Accuracy and Consistency of Backcalculated Pavement Layer Moduli

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Backcalculation of pavement layer moduli from deflection measurements has been a focus of recent pavement research because of the need to adopt mechanistic design and analysis methods and the widespread use of nondestructive testing devices such as the falling weight deflectometer and Dynaflect. A number of pavement structural models and computerized procedures have been developed to perform backcalculation. However, the results often vary among analysts because of the assumptions made in each procedure and the different input assigned by individual analysts. Such variation causes concern because engineers will not have confidence using the backcalculated moduli in pavement evaluation or design if the size of the error associated with the backcalculated moduli values is unknown. To better understand the accuracy and consistency of the available backcalculation procedures, backcalculation results from different agencies using various procedures were compared. The results indicate that discrepancies among agencies can be large; however, a few agencies reached good agreement in many cases. The sources of systematic errors and ways to reduce them are discussed. Finally, an expert system approach that uses a specific analyst's knowledge to prepare input for the mechanistic backcalculation program and to interpret results is described.

Backcalculation of pavement layer moduli from nondestructively measured deflection basins has become the state-of-the-art method in pavement structural evaluation (*1*). A number of backcalculation computer procedures are available, for example, MODCOMP2 (*2*), BISDEF (*3*), CHEVDEF (*4*), ELSDEF (*4*), MODULUS (*5*), and ELMOD (*6*). Most of these programs model the pavement structure with a layered elastic system and use an iteration scheme to find the set of layer elastic moduli that best matches the computed theoretical deflections with the measured pavement deflections. The iteration process may require a large amount of computer time. Many programs use the influence zone concept to reduce the iterations.

Only two material parameters (Young's modulus and Poisson's ratio) are needed to describe the possible deformation in linear elastic theory, which is one of the major reasons why layer elastic theory is used by many backcalculation programs (*7*). In backcalculation, the less important parameter, Poisson's ratio, is usually assumed, and only the Young's modulus of each layer must be calculated to match the surface deflections. Because each layer is represented by only one unknown, the number of surface deflection readings needed in backcalculation is equal to the number of layers with unknown moduli. This reduces the number of variables to be solved for and allows a direct search technique to be used in converging to the effective layer moduli values.

Other methods of modeling pavement structures include the finite element method and the elastic-dynamic method. The finite element method is considered more accurate in its ability to model stress-sensitive materials. However, the increase in accuracy is usually accompanied by a greater number of unknown parameters, which makes backcalculation more difficult. In addition, the finite element method usually demands much greater computing power, and still it is not entirely successful in dealing with granular materials. The elastic-dynamic method may provide a better representation of the dynamic loading, but it is also more complicated in its analysis and, hence, in backcalculation. This study focuses on backcalculation by static, linear elastic analysis.

The basic assumption of backcalculation is that when the computed surface deflections match the measured deflections, the resulting layer moduli values represent the material moduli in the field. In other words, a unique set of layer moduli exists such that the theoretically computed deflection basin is equivalent to the measured basin. In nondestructive testing (NDT) backcalculation, only a few discrete surface deflection readings represent the deflection basin. The number of readings sampled must be at least equal to the number of layer moduli to be backcalculated to avoid a nonunique solution. Because of the rounding and truncation errors introduced during backcalculation, it may not even be possible to reproduce exactly the original layer moduli from a basin generated by the linear elastic solution.

In reality, inaccurate layer thicknesses and subgrade depth input and, more important, the deviation of material behavior from linear elastic modeling, prevent the use of a small tolerance for surface matching error, because no theoretical solution may exist with the given model that matches the measured basin perfectly. The increased tolerance introduces other nonuniqueness of the backcalculated moduli values.

Thus, dividing a pavement structure model into many layers may produce nonunique solutions, whereas assuming fewer layers may not produce solutions that match the measured deflection readings. This dilemma leads to the following understanding: the objective of backcalculation is not to match surface deflections perfectly, but to obtain a reasonably good assessment of the underlying structure. Such an assessment can usually be achieved if other pertinent information (e.g., layer thickness, subgrade depth and component, layer material type, pavement construction history, and existing distresses, if any) is used. Without a thorough knowledge of the pavement structure, achieving a good match of the surface deflection may not be meaningful in pavement evaluation.

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The error of backcalculation methods here means the accuracy in estimating the in situ layer moduli, not the error in matching the surface deflections.

Because backcalculation relies solely on measured pavement surface deflection under a given load, it is difficult to backcalculate moduli of thin layers and material properties other than moduli. Simultaneous measurement of impulse loads and dynamic deflections generated by the falling weight deflectometer (FWD) may provide more information, but this technique is still under development (*1*).

With the available layer elastic solution, several things can still be done to improve the backcalculation process. They include reduction of the errors caused by convergence schemes and better estimation of the given input parameters, such as Poisson's ratio, effective layer thickness, and depth to bedrock. The latter is a significant contributor to the size of errors and is more difficult to assess because it varies with each problem. Experience, engineering judgment, and accurate data must be relied on for every backcalculation problem.

MODULUS—A NONITERATIVE BACKCALCULATION PROCEDURE

The computer time required to perform backcalculation for a single deflection basin depends on the complexity of the problem, the efficiency of the convergence scheme, and the type of computer. For most iterative-type backcalculation programs, the initial moduli values (or "seed" moduli) given by the analyst also affect convergence speed. In general, on an IBM-PC type of computer, 30 min to 1 hr or more is needed to perform a single backcalculation. This does not include time for preparing input data, interpreting the result, or possibly rerunning the backcalculation with modified input data. Most highway agencies have limited computer resources, so the discussion is based on microcomputers—the most widely owned computers in highway communities.

In both network- and project-level testing, hundreds of deflection basins usually must be analyzed. The computing time can be prohibitive. Sometimes a few selected "typical" deflection basins are backcalculated instead of backcalculating every basin. However, the typical basin is difficult to determine, and much information about the variability of pavement materials is lost by doing so. Backcalculation of layer moduli from every deflection basin measured is desirable. To achieve this despite limited time and manpower, two approaches have been used. One is to replace the layer elastic solution by a simpler and faster scheme (e.g., Odemark's solution, as in the ELMOD program). The result is an approximation to the layer elastic solution.

The other approach is to store many generated deflection basins and corresponding layer moduli in a data base. When a measured basin is given, the data base can be searched and interpolated to find a deflection basin that best resembles the measured basin. The corresponding layer moduli are then determined. This method eliminates the iteration process and greatly speeds backcalculation. The overhead time needed to generate the deflection data base is often offset by the saving of time in analyzing individual basins when dozens of basins must be analyzed.

One of the data base backcalculation programs is called MODULUS (*5*). MODULUS uses a unique method to reduce the size of the data base so that the time to generate it and the time to find the solution from it are greatly reduced.

The generated deflection data base is based on the ratio of layer moduli to subgrade moduli; thus the size of the data base is reduced by an order. The pattern search algorithm developed by Hooke and Jeeves (*8*) and the Lagrange interpolation technique (*9*) are used to find the layer moduli that minimize the error between measured and computed basins. Figure 1 shows a typical error surface that the MODULUS program searches to find the least error. The solution found may only be a local minimum, and a global minimum may not exist in the given ranges if the problem is not modeled correctly.

MODULUS can backcalculate up to four unknown layer moduli (including subgrade modulus). Backcalculating more than four unknown moduli is not recommended because of possible nonuniqueness. Furthermore, none of the available design methods uses more than four layer moduli. The calculated surface deflections and matching errors reported by the MODULUS program are obtained by interpolation of the pregenerated data base; thus, the values are not exact. Nevertheless, the backcalculated moduli compare well with the results of BISDEF, an iterative program that takes much longer to run, and MODULUS can essentially reproduce input moduli when a forward-calculated deflection basin is given. When comparing a backcalculated modulus with laboratory test results, the actual field condition plays an important role. A case study is described later. MODULUS is used as the target program in the following comparative study.

COMPARATIVE STUDY OF BACKCALCULATIONS

Different backcalculation programs often give different results for the following reasons:

1. The numerical routine used to calculate pavement surface deflections may be different.

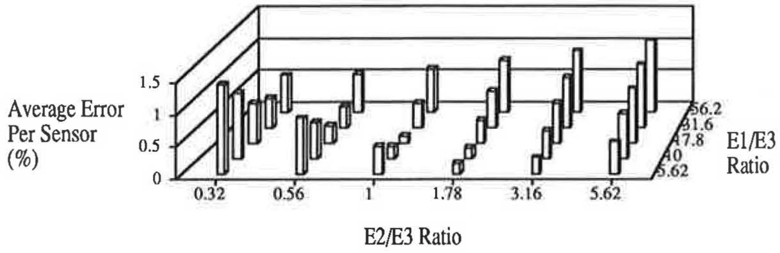

FIGURE 1 Typical error surface (bars show interpolation points).

2. The method of searching for new values of the layer moduli may be different.
3. Some methods try to correct for the stress dependency of the layer moduli; others do not.
4. Criteria for determining convergence (e.g., minimize surface deflection matching error) may be different.
5. Moduli ranges set by individual analysts may be different.

It was believed that a comparison of solutions from different programs would give an idea of the range of solutions that can be expected. Furthermore, it would be interesting to see how the experience and knowledge of the individual analyst contribute to the range of solutions for identical problems. Such an exercise was conducted as an activity of TRB's Committee on Strength and Deformation Characteristics of Pavements.

A total of 26 deflection basins were included in the study. Three types of NDT device (FWD, Dynaflect, and Road Rater 2000) were compared on two pavement sections. Deflections from three FWD load levels were also obtained from the same two sections for comparison. The deflection data are shown in Tables 1 and 2.

Four FWD basins were measured on different in-service pavement sections, and seven were measured on sections at the Texas Transportation Institute (TTI) Pavement Test Facility. In addition, four deflection basins were generated by using the layer elastic program BISAR, and four were generated by using the nonlinear finite element program ILLI-PAVE.

The NDT pavement deflection data, with their thickness and material information, were submitted to participating pavement research agencies in the United States and Britain. They were asked to report their backcalculation results. Thirteen results, with varying degrees of completeness, were obtained. The results were denoted anonymously as those of Agency A, B, . . . , M. Ten were based on the theory of elasticity. The other three, which found their solutions on the basis of a layer equivalency concept, used ELMOD. The backcalculation procedures used included MODULUS, BISDEF, PADAL, ELMOD, ELSDEF, MODCOMP2, CHEVDEF, and a BISAR-based procedure developed at Purdue University. BISDEF and ELMOD were each employed by three agencies, and MODCOMP2 was employed by two agencies.

The backcalculation results indicate a wide dissimilarity among agencies. Figure 2 shows the relative closeness of the modulus values backcalculated by other agencies to those of Agency A. The closer the plotted data are to the diagonal line, the more closely the results from the two agencies agree. For example, Agency A's results agree well with those of Agencies B and C but differ widely from those of Agencies G, H, and I. Agencies A, B, C, F, and I employed BISAR-based procedures, whereas Agencies E, J, and L used ELMOD. Agencies using the same procedure can produce very different results. Figure 2 is intended only to show the size of the dissimilarities among agencies. It should not be used to judge the success of backcalculation, because the selection of Agency A's result as a standard was arbitrary.

Device Comparison

The results of backcalculation comparing three NDT devices are shown in Table 3. Only three agencies completed this part of the exercise. The following observations may be made:

1. The backcalculated moduli were generally in the "reasonable" range for the given layer materials, although the values are quite different among NDT devices.
2. Because modes of loading are different among NDT devices, the relationship of backcalculated layer modulus values among various NDT devices depends on the individual pavement's structure and layer materials.
3. The three agencies produced similar results for each device. The differences may be attributed to the different modulus range set by individual analysts, because most of the backcalculated asphalt concrete layer moduli reached the upper limits.
4. The averaged deflection matching errors were larger for Test Section 10.1, which has a thin (1-in.) surface layer, than for Test Section 19.4, which has a thicker (5-in.) surface layer. This is true for all three agencies, which indicates that the

TABLE 1 DEFLECTION DATA COMPARING THREE NDT DEVICES

SECTION ID	FWD								ROADRATER						DYNAFLECT LOAD = 1000lbs Hz = 8			
	LOAD (lb)	DEFLECTIONS (mils) Radii (inches)							FREQ	LOAD (lb)	DEFLECTION (mils) Radii (inches)				DEFLECTION (mils) Radii (inches)			
		0"	7.87"	11.8"	23.6"	35.4"	49.2"	63"			0"	12"	24"	36"	0"	12"	24"	36"
19*- 1	9224	14.32	9.95	7.10	4.15	2.96	2.22	1.79	10.3	2040	3.14	1.73	0.99	0.75	0.81	0.55	0.39	0.29
19*- 4	9504	5.5	5.20	4.95	4.23	3.52	2.76	2.16	10.2	2010	1.65	1.27	1.11	0.96	0.56	0.52	0.45	0.38

*Refer to TTI PAVEMENT TEST FACILITY Tables for layer thicknesses and materials

1 mil = 0.001 inches

TABLE 2 DEFLECTION DATA COMPARING THREE FWD LOAD LEVELS (SURFACE TEMPERATURE = 100°F)

Section 10*- 1

	Deflections (mils)						
SPACING (inches) LOAD (lb)	0	7.87	11.8	23.6	35.4	49.2	63.0
6312	10.04	6.71	4.62	2.63	1.96	1.48	1.10
9224	14.32	9.95	7.10	4.15	2.96	2.22	1.79
14928	21.97	15.56	11.76	6.91	4.92	3.65	2.89

Section 19*- 4

	Deflections (mils)						
SPACING (inches) LOAD (lb)	0	7.87	11.8	23.6	35.4	49.2	63.0
6440	3.50	3.32	3.09	2.71	2.32	1.75	1.34
9504	5.55	5.20	4.95	4.23	3.52	2.76	2.16
14848	9.67	9.09	8.54	7.47	6.17	4.78	3.82

*Refer to TTI PAVEMENT TEST FACILITY Tables for layer thicknesses and materials

1 mil = 0.001 inches

layer elastic backcalculation procedures have difficulty dealing with thin surface pavement structures.

5. Results from Agencies A and B indicate that both base and subgrade moduli backcalculated from FWD sections are larger than from Dynaflect. This may be attributed to the stress-stiffening effect caused by the higher load of FWD, but it was not apparent in Agency C's result. The compensation of base and subgrade moduli during backcalculation may prevent identification of such a trend.

Load Comparison

Results of backcalculations comparing three FWD load levels are shown in Table 4. The relationship of backcalculated layer modulus values under different load levels depends on the individual pavement structure and layer materials. For example, the calculated granular base modulus values of Test Section 10.1 are higher at higher load levels (stress stiffening), whereas the sandy clay subgrade of Test Section 19.4 has decreasing modulus with increasing load (stress softening). Backcalculated lime-stabilized base modulus values of Test Section 19.4 are lower at higher load levels. The sandy gravel (coarse-grained) subgrade of Test Section 10.1 shows a stress-stiffening effect. Different results may be reached for other pavement structures, depending on the state of stresses (i.e., mean principal stress and deviator stresses) to which the materials are subjected.

The different load level does not change the averaged deflection matching error significantly. Again, it is more difficult to match measured deflection basins for thin pavement (Test Section 10.1) than for thicker pavement (Test Section 19.4).

Backcalculation of Generated Basin

Comparisons of backcalculated moduli from generated basins with moduli used in forward calculations are shown in Figures 3 to 8. Two forward-calculation methods, BISAR (a linear elastic program) and ILLI-PAVE (a nonlinear elastic finite element program), were employed to generate the deflection basins. Figures 3 to 5 show the moduli used in BISAR (the heavy vertical line) compared with the range of values backcalculated by each agency. For ILLI-PAVE, the modulus values at the middle of each layer and under the center of the load, obtained by substituting the computed stresses at that location into the modulus-stress relationship, are used as the basis (Figures 6 to 8).

Ideally, backcalculation should reproduce the layer moduli used to generate the theoretical basin. However, it can be

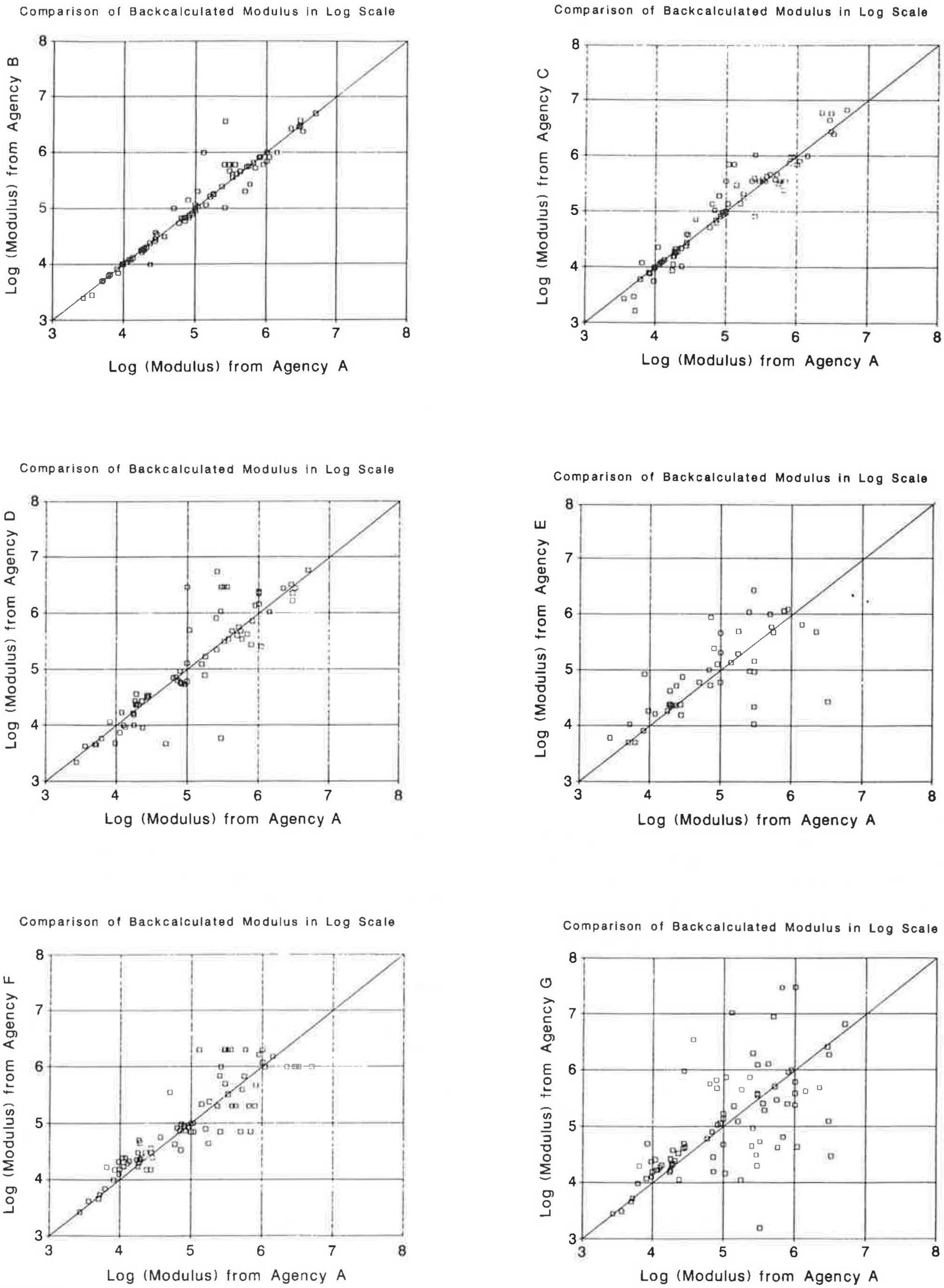

FIGURE 2 **Closeness of modulus values backcalculated by other agencies to those of Agency A.** ***(continued on next page)***

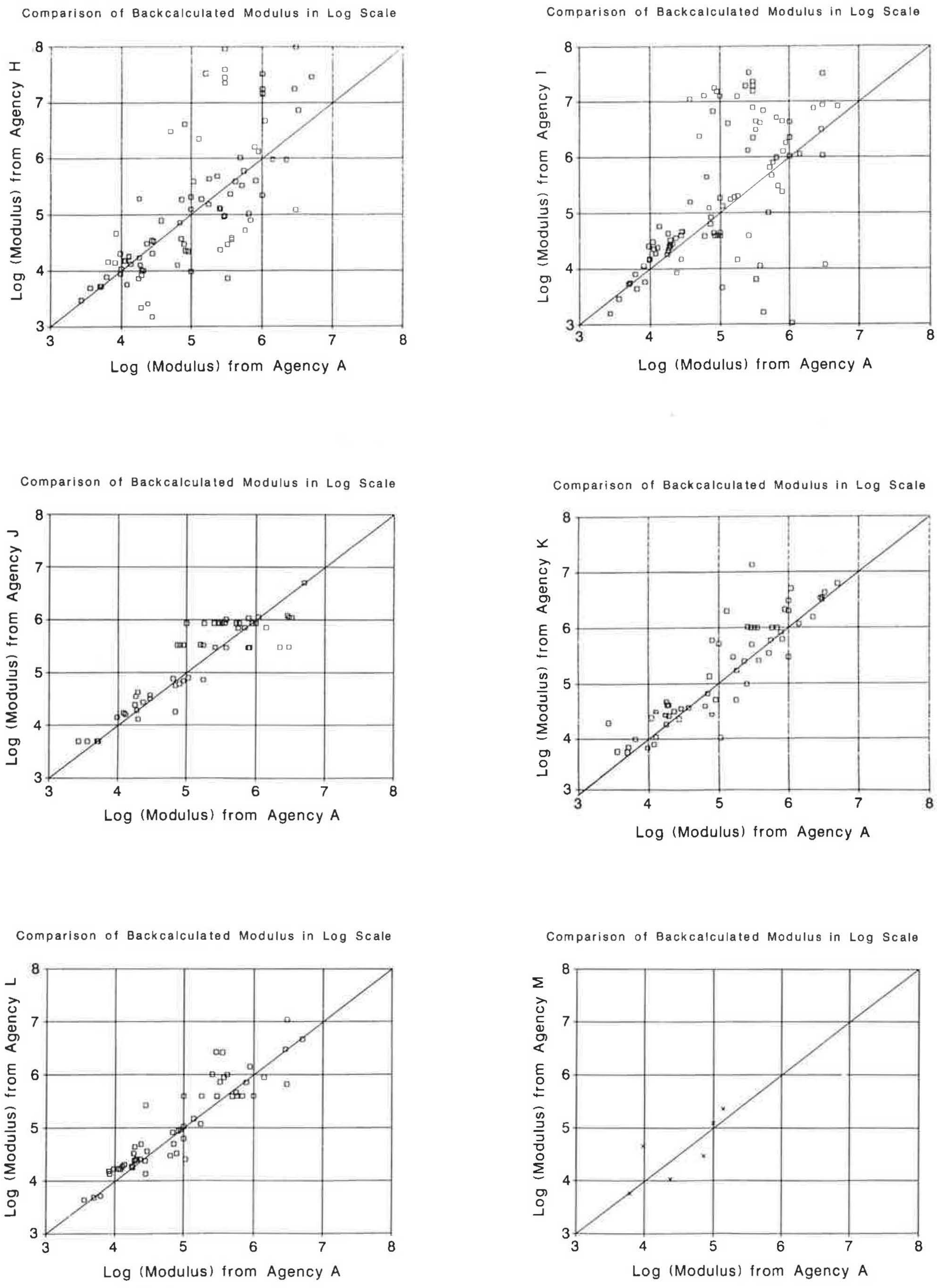

FIGURE 2 *(continued)*

TABLE 3 NDT DEVICE COMPARISON

Section 10.1		A (MODULUS)	B (BISDEF)	C (BISDEF)
FWD				
1" AC	E1	300,000	600,000	350,000
16" Cr Limestone	E2	90,000	80,509	93,790
Sandy Gravel	E3	19,600	18,706	17,661
		(7.8%)*	(6.7%)	(6.3%)
Road Rater				
1" AC	E1	300,000	600,000	350,000
16" Cr Limestone	E2	58,800	54,575	51,330
Sandy Gravel	E3	18,800	18,624	18,986
		(4.2%)	(3.7%)	(5.1%)
Dynaflect				
1" AC	E1	300,000	600,000	350,000
16" Cr Limestone	E2	37,000	31,442	70,832
Sandy Gravel	E3	11,000	10,879	22,469
		(4.7%)	(3.9%)	(4.9%)
Section 19.4				
FWD				
5" AC	E1	1,000,000	1,000,000	700,000
16" LimeStabilized	E2	375,100	409,642	429,101
Sandy Clay	E3	12,800	12,448	12,513
		(3.8%)	(4.7%)	(3.5%)
Road Rater				
5" AC	E1	108,600	107,017	700,000
16" LimeStabilized	E2	650,000	655,088	242,896
Sandy Clay	E3	9,900	9,906	9,918
		(0.1%)	(0.4%)	(3.7%)
Dynaflect				
5" AC	E1	130,000	1,000,000	700,000
16" LimeStabilized	E2	232,200	241,983	351,421
Sandy Clay	E3	6,500	6,548	11,884
		(0.2%)	(0.2%)	(1.1%)

* Numbers in parenthesis are the average deflection matching errors reported by each agency

TABLE 4 FWD LOAD LEVEL COMPARISON

Section 10.1		A (MODULUS)	B (BISDEF)	C (BISDEF)	D* (PADAL)
6312lb					
16" Cr.L.S.	E2	83,500	75,000	80,751	54,969
Sandy Grav	E3	20,700	20,060	19,220	23,061
		(8.0%)	(7.1%)	(8.7%)	
9224LB					
1" AC	E1	300,000	600,000	350,000	2,900,755
16" Cr.L.S.	E2	90,000	80,509	85,584	53,954
Sandy Grav	E3	19,600	18,706	17,998	24,076
		(7.8%)	(6.7%)	(8.0%)	
14928LB					
1" AC	E1	300,000	600,000	350,000	2,900,755
16" Cr.L.S.	E2	99,800	89,422	93,790	59,756
Sandy Grav	E3	19,100	18,137	17,661	23,061
		(7.0%)	(6.1%)	(6.3%)	
Section 19.4		A	B	C	D
6440lb					
5" AC	E1	1,000,000	1,000,000	700,000	2,215,451
16" LimeSta	E2	419,500	456,009	469,705	477,319
Sandy Clay	E3	13,600	13,244	13,402	9,137
		(4.9%)	(5.4%)	(4.5%)	
9540lb					
5" AC	E1	1,000,000	1,000,000	700,000	2,295,077
16" LimeSta	E2	375,100	413,159	429,101	340,259
Sandy Clay	E3	12,800	12,390	12,513	9,863
		(3.8%)	(4.3%)	(3.5%)	
14848lb					
5" AC	E1	1,000,000	1,000,000	700,000	2,402,695
16" LimeSta	E2	330,900	358,206	374,154	308,205
Sandy Clay	E3	11,300	10,999	11,047	7,397
		(3.9%)	(4.3%)	(3.5%)	

* Did not report deflection matching errors

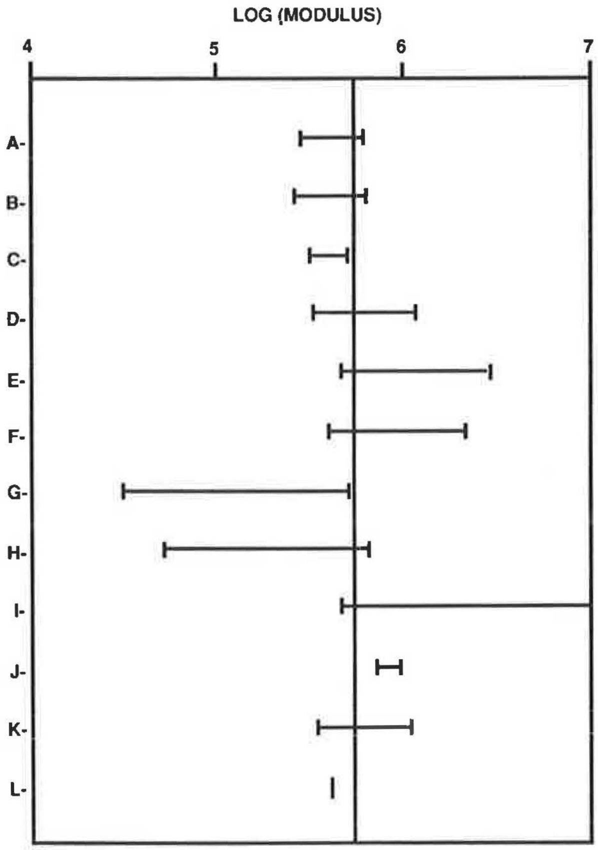

FIGURE 3 Comparison of backcalculated asphalt concrete modulus with modulus used in forward calculation.

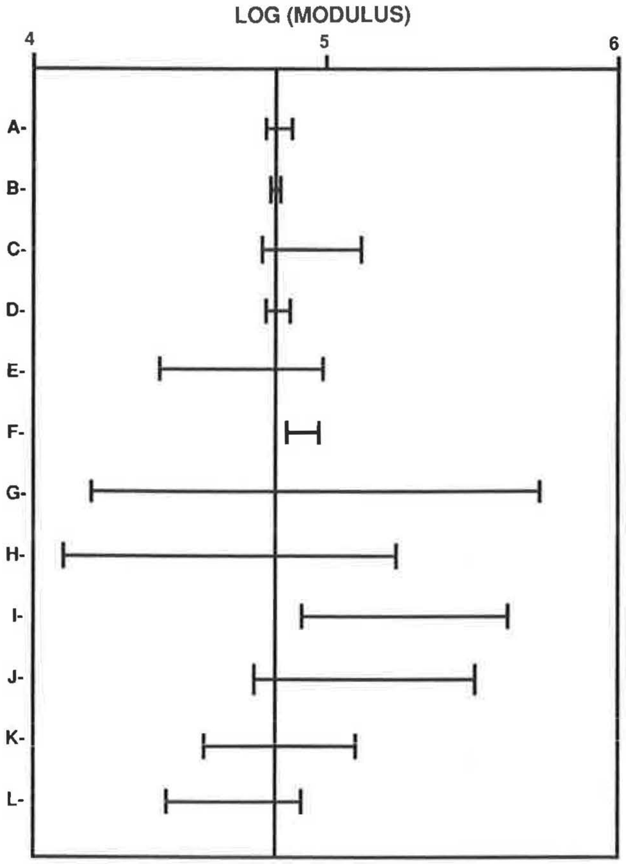

FIGURE 4 Comparison of backcalculated crushed limestone modulus with modulus used in forward calculation.

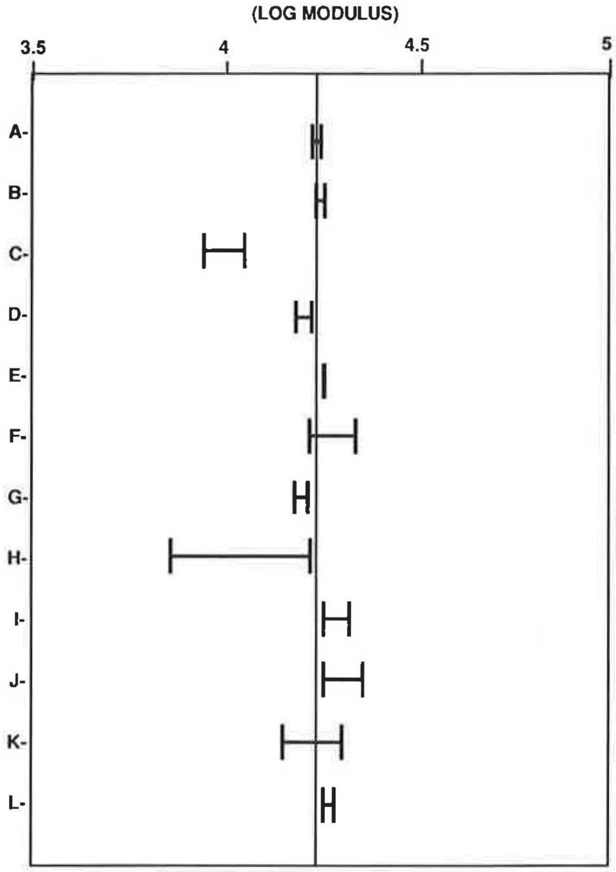

FIGURE 5 Comparison of backcalculated sandy gravel modulus with modulus used in forward calculation.

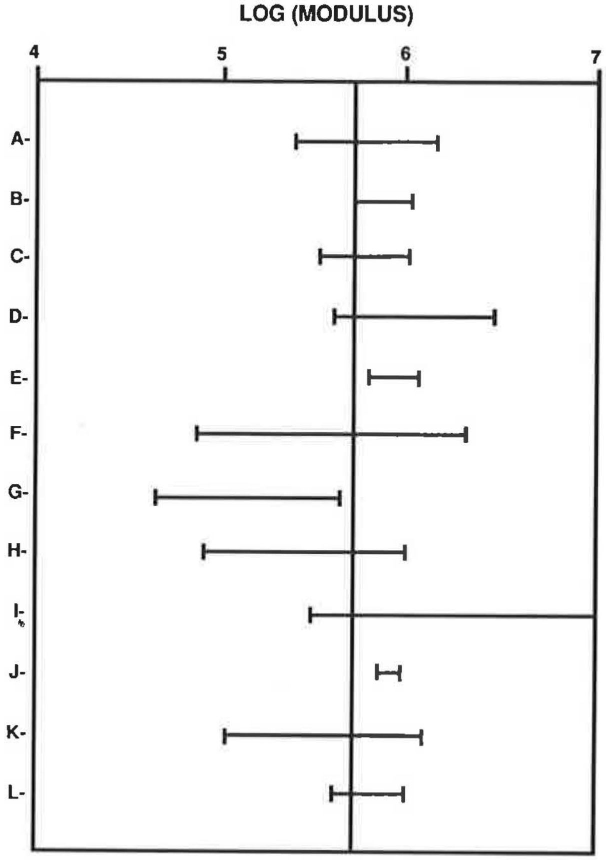

FIGURE 6 Comparison of backcalculated asphalt concrete modulus with averaged modulus in ILLI-PAVE forward calculation.

seen from these figures that the ranges of moduli backcalculated from theoretically generated deflection basins can be large due to different analysis methods and input parameters. Several agencies backcalculate accurately from the BISAR-generated basin, particularly the subgrade moduli. Much poorer results are obtained, as expected, when backcalculating from the nonlinear ILLI-PAVE–generated basins.

Backcalculation of Measured Basin

Comparison of backcalculated layer moduli at the TTI Research Annex included the following seven materials: asphalt concrete, cement-stabilized crushed limestone, lime-stabilized crushed limestone, crushed limestone, plastic clay subgrade, sandy clay subgrade, and sandy gravel subgrade. The results of backcalculation from measured surface deflection basins are shown in Figures 9 to 12. No datum value is given in the figures for these in situ materials because the correct value is unknown. Because each material is present in more than one pavement section, a range of backcalculated modulus values for the same material is given. Considering the scale factor of these figures, it is clear that much smaller (i.e., more consistent) ranges are obtained compared with the asphalt concrete moduli. Agreement of the backcalculated moduli for base layer materials (cement-stabilized, lime-stabilized, and crushed limestone) is better than for asphalt concrete but worse than for subgrade materials. A numerical representation of this observation is shown in Table 5, in which Agency A is chosen as the basis for calculating the average absolute relative difference (AARD) because of its consistent accuracy with the calculated basin. The AARD of backcalculated moduli for a specific material is defined as follows:

$$\text{AARD} = \frac{\sum_{i=1}^{n} |E_k^i - E_a^i|}{n}$$

where

E_k^i = the modulus of the specific material backcalculated by Agency k at Section i,
E_a^i = the modulus of the specific material backcalculated by Agency a at the same Section i, and
n = the number of pavement sections that have the specific material in their structures.

Statistical tests of significance by analysis of variance indicate that significant differences exist between several agencies. There are significant differences between materials within each agency. When results of the three agencies (G, H, and I) that compared poorly with those of other agencies are neglected, there are also significant differences between BISAR- and non-BISAR-based methods in average values of AARD.

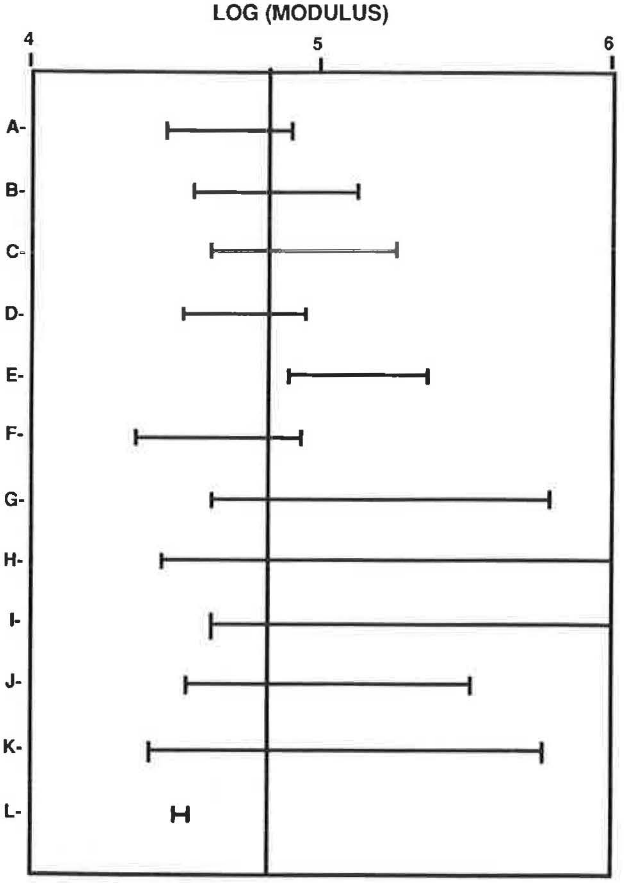

FIGURE 7 Comparison of backcalculated crushed limestone modulus with averaged modulus in ILLI-PAVE forward calculation.

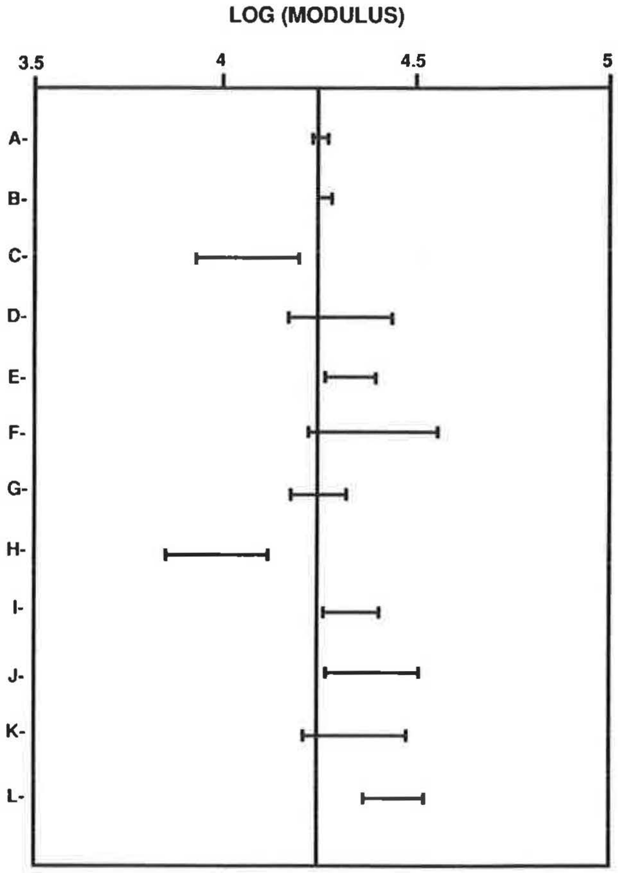

FIGURE 8 Comparison of backcalculated sandy gravel modulus with averaged modulus in ILLI-PAVE forward calculation.

Even agencies using the same backcalculation program produce considerably different backcalculated moduli values. This can be attributed to the various degrees of experience of and differing assumptions used by the individual analysts. Such inconsistency shows why the analysis of NDT data is difficult for practicing pavement engineers. Unlike researchers, practicing engineers usually do not have the time or resources to experiment with the many possible assumptions that may change backcalculation results.

It is difficult to assess the errors in each analyst's results. The comparisons show the relative affinities among solutions from different agencies. No solution can be considered correct, because each is associated with an error of unknown size. However, it is clear that several agencies produced solutions that were more reasonable than others, and the same agencies performed better in backcalculating theoretically generated deflection basins. Hence, it is reasonable to infer that these agencies have better knowledge in backcalculation of moduli values than the others.

The backcalculated moduli should not be expected to match the laboratory test results, because in situ field conditions are difficult to reproduce in the laboratory. Many of today's pavement design procedures (especially the AASHTO Guide) depend on laboratory estimates of moduli. Direct use of backcalculated moduli in these procedures can result in a systematic error that is not conservative because backcalculated moduli, especially for soils, are generally higher than laboratory-based resilient moduli. Furthermore, pavement materials often have large variations in their properties. Backcalculated layer moduli from NDT devices are averaged estimates instead of absolute measurements. If cautiously performed, however, laboratory results do provide a basis for assessing the reasonableness of backcalculated moduli.

NEED FOR EXPERT SYSTEMS IN BACKANALYSIS

Backcalculation programs appear to work well in many cases but do not produce good results in others. The reasons for this may be summarized into the following two categories.

First, pavement materials have a wide range of possible properties that do not always comply well with the linear elastic, homogeneous, and isotropic assumptions used inelasticity theory. The loading conditions of some NDT devices may be modeled incorrectly. The accuracy of deflection measurements may be affected by the accuracy of sensors and how they rest on the rough pavement surface. These are problems associated with the mechanistic modeling.

Second, to backcalculate layer moduli from surface deflections, the thickness of each layer, the Poisson's ratio of layer materials, and the depth of the subgrade must be known, or at least susceptible to close estimation. The moduli of thin

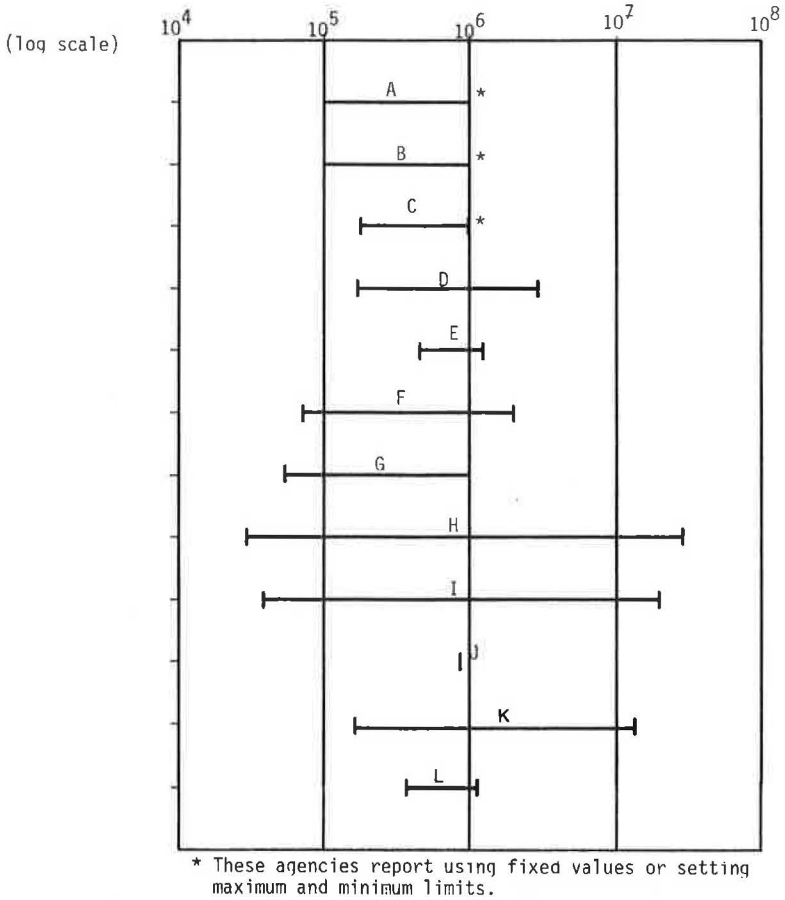

FIGURE 9 Comparison of backcalculated asphalt concrete modulus (deflection measured at TTI Pavement Test Facility).

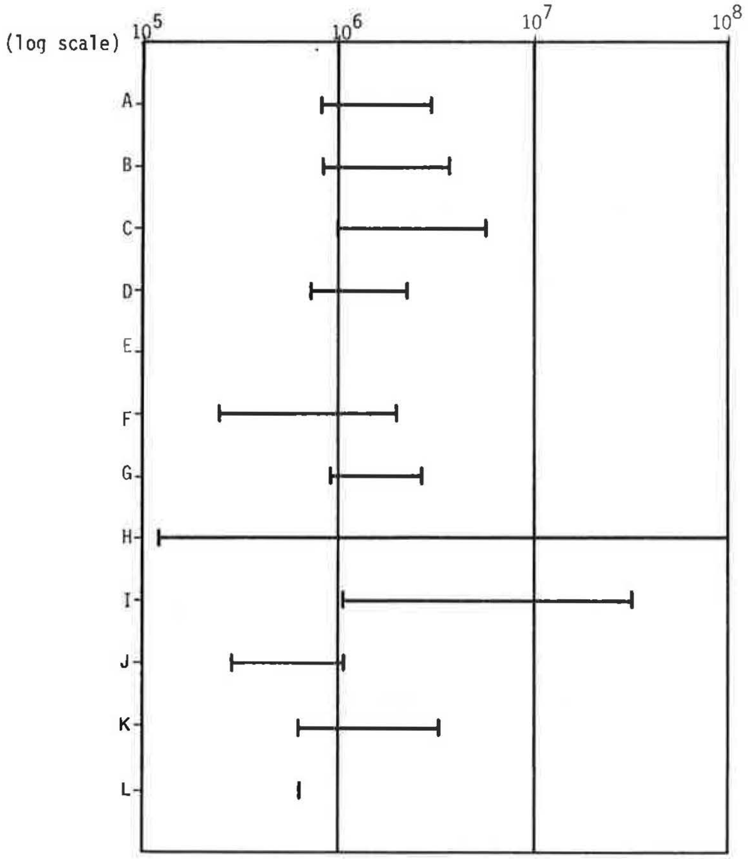

FIGURE 10 Comparison of backcalculated 4 percent cement-stabilized crushed limestone modulus (deflection measured at TTI Pavement Test Facility).

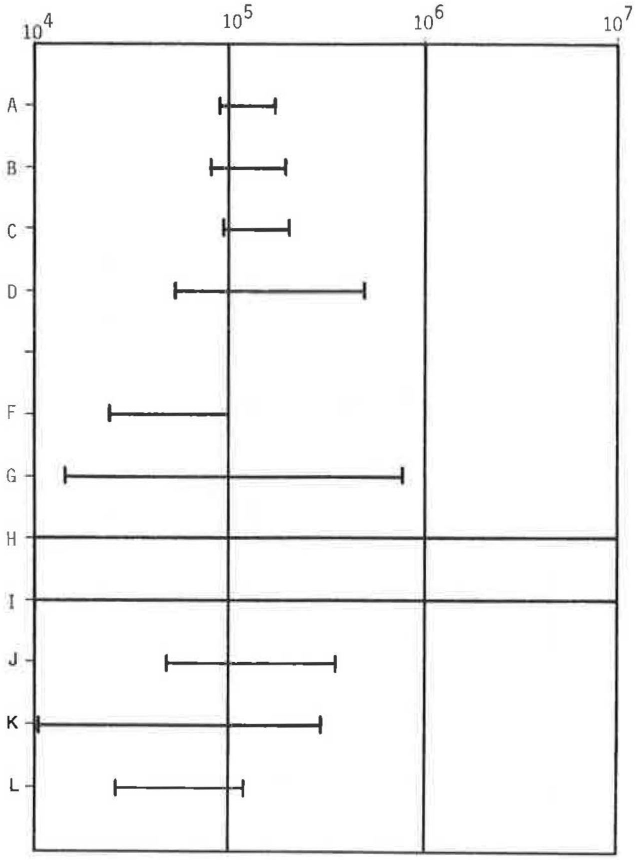

FIGURE 11 Comparison of backcalculated crushed limestone modulus (deflection measured at TTI Pavement Test Facility).

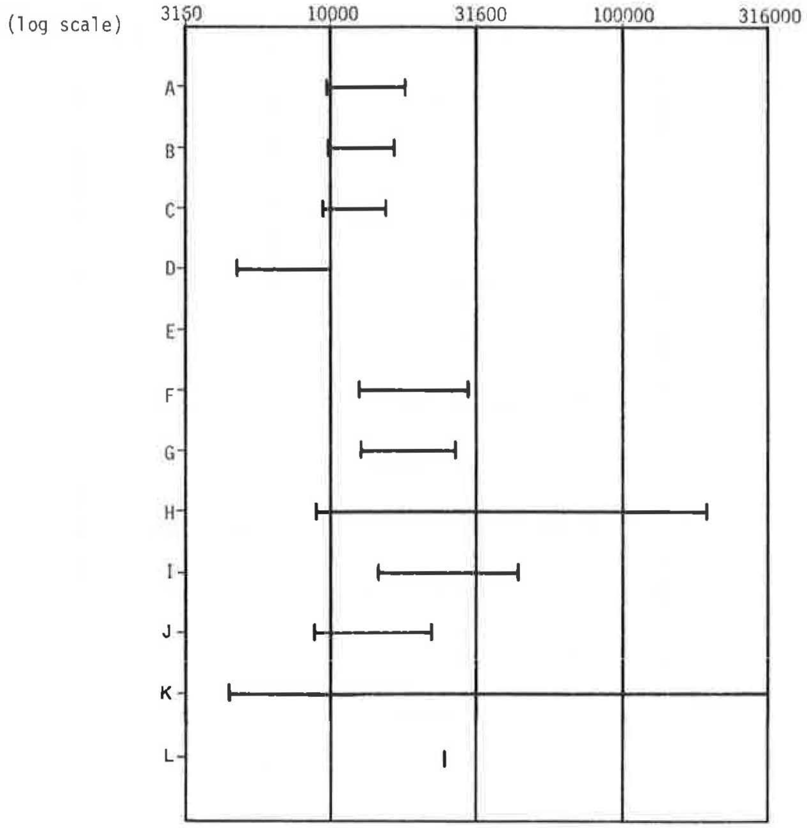

FIGURE 12 Comparison of backcalculated plastic clay modulus (deflection measured at TTI Pavement Test Facility).

TABLE 5 AARD OF BACKCALCULATED MODULI COMPARED WITH RESULTS OF AGENCY A

	Agencies									
Materials	B	C	D	E	F	G	H	I	K	L
Asphalt Concrete	.263	.494	6.701	1.890	2.038	.623	20.646	11.269	7.644	.379
Cement Stab. Limestone	.091	.400	.272	.836	.586	.393	59.116	3.178	.140	.217
Lime Stab. Limestone	.065	.098	.372	.463	.605	.530	15.055	4.101	.188	.867
Crushed Limestone	.249	.157	1.214	.099	.424	.997	259.446	40.290	.914	.292
Sandy Gravel	.032	.083	.428	.606	.603	.509	.452	.538	.610	.148
Sandy Clay	.022	.011	.322	.358	.768	.433	.481	.740	.229	.456
Plastic Clay	.044	.083	.475		.484	.393	4.915	.953	.965	.217
Average	.109	.189	1.398	.709	.787	.554	51.444	8.724	1.527	.368

surface layers or sandwiched layers are usually difficult to obtain, because surface deflections are often insensitive to changes in the moduli of these layers. Changes in the moduli of subgrade or other thick layers may mask changes in thin layers. These are difficulties resulting from the uncertainty of input parameters and the limitations of the basin-matching algorithms.

Any of these nonideal situations may render the results of purely numerical backcalculation schemes unreliable. Analysis error may be divided into two types: random and systematic. Random errors include load and deflection measurement errors, variation of layer thickness from mean thickness, and spatial variations of material properties. Systematic errors include deviation of the theoretical model from actual pavement behavior (e.g., using a linear elastic layer system to describe real pavement that may be nonlinear, viscoelastic, anisotropic, and nonhomogeneous, and using static analysis to characterize dynamic impulse loading); incorrectly assumed material parameters, such as Poisson's ratios; and incorrectly assumed layer thickness and subgrade depth.

The sizes of random errors may be estimated by replications of the test and reduced by averaging over several tests, but the sizes of systematic errors are often confounded and difficult to estimate. Some systematic errors cannot be eliminated without a better analysis method than current layer elastic theory, but some systematic errors can be reduced with a better knowledge of actual pavement behavior and limitations of the analysis method. The use of an expert system technique provides a means to convey the knowledge and experience possessed by an expert analyst to a less-experienced analyst so that systematic errors are kept to a minimum.

Sensitivity of Input Parameters

One of the main reasons for the variation of backcalculation results produced by different analysts, given the same backcalculation program, is the difference in assigning input parameters. Input parameters needed by most backcalculation programs include layer thickness, Poisson's ratios, load configuration, error tolerance, maximum number of iterations, seed moduli, and depth to bedrock. Sensitivity analyses of some of these parameters have been conducted by several researchers on different backcalculation programs (*6,10–12*). Results from the studies indicate that, except for seed moduli, all these parameters have significant effects on the values of backcalculated layer moduli. Surface layer moduli are the most sensitive, followed by base and subbase layer moduli. Subgrade moduli are relatively stable regarding variation of input parameters. The reason for this is the influence of layer moduli on surface deflection. This has been pointed out by Ullidtz (*13*):

> The subgrade usually contributes 60% to 80% of the total center deflection. A small error in the determination of the subgrade modulus will, therefore, lead to very large errors in the moduli of the other pavement layers.

Layer thickness is one of the crucial inputs that can change the backcalculation result drastically. The thinner the layer, the more accurate the thickness input must be to backcalculate accurate layer moduli. It is prudent to perform a few field borings to verify the actual layer thickness. However, layer thickness of constructed pavement may vary along the road depending on the contractor's quality control and local topography.

Poisson's ratios for pavement materials are seldom determined from experiment; they are usually estimated. Poisson's ratios of unbound materials are not well defined and may be different because of different confining pressure, moisture content, and gradation.

The load configuration depends on the NDT device being used and can affect the backcalculation results significantly. A uniformly distributed circular load is usually assumed. However, the actual loading applied to the pavement surface may not be uniformly distributed and depends on the relative rigidity of the loading plate and surface layer.

A small error tolerance is usually better in obtaining an accurate backcalculation result, but a very small error tolerance may prevent convergence to a solution, particularly when backcalculating from a measured deflection basin, as has been explained previously. A small error tolerance must be accompanied by a larger number of allowed iterations, which can increase the time required to backcalculate each basin. The analyst must compromise between accuracy and efficiency of backcalculation.

The depth to bedrock can have a significant effect on the resulting backcalculated moduli, especially when the depth is shallow (e.g., less than 20 ft). The depth to bedrock can vary considerably according to local topography. If the assumed depth to bedrock is substantially different from the actual depth, backcalculation usually results in large errors in matching the surface deflections.

Role of Judgmental Knowledge

Results from the comparative study also indicate that analysts with specialized knowledge can often produce similar and more reasonable results than less-experienced analysts. When these "experts" encounter deflection basins that do not give reasonable layer moduli through backcalculation, they usually make judgments of the validity of assumptions, correctness of input, and usefulness of results on the basis of their knowledge. This knowledge may be gained from experience with a particular pavement section, research reports, textbooks, general experience, common sense, and engineering rules of thumb. These sources of knowledge are often called upon during analysis, especially when results from numerical backcalculations do not seem reasonable and when input parameters must be estimated.

Drawing on expert knowledge during routine pavement structural evaluation or overlay design requires easy access to expertise. Development of expert system technology has made possible the capture of specialized knowledge and the incorporation of this knowledge into numerical computation schemes. An expert system can assist pavement engineers in analyzing pavement deflections and obtaining effective layer moduli for evaluation and design purposes (*14,15*).

STRUCTURE OF A BACKCALCULATION EXPERT SYSTEM

The knowledge in a backcalculation expert system may include the following:

1. General knowledge of the properties of paving materials—for example, the possible range of modulus values and Poisson's ratios for particular types of material, nonlinearity (stress dependency), the effect of temperature on asphalt layer modulus, and the effect of moisture on base and subgrade moduli;
2. General knowledge of pavement structures, such as variation of layer thickness resulting from construction practices and the possible depth to bedrock according to local topography;
3. Knowledge of pavement behavior—for example, that deflections under or closer to the load are influenced more by the upper layer modulus, whereas deflections at greater distances from the load are affected more by the subgrade modulus; that moduli of thin layers usually have a small influence on the surface deflection; that the effect on surface deflections of a soft layer under a much stiffer layer (e.g., a flexible subbase under a cement-stabilized base) is often masked by the stiffer layer; and that stabilized layers may have warping induced by a temperature gradient;
4. Knowledge of the backcalculation computer program—for example, the sensitivity of input parameters, assumptions and limitations of the mathematical model, accuracy of the numerical solution of the model, and accuracy and sensitivity of the numerical search scheme;
5. Knowledge of the sources and approximate sizes of errors introduced because of instrumentation, differences between the model and reality, and the search scheme; and
6. Knowledge of the variability of paving material properties.

The knowledge may be separated into two parts: a pre- and a postprocessor. Figure 13 shows a general flow diagram of the backcalculation process assisted by an expert system. Details of the knowledge stored in the pre- and postprocessors will be reported in another paper.

Although expert judgment may be useful in providing general guidelines, it cannot substitute for essential data. The

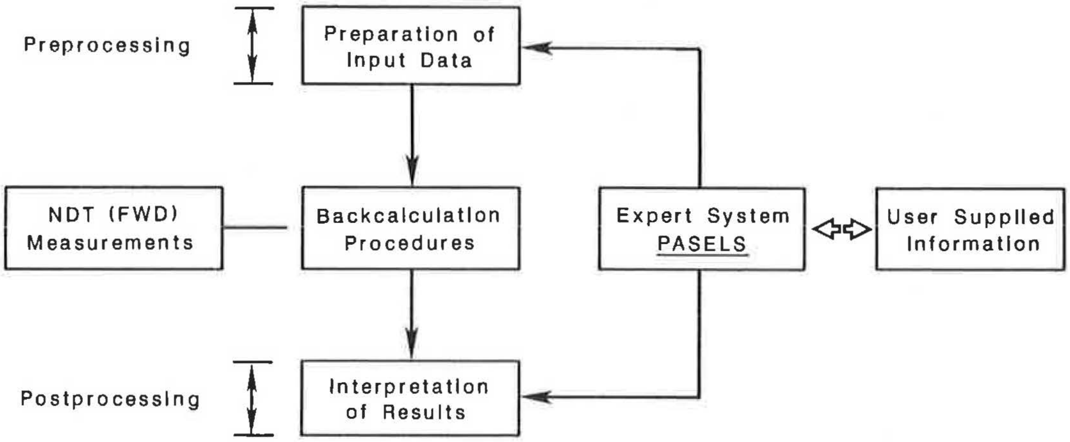

FIGURE 13 Concept of using expert systems in backcalculation.

availability and accuracy of input data such as layer thickness and depth to bedrock are still critical to the success of backcalculation. The preprocessors, however, may help to estimate reasonable input data that are not available from measurement or that are judgmental.

The results of the expert system analysis should be viewed as a probable estimation rather than as a "correct" solution. Improvements in backcalculation procedures, such as better constitutive relationships, more accurate modeling of dynamic loading, and so forth, may provide more accurate solutions than those of expert systems.

SUMMARY

Pavement layer materials are characterized by their elastic modulus, which can be estimated from surface deflections through backcalculation. A comparative survey of backcalculation procedures was conducted. The major findings are as follows:

1. Results from algorithmic backcalculation methods must be examined carefully for correctness. Large discrepancies may be found among different analysis methods and among different analysts.
2. Differences in input parameters may produce significantly different backcalculation results. Some parameters (e.g., subgrade depths and Poisson's ratios) are seldom measured; the analyst's judicious estimates must be relied on.
3. Backcalculated surface layer and base layer moduli are usually less reliable than backcalculated subgrade moduli.
4. An automated basin-by-basin scrutiny of backcalculation results can be achieved through the use of expert systems.
5. Knowledge and experience of pavement experts can be acquired and stored as rules in a knowledge base. A knowledge-based expert system can help perform mechanistic analysis by modeling the pavement structure more accurately and by recognizing possible errors in the results.
6. The use of expert systems reduces the expertise required to perform a difficult and tedious task and enables pavement experts to devote their time to more creative work.
7. Further improvements in backcalculation methods are needed.

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