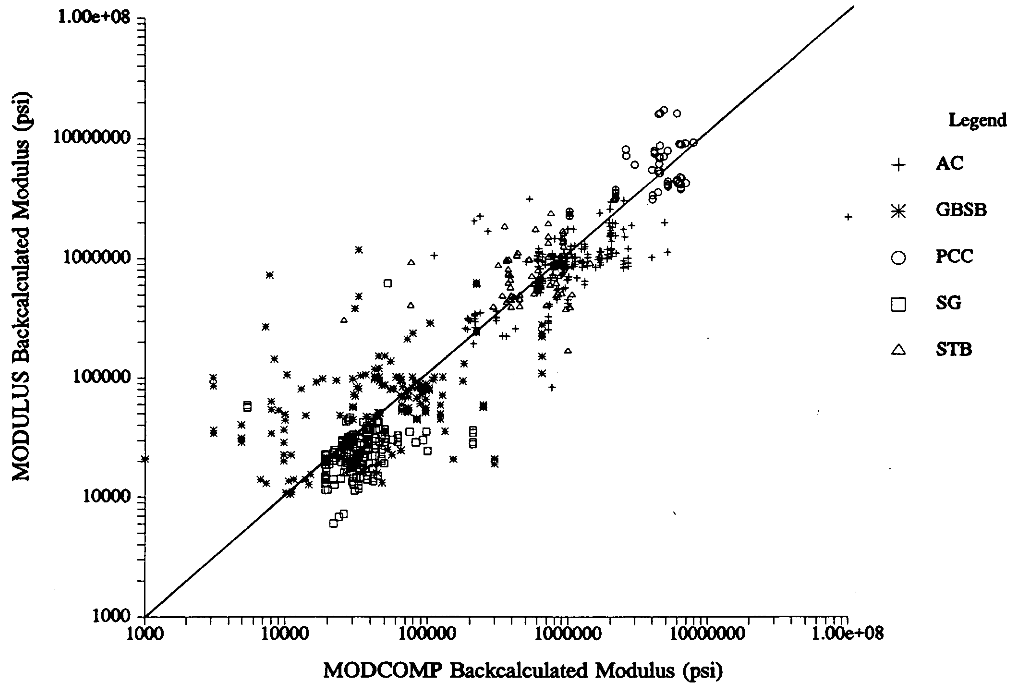

FIGURE 2 Comparison of MODCOMP and MODULUS programs.

section showed that bedrock was not present within the top 20 ft; thus most evaluators modeled the subgrade as a semi-infinite layer.

If a rigid base layer is included in the analysis, the subgrade moduli tend to be lower when compared with a solution in which such layer is not included. In turn, there is a compensating moduli effect on the remaining pavement layers; i.e., higher surface and base layer moduli. Hence, the better correlation of results between MODULUS and WESDEF and the higher subgrade moduli for MODCOMP3. Unfortunately, this rigid base question cannot be put to rest by this SHRP exercise, because true moduli or approximately true values are not known.

User Sensitivity

The next analysis in the software evaluation involved a comparison of the results generated by each individual evaluator to assess user variability. Because all three program developers were a part of the evaluation panel, their results were used as the reference datum in this comparison. It was assumed that the program developers were experts in the use of their program and hence would arrive at the "best" set of results.

Plots of the moduli predicted by the program developer versus those predicted by the other evaluators were developed for each program and are illustrated in Figure 3. The degree of correlation (R^2) found for each developer-evaluator comparison by program averaged 0.92 for MODULUS, 0.87 for MODCOMP3, and 0.72 for WESDEF. Thus, it appears that MODULUS is less user dependent than the other programs. However, this observation must be tempered by the fact that the degree of versatility and hence degree of sophistication required on the part of the user varies from program to program; this is particularly true when comparing MODCOMP3 to MODULUS and WESDEF.

The variability of the MODCOMP3 results is primarily associated with the unbound granular base/subbase layers. In the case of MODULUS, the variability is mostly related to the subgrade and granular base/subbase layers; lower subgrade moduli and higher base/subbase moduli were generally predicted by the evaluators compared with the program developer. For WESDEF, all material types contribute to the variability, with the exception of the subgrade layer, which shows excellent agreement among all evaluators. For all three programs, it is hypothesized that the variability is primarily associated with the modeling of the pavement by each evaluator. More importantly, these findings clearly emphasize the need to develop detailed guidelines and specifications for the application of the selected software to achieve consistent results from one program user to another.

Reasonableness of Results

Although true moduli or approximately true values are not known, an analysis aimed at determining the reasonableness of the predicted moduli was undertaken. Using data generated by the program developers, a series of bar charts comparing the backcalculated moduli by program and pavement section were developed for each material type and are shown in Figures 4 through 7 for all materials, except portland cement concrete. Each bar shown in these charts was generated from the analysis of four load levels—nominal 6,000-, 9,000-, 12,000-, and 16,000-lb loads.

Figure 4 shows that the backcalculated moduli for the asphaltic concrete layer appear reasonable for all three programs, except as follows. Layer moduli predicted by MODCOMP3 for Sections D and G seem high whereas that for Section H

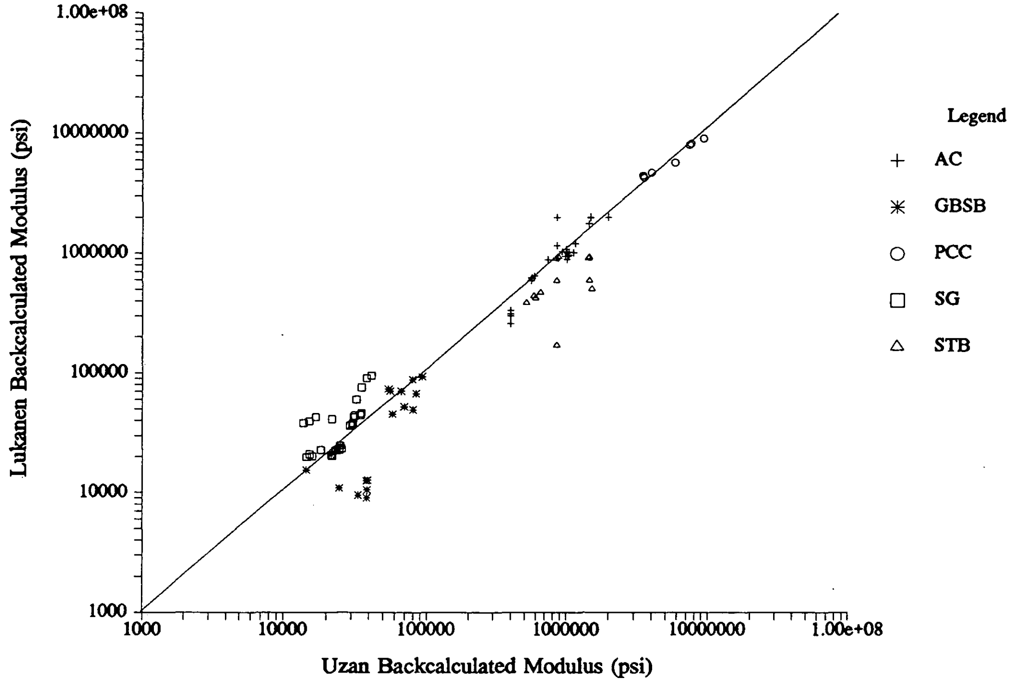

FIGURE 3 User comparison: MODULUS.

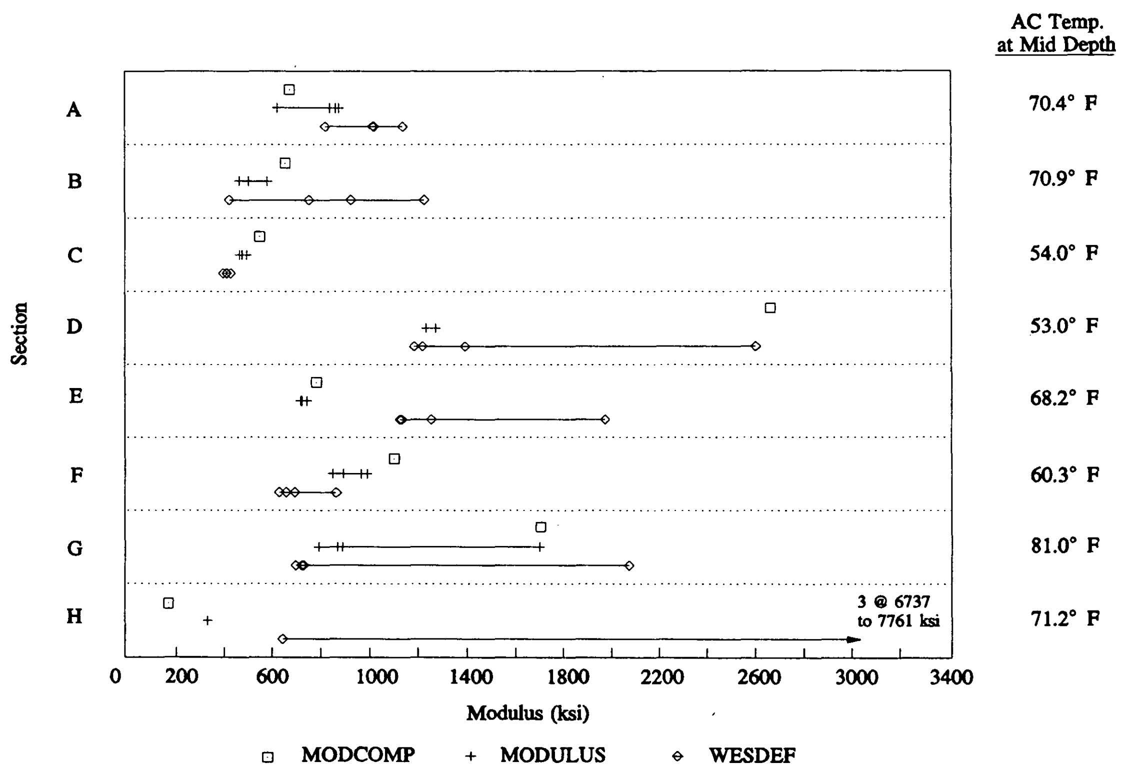

FIGURE 4 Comparison of backcalculated moduli: asphalt concrete (no temperature correction).

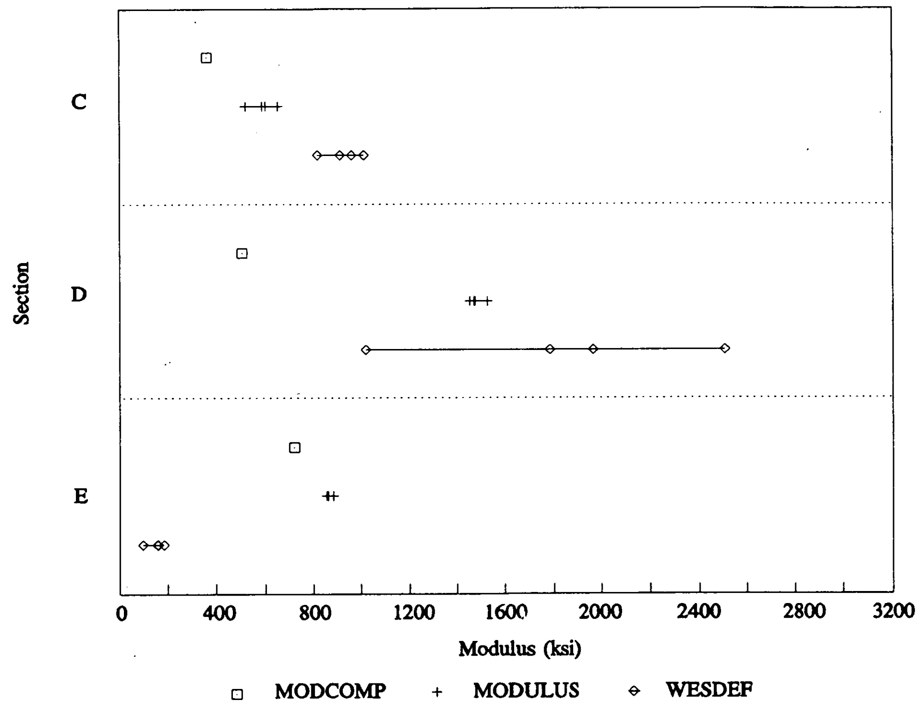

FIGURE 5 Comparison of backcalculated moduli: stabilized base.

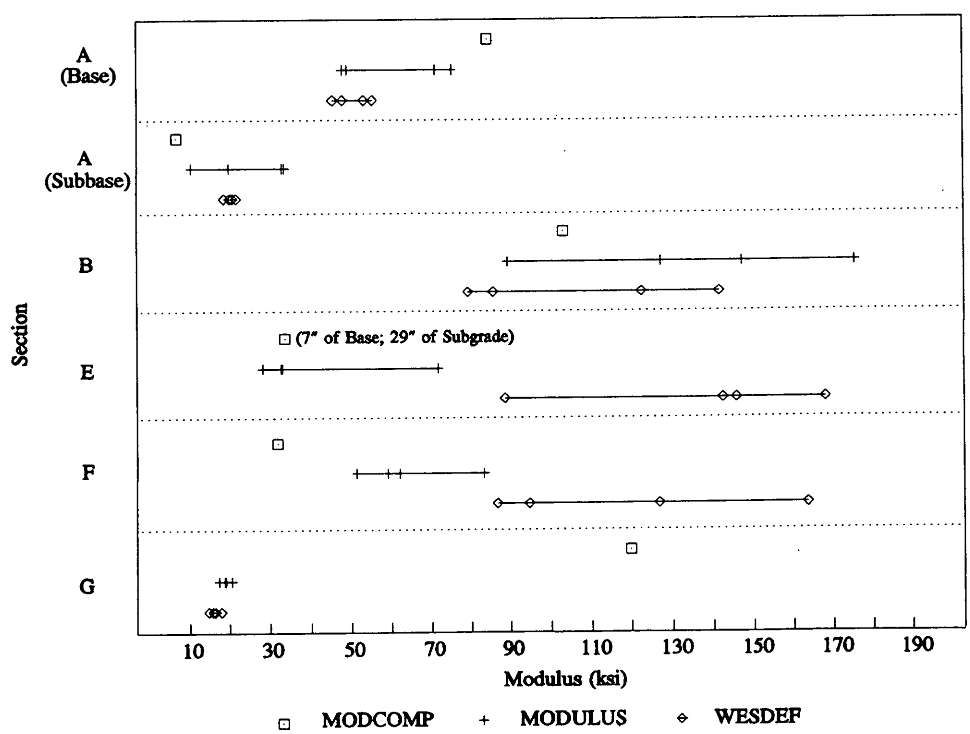

FIGURE 6 Comparison of backcalculated moduli: unbound base/subbase.

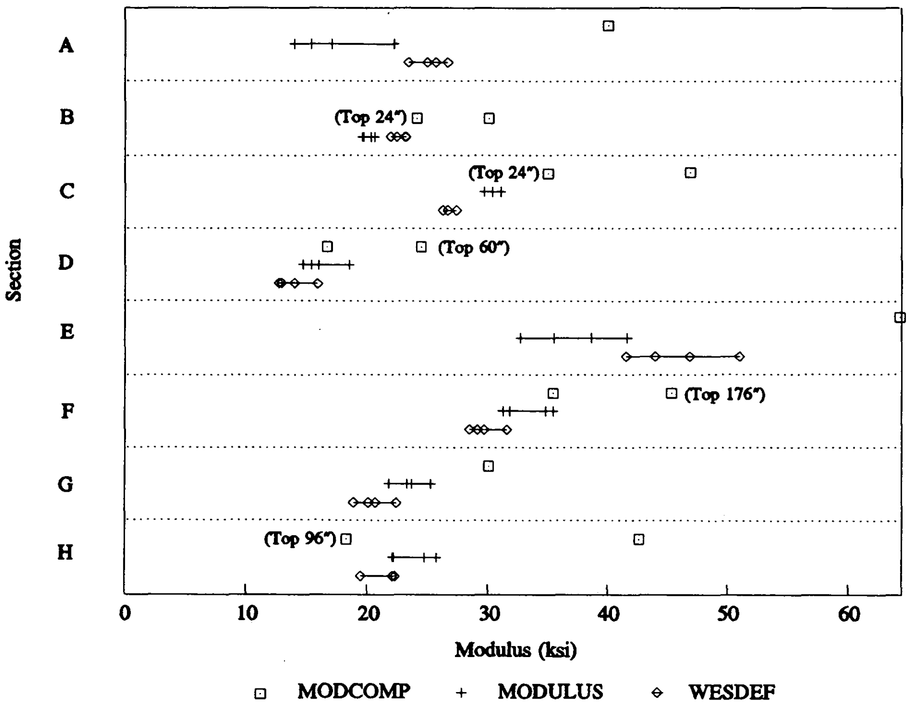

FIGURE 7 Comparison of backcalculated moduli: subgrade.

appears low. For Section G, the value predicted by MODULUS for the lowest load level appears to be high, especially when compared with the moduli for the remaining load levels. WESDEF results corresponding to the lowest load level for Sections D, E, and G seem unusually high as do the results for the three highest load levels in Section H. Also, the degree of variability associated with Section B seems high. In all fairness to the three programs, it should also be noted that Section G contained nondecreasing deflections, a situation these programs were not developed to handle.

Although only two of the eight sections had a portland cement concrete layer, the MODCOMP3 predicted values appeared reasonable for both sections. The MODULUS results appeared reasonable for Section H but high and variable for Section G. WESDEF, on the other hand, seemed to have a problem with this material type; three of the four values for Section G seem unusually high whereas all of those for Section H were very low.

Figure 5 shows that the backcalculated moduli for the stabilized base and subbase materials appeared reasonable, except as follows. For Section D, the MODCOMP3 modulus value seem somewhat low for a cement aggregate base, especially when compared with that of the soil cement in Section A or with the values obtained by the other two programs for this same section. The MODULUS results for Section E appear high at first glance, but this is because this layer was combined with the AC surface layer in the analysis. Hence, the values reflect a composite response of the two layers. WESDEF results for Section D are unusually variable, and some of the values appear to be high. In addition, predicted moduli for Section E seem low.

Compared with the previous material types, the results for the unbound granular base and subbase materials are considerably more variable, as shown in Figure 6, and thus more difficult to assess. MODCOMP3 results are mostly in the range of expected values, with the exception of Section G, which has an unusually high modulus value, especially when compared with those from the two other programs. All MODULUS predicted values appear reasonable, although somewhat high and variable for Section B. Likewise, WESDEF predicted moduli appear reasonable, although somewhat high and variable for Sections B, E, and F.

With regard to the backcalculated subgrade moduli, Figure 7 shows that MODCOMP3 consistently predicted higher modulus values than both MODULUS and WESDEF, which had similar values. On the basis of an earlier analysis, this difference between MODCOMP3 and the other two programs was attributed to the inclusion or omission of a rigid base layer.

Overall, the results of this analysis appear to indicate that both MODCOMP3 and MODULUS generate reasonable moduli more consistently than WESDEF. However, this conclusion must be tempered by the fact that reasonableness, as defined here in the absence of true moduli, refers to the subjective judgment of the authors.

Deflection Matching Errors

The most objective measure of the performance of a backcalculation program is how well it matches the measured deflection basin. As with the previous analysis, only the results generated by the program developers were used to evaluate the goodness of fit obtained with the programs. Table 2 summarizes the results of the analysis in terms of the absolute sum of errors and the root mean square parameters. On the basis of the work done for this evaluation, it appears that MODULUS does a better job of matching the measured deflection basin. This program, however, did not consider all of the deflections for some basins; for example, deflections

TABLE 2 Summary of Deflection Errors

Section	Load	Absolute Sum of Errors (%)			Root Mean Square (%)		
		MODCOMP	MODULUS	WESDEF	MODCOMP	MODULUS	WESDEF
A	1		3.73[1]	11.80		0.73[1]	2.24
	2		2.80[1]	6.00		0.57[1]	1.22
	3		4.43[1]	5.54		0.82[1]	0.92
	4	4.57	3.02[1]	7.18	1.09	0.61[1]	1.36
B	1		2.81[2]	76.88		0.61[2]	12.15
	2		2.72[2]	59.21		0.60[2]	10.30
	3		2.70[2]	52.87		0.61[2]	9.11
	4	14.71	2.63[2]	49.43	4.35	0.63[2]	8.44
C	1		21.37	37.26		3.95	6.23
	2		17.21	24.92		3.25	4.42
	3		13.76	20.63		2.53	3.23
	4	8.25	13.76	21.01	2.02	2.61	3.52
D	1		12.71	11.32		2.30	1.96
	2		11.30	16.23		1.81	2.44
	3		8.21	9.05		1.36	1.52
	4	10.72	9.44	9.04	3.61	2.01	1.54
E	1		12.35[1]	23.03		3.11[1]	3.84
	2		9.41[1]	13.89		2.08[1]	3.15
	3		13.41[1]	9.30		2.69[1]	1.47
	4	22.31	18.19[1]	11.86	5.80	3.88[1]	1.91
F	1		4.47[1]	30.73		0.81[1]	6.11
	2		8.75[1]	21.56		1.70[1]	3.72
	3		12.52[1]	13.61		3.99[1]	2.48
	4	3.94	2.22[1]	12.90	0.85	0.44[1]	1.97
G	1		13.49	5.89		2.07	1.11
	2		2.73	5.12		0.49	0.94
	3		1.85	8.86		0.33	1.39
	4	5.45	1.73		1.71	0.31	
H	1		10.50	12.36		1.71	2.21
	2		12.46	7.09		2.17	1.22
	3		10.43	7.06		1.77	1.30
	4	30.38	9.85	10.54	10.75	1.71	1.92
Average		12.54	8.66	19.75	3.77	1.70	3.40
Std. Dev.		9.47	5.50	17.77	3.30	1.13	2.96
COV		0.76	0.64	0.90	0.87	0.67	0.87
Min		3.94	1.73	5.12	0.85	0.31	0.92
Max		30.38	21.37	76.88	10.75	3.99	12.15

[1] Excludes deflection at r=60 inches
[2] Excludes deflection at r=36 and 60 inches

at 60 in. from the center of the load plate were excluded from the analysis of Sections A, E, and F, and those at 60 in. were excluded from Section B. Thus, it is postulated that the deflection matching errors would be worse for this program if the excluded deflections were considered.

A theoretical analysis was conducted in an attempt to further assess the accuracy of the moduli predicted by each program. Specifically, the BISAR layered elastic computer code was used to simulate deflection basins for nine pavement structures with varying material types and layer thicknesses. In turn, these basins were analyzed with the programs in question to backcalculated layer moduli for comparison with those assumed in the BISAR runs.

All simulated deflection basins were generated by R. Briggs (Texas Department of Transportation). These data were provided to the authors, along with information on the pavement structures (layer thicknesses and material types), but not the moduli used in the generation of the basins. These assumed moduli were later provided to the authors, after all backcalculation analyses had been completed. Thus, seed moduli or moduli ranges were assigned for each pavement layer on the basis of material type. In the absence of knowledge or algorithms to compute the depth to rigid layer, a semi-infinite subgrade was assumed in this simulated analysis.

Table 3 presents the pavement structure and simulated deflection basins used in the analysis; Table 4 summarizes the backcalculated moduli and the comparison of assumed and predicted values; and Table 5 gives the corresponding deflection matching errors. In general, the analysis results show that all three programs do an excellent job of matching the assumed moduli as well as the corresponding deflection basins. However, MODULUS is given higher marks on the basis that it more closely and consistently matched the simulated moduli and deflections.

In all fairness to MODCOMP3, which uses the CHEVRON code, it should be noted that differences in deflection cal-

TABLE 3 BISAR Simulated Deflection Data

ID	Layer	Material	Thickness (inches)	Surface Deflection (mils)						
				r=0"	r=8"	r=12"	r=18"	r=24"	r=36"	r=60"
1	1	Asphalt Concrete	3	32.90	23.20	17.80	12.60	9.51	6.15	3.57
	2	Granular Base	6							
	3	Subgrade								
2	1	Asphalt Concrete	6	30.10	24.50	21.70	18.50	15.90	12.20	7.73
	2	Granular Base	12							
	3	Subgrade								
3	1	Asphalt Concrete	8	8.97	7.95	7.56	7.07	6.57	5.61	4.00
	2	Cement Stab. Base	6							
	3	Subgrade								
4	1	PCC Slab	9	8.94	8.41	8.05	7.48	6.91	5.80	4.02
	2	Lime Stab. Base	6							
	3	Subgrade								
5	1	PCC Slab	6	18.10	16.60	15.50	13.70	11.90	8.97	5.26
	2	Subgrade								
6	1	PCC Slab	12	8.38	8.06	7.91	7.71	7.50	7.05	6.10
	2	Cement Stab. Base	6							
	3	Subgrade								
7	1	Asphalt Concrete	3	7.50	6.13	5.87	5.43	4.97	4.09	2.72
	2	PCC Slab	9							
	3	Subgrade								
8	1	Asphalt Concrete	5	6.56	5.48	5.27	5.01	4.73	4.14	3.08
	2	PCC Slab	10							
	3	Lime Stab. Base	8							
	4	Subgrade								
9	1	Asphalt Concrete	4	6.89	5.87	5.74	5.59	5.42	5.05	4.28
	2	PCC Slab	12							
	3	Asphalt Stab. Base	8							
	4	Subgrade								

Load = 16,000 lbs Load Radius = 5.91 inches

culations, particularly near the load plate, exist between the CHEVRON and BISAR codes. Thus, some of the poorer fit obtained with MODCOMP3, as compared with MODULUS, could be caused by differences between the two forward calculation routines.

Other Factors and Program Features

It is clear from the preceding discussion, and the analyses that support it, that MODCOMP3, MODULUS, and WESDEF, are useful tools for backcalculation that can produce good results. The programs do, however, have various strengths and weaknesses. On the basis of work done for this evaluation, it can be concluded that MODCOMP3 produces results that match quite well the measured deflection basins, are reasonably independent of the user, and are generally "reasonable." In addition, MODCOMP3 is the most flexible of the programs evaluated because it allows the user to model up to 15 layers (although not more than 5 should be modeled as having unknown moduli that are to be backcalculated), with the deepest layer treated as a layer of known high modulus (i.e., bedrock or a "rigid" layer) or not, as the user desires, and because it is the only program of those evaluated that allows the user to model stress sensitivity of the pavement layers. This ability was not significant in the analyses conducted for this evaluation, because the pavement investigated did not demonstrate significant nonlinear materials behavior, but it could be important in some circumstances.

In the same analyses, MODULUS does a slightly better job of matching the measured deflections basins, is slightly more independent of the user, and also produces results that are generally reasonable. It is postulated that the closer fit of the measured deflection basins is partially due to the use of an algorithm in MODULUS to calculate effective depth to rigid layer and to the exclusion of some of the outer deflections from the calculations for some of the deflection basins. Although it is widely recognized that the presence of a true or effective rigid layer in the pavement cross section can have a significant effect on measured deflections and, hence, back-

TABLE 4 Comparison of Assumed Versus Backcalculation Moduli

Material Type	Layer Thickness (inches)	Assumed Moduli (BISAR) (psi)	Backcalculated Moduli			% Difference		
			Modcomp	Modulus	Wesdef	Modcomp	Modulus	Wesdef
AC	3	500000	553118	481700	480658	-10.62%	3.66%	3.87%
GB	6	50000	49520	51100	60371	0.96%	-2.20%	-20.74%
SG	---	20000	19973	20000	18723	0.14%	0.00%	6.39%
AC	6	300000	288840	311000	254599	3.72%	-3.67%	15.13%
GB	12	60000	65227	59100	75465	-8.71%	1.50%	-25.77%
SG	---	10000	9854	10000	9359	1.46%	0.00%	6.41%
AC	8	1000000	1100365	969700	960804	-10.04%	3.03%	3.92%
CTB	6	2000000	1610059	2130900	2436563	19.50%	-6.54%	-21.83%
SG	---	20000	19826	20100	18433	0.87%	-0.50%	7.84%
PCC	9	4000000	3572500	3118800	3645284	10.69%	22.03%	8.87%
LTB	6	60000	118685	237300	176950	-97.81%	-295.50%	-194.92%
SG	---	20000	19808	19700	18268	0.96%	1.50%	8.66%
PCC	6	3000000	2622308	2970800	3257227	12.59%	0.97%	-8.57%
SG	---	15000	15495	15100	13978	-3.30%	-0.67%	6.81%
PCC	12	4000000	4000000 *	4246400	3757139	0.00%	-6.16%	6.07%
CTB	6	2000000	1794517	1829600	2406254	10.27%	8.52%	-20.31%
SG	---	10000	9907	10000	8594	0.93%	0.00%	14.06%
AC	3	300000	298462	304000	256023	0.51%	-1.33%	14.66%
PCC	9	4000000	3240565	3883500	4899980	18.99%	2.91%	-22.50%
SG	---	30000	31381	30300	26828	-4.60%	-1.00%	10.57%
AC	5	600000	946524	649300	591949	-57.75%	-8.22%	1.34%
PCC	10	4000000	2223404	2764400	3871242	44.41%	30.89%	3.22%
LTB	8	100000	234554	254900	174140	-134.55%	-154.90%	-74.14%
SG	---	25000	24056	24700	22760	3.78%	1.20%	8.96%
AC	4	500000	500000 *	447900	493080	0.00%	10.42%	1.38%
PCC	12	4000000	4000000 *	7096600	3733876	0.00%	-77.42%	6.65%
STB	8	1000000	940431	367300	1300568	5.96%	63.27%	-30.06%
SG	---	15000	14796	15100	12996	1.36%	-0.67%	13.36%
AC	6	300000	261094	303700	288906	12.97%	-1.23%	3.70%
GB	12	60000	73236	59900	61677	-22.06%	0.17%	-2.80%
SG	36	10000	7817	10000	10175	21.83%	0.00%	-1.75%

Note: (1) AC = Asphalt Concrete, GB = Dense Graded Aggregate, PCC = Portland Cement Concrete, SG = Subgrade
CTB = Cement Stabilized Base, LTB = Lime Stabilized Base, ATB = Asphalt Stabilized Base
* Fixed Modulus Value

TABLE 5 Summary of Deflection Errors: Simulated Data

Section	Absolute Sum of Errors (%)			Root Mean Square (%)		
	MODCOMP	MODULUS	WESDEF	MODCOMP	MODULUS	WESDEF
1	11.62	0.85[1]	14.20	2.36	0.16[1]	2.32
2	1.74	0.82	7.20	0.34	0.17	1.12
3	4.03	1.27	1.60	0.81	0.22	0.26
4	4.13	3.06	1.40	0.81	0.52	0.23
5	18.71	1.29	4.70	3.68	0.20	0.91
6	25.97	0.63	1.40	6.80	0.12	0.21
7	14.19	0.75	8.60	3.24	0.15	1.47
8	1.59	2.06	4.00	0.37	0.37	0.58
9	21.72	1.11	3.90	5.42	0.19	0.57
Average	11.52	1.32	5.22	2.65	0.23	0.85
Std. Dev.	9.20	0.78	4.21	2.34	0.13	0.70
COV	0.80	0.59	0.81	0.88	0.56	0.82
Min	1.59	0.63	1.40	0.34	0.12	0.21
Max	25.97	3.06	14.20	6.80	0.52	2.32

[1] Excludes deflection at r=60 inches

calculated moduli, the book on how to address this effect in the analysis of pavement deflection data clearly has not been completed. Also, it is logical to conclude that the lower degree of user dependence of MODULUS, as compared with MODCOMP3, comes about as a result of fewer options with respect to modeling of the pavement structure.

The performance of WESDEF was similar to that of MODCOMP3 (i.e., not quite as good as MODULUS) with respect to the ability to match measured deflection basins. However, the results are somewhat less independent of the user, and are subjectively judged to be slightly less reasonable for the sections evaluated. Again, it may be postulated that these results are at least partially attributed to the manner in which the presence or absence of a rigid layer in the subgrade is handled.

On the basis of evaluations that have been performed, the demonstrated performance of MODULUS is somewhat superior to that of the other programs, although one or both of the other programs may be better for an individual section. Thus, MODULUS has been selected as the primary backcalculation program to be used in the initial analysis of the SHRP deflection data.

Procedure Development and Application

The procedure development stage of this study is currently in progress. SHRP's goal in this stage of the process is to glean from the results of the software evaluation exercise as much information as possible about what input criteria to apply to make the backcalculation process straightforward, productive, successful, and consistent. However, the limited size of the data set used in the evaluation, and the evolving nature of the science (or art) of backcalculation, make it likely that early experience with this procedure will bring to light areas in which further refinement is needed. Hence, it is anticipated that the initial release of the SHRP backcalculation procedure will be followed up, as we learn more about the strengths, weaknesses, and requirements of the process.

SHRP has a distinct advantage over most agencies that have done backcalculation in the past, because the SHRP data base contains a wealth of information that can and will be used to generate the input data for the backcalculation process. The SHRP backcalculation procedure will make use of data base queries to extract the information needed as input for the backcalculation procedure from the SHRP data base. For example, SHRP can draw on the laboratory materials data in the data base to determine ranges of moduli for each of the pavement layers. In instances in which the surface layer is thin, a conditional query can be established to set the surface modulus as a known value, on the basis of the temperature at the time of testing and other known properties of the asphalt concrete.

Initially, the SHRP backcalculation procedure will be applied to the data from one test point on each of the SHRP test sections—the "test pit location"—a point for which SHRP has deflection data and accurate layer thickness information, as well as field and laboratory materials data. Eventually, the procedure will be applied to all of the SHRP deflection data.

SUMMARY AND CONCLUSIONS

The objective of the study discussed in this paper was to evaluate existing software for the purpose of developing an SHRP flexible pavement backcalculation procedure for the initial analysis of the LTPP deflection data. Using ETG recommended criteria, four programs were selected for detailed evaluation: ISSEM4, MODCOMP3, MODULUS, and WESDEF. These programs, along with SHRP deflection data and other pertinent information, were provided to each member of a group of evaluators that also included the program developers.

On the basis of initial review of the backcalculation results and evaluator's comments, ISSEM4 was eliminated from further study. The three remaining programs—MODCOMP3, MODULUS, and WESDEF—were analyzed for user repeatability, reasonableness of results, deflection matching errors, ability to match assumed moduli from simulated deflection basins, and versatility. It was concluded from these analyses that the performance of MODULUS was superior to that of the other programs; hence, MODULUS has been selected as the primary program to be used by SHRP in the initial data analysis.

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REFERENCES

1. *Description of and User's Guide for the Dynatest ISSEM4 Computer Program*. Dynatest Consulting, Inc., Ojai, Calif., April 1988.
2. L. Irwin and T. Szebenyi. *User's Guide to MODCOMP3, Version 3.2*. CLRP Report 91-4. Cornell University Local Roads Program, Ithaca, N.Y., March 1991.
3. *MODULUS: Preliminary User's Manual—Version 4.0*. Texas Transportation Institute, Texas A&M University, College Station, 1990.
4. D. R. Alexander, S. D. Kohn, and W. P. Grogan. Nondestructive Testing Techniques and Evaluation Procedures for Airfield Pavements. In *Nondestructive Testing of Pavements and Backcalculation Moduli*. (A. J. Bush III and G. Y. Baladi, eds.), ASTM STP 1026, ASTM, Philadelphia, Pa., 1989, pp. 502–524.
5. 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, pp. 171–188.