Verification of Backcalculation of Pavement Moduli

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This paper introduces a backcalculation computer program which can be used to estimate the elastic modulus for each pavement layer. This microcomputer program, EVERCALC, is based on the Chevron N-layer elastic analysis computer program and was developed primarily for flexible pavement analysis and falling weight deflectometer (FWD) data. The program is capable of estimating the elastic modulus for each layer of a pavement structure (up to a maximum of three layers) directly from surface deflection measurements. Further, the stress sensitivity coefficients for unstabilized layers (both base and subgrade) are estimated, as well as a "standard" asphalt concrete modulus analogous to a laboratory condition. Results from EVERCALC were verified in two ways. The first approach was to compare theoretical and backcalculated moduli for a range of three layer pavements. These comparisons showed modest differences among the moduli (about 8% for asphalt concrete, 6% for base course, and less than 2% for the subgrade soils). The second verification approach was to compare backcalculated and laboratory moduli based on FWD tests and field material sampling, along with appropriate laboratory testing. In general, the differences in moduli are significantly less than the "natural" variation of these materials within a relatively short pavement segment. (Pavement segments were originally selected for their apparent uniformity.)

The need to evaluate in situ pavement properties, such as layer moduli, is readily apparent to pavement engineers. The evolution of pavement structural characterization by use of both mechanistic analysis and nondestructive testing equipment, such as the falling weight deflectometer (FWD), has resulted in new pavement analysis tools.

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NONDESTRUCTIVE TESTING

Of the various nondestructive testing (NDT) devices available, the FWD was chosen as the primary focus of the reported work. There are a number of reasons for this. First, the FWD is the primary deflection measuring instrument used by the Washington State Department of Transportation (WSDOT). Second, it can provide variable and large impulse loadings to the pavement surface which to some degree simulate actual truck traffic.

With the FWD (Dynatest model 8000), a transient impulse load is applied through a set of rubber cushions, which results in a load pulse of 25 to 30 milliseconds. The pavement deflections are measured at up to seven locations with velocity transducers (*1, 2*). As with any NDT device, the FWD has a few (but generally minor) drawbacks. For example, the depth to a "rigid layer" in a pavement may affect the deflection basin and, hence, the backcalculation analysis (*3*). Further, the accelerations of the FWD load and moving wheel loads are different. (The FWD is higher.) Thus, the inertia of the pavement mass may play an important role for the FWD, while it is negligible for the moving wheel (*4, 5*).

Overall, the FWD has been shown to be a powerful, if not the best, NDT device currently available (*6, 7*).

CHARACTERISTICS OF PAVEMENT MATERIALS

General

A "typical" flexible pavement system consists of layers of both bituminous bound (asphalt concrete) and unbound (base and subgrade) materials. The treatments performed on these materials in the backcalculation process will be described in this section.

Asphalt Concrete

The stiffness of asphalt concrete is a function of numerous parameters, two of the most important being temperature and load duration (*8*). Based mostly on laboratory resilient moduli data for WSDOT class *B* asphalt concrete mixtures (traditional, dense mixes), the following regression relationship was obtained (*9*):

$$\log E_{ac} = 6.4721 - 1.4736 \times 10^{-4}(T)^2$$

where

E_{ac} = modulus of asphalt concrete (psi), and
T = pavement temperature (°F).

Thus, this straightforward relationship can be used to adjust a "backcalculated" modulus at a given field temperature to any other temperature (presumably to some "standard" temperature, such as 77°F). This adjustment is made by multiplying the backcalculated modulus by the ratio of the moduli at the desired (or standard) temperature and the field temperature (pavement temperature at the time of FWD testing).

The effect of different load durations for asphalt concrete mixtures is accounted for by use of an equation developed for the Asphalt Institute (*10*). This is necessary if one wishes to view backcalculated asphalt concrete moduli in terms of the "traditional" laboratory values, since the durations of laboratory load pulses are generally at the *a* level of 100 milliseconds and FWD load pulses closer to 25 to 30 milliseconds. Using normal WSDOT asphalt concrete mixture parameters, the differences in load durations (FWD vs. laboratory) and the Asphalt Institute relationship, the following regression equation was developed:

$$R = 0.791 + 0.00813\,(T)$$

where

R = ratio of FWD to laboratory moduli, and
T = pavement temperature (°F) during FWD testing.

This relationship adjusts the "field" backcalculated asphalt concrete modulus by multiplying the backcalculated modulus by $1/R$.

Clearly, pavement temperature is a significant factor for asphalt concrete stiffness. In the described backcalculation procedure, the pavement temperature at the time of FWD testing is required. To determine the pavement temperature, one can either measure it directly (which is time consuming) or use an approximate computational technique for estimation. Southgate and Deen's method (*11*) was chosen for the latter technique. Their procedure requires the pavement surface temperature, the previous five-day mean temperature, and pavement thickness to estimate the temperature at mid-depth in the asphalt concrete layer.

Base and Subgrade

The modulus of unbound (or unstabilized) materials is a function of numerous factors, such as degree of saturation, density, gradation, stress level, and load duration and frequency. Thus, most unbound base materials and subgrade soils exhibit a direct relationship between modulus and stress state (*8*). This relationship is generally as follows:

$$E_b = K_1(\Theta)^{K_2}$$

and

$$E_s = K_3(\sigma_d)^{K_4}$$

where

E_b = elastic (or resilient) modulus for base materials and/or coarse-grained soils (psi),
E_s = elastic (or resilient) modulus for fine-grained soils (psi),
Θ = bulk stress (psi),
σ_d = deviator stress (psi), and
K_1, K_2, K_3, K_4 = regression coefficients.

If varying load levels are obtained with the FWD at a specific pavement location, backcalculated moduli and associated stress states can be estimated and the K values obtained by simple linear regression.

EVERCALC

EVERCALC is a mechanistic-based pavement analysis computer program based on the Chevron N-layer program. This microcomputer program (which runs on an IBM AT or compatible computer) uses an iterative procedure of matching the measured surface deflections with the theoretical surface deflections calculated from assumed elastic moduli. The program produces a solution when the summation of the absolute values of the discrepancies between the measured and theoretical surface deflections falls within a preset allowable tolerance (generally 10%). Lower tolerance levels will produce more accurate solutions; however, the 10% tolerance results in modest computer run time (about 5 minutes for a three-layer pavement case). The program is primarily for the analysis of flexible pavement using FWD deflection measurements. The acquired input data for this program are six surface deflection measurements at the offsets of 0, 8, 12, 24, 36, and 48 inches from the center of the load (refer to Figure 1), pavement layer thicknesses, and appropriate temperature data.

The program is capable of evaluating a flexible pavement structure containing up to three layers. The program can be run with or without a "rigid base." The program estimates the initial "seed" moduli and performs backcalculation of the elastic modulus for each pavement layer. It also determines the stress sensitivity coefficients (K values) for the base materials and subgrade soil when the FWD data for at least two load levels are available at a given point. Further, the asphalt concrete moduli are adjusted to WSDOT laboratory standard conditions (77°F temperature and 100-millisecond load duration).

The seed moduli are estimated using internal regressions, which are algorithms developed using regression between pavement layer moduli, load, and various kinds of deflection basin parameters (*12*).

Prior studies have found that the Chevron N-layer computer program has a computational error in calculated pavement surface deflection as compared with those calculated by BISAR (*13, 14*). The problem appears to be more severe near the applied load and is exacerbated if a rigid base is used. To examine these surface deflection differences between Chevron N-layer and BISAR, surface deflections were calculated (without rigid base) by both computer programs for the following cases using an 11.8-inch diameter circular load area. (see Table 1).

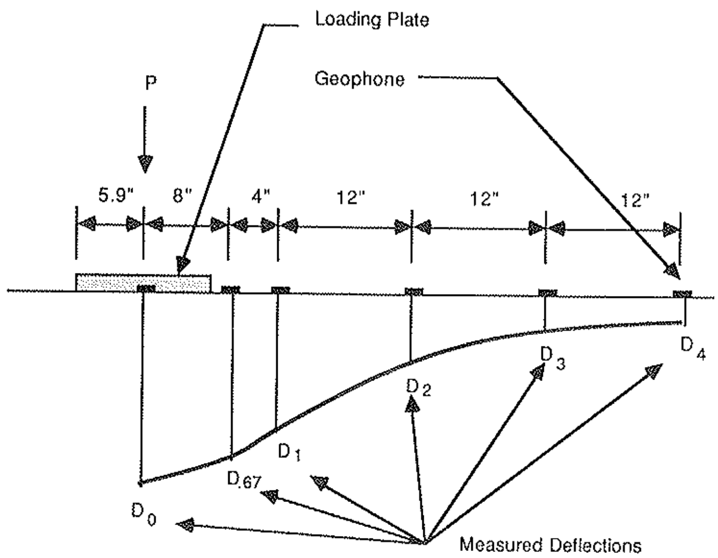

FIGURE 1 Present configuration of WSDOT FWD.

TABLE 1 COMPARISON OF CHEVRON N-LAYER AND BISAR CALCULATIONS OF SURFACE DEFLECTION DIFFERENCES

Asphalt Concrete	Stiffness (ksi):	50	500	1,000
	Thickness (in):	6	12	
	Poisson's ratio:	0.35		
Base	Stiffness (ksi):	10	20	40
	Thickness (in):	12	24	
	Poisson's ratio:	0.40		
Subgrade	Stiffness (ksi):	5	15	30
	Thickness (in):	semi-infinite		
	Poisson's ratio:	0.45		
Load levels (lb)	9,000 and 15,000			

The average surface deflection and associated standard deviation differences for 216 cases are shown in Table 2.

Further, the maximum deflection difference was 8.2% directly under the load (E_{ac} = 1,000 ksi, h_{ac} = 12 in., E_b = 40 ksi, h_b = 24 in., E_{subg} = 5 ksi), with only 12 of the 216 cases over 5%. Generally, the largest differences (2.0% or more) were for the thick, higher stiffness surfaces on lower stiffness subgrades.

The basic conclusion drawn from the above information is that the Chevron N-layer program is adequate for backcalculation of typical moduli for flexible pavements (given normally used convergence errors). However, backcalculation programs based on the Chevron N-layer should not be used on rigid pavements at this time.

ACCURACY OF BACKCALCULATION SOLUTIONS

A number of concerns about backcalculation of elastic moduli can be raised. These can include (1) nonunique solutions, (2) requirement for equivalent moduli for a limited number of layers (three or four), (3) differences between backcalculated and laboratory obtained elastic moduli, and (4) selection of the optimum number and location of surface deflection measurements.

Nonunique solutions simply mean that if different initial seed moduli are used, then different backcalculated moduli result in a final solution. The equivalent moduli problem arises from the fact that a limited number of pavement layers can

TABLE 2 AVERAGE SURFACE DEFLECTION AND ASSOCIATED STANDARD DEVIATION DIFFERENCES FOR 216 CASES

Statistics	Radial Offset (in.) 0	8	12	24	36	48
Mean (%)	1.1	0.4	0.2	0.0	0.1	0.1
Std. Dev. (%)	1.7	0.6	0.3	0.1	0.1	0.1

be used in the backcalculation process (in part limited by the number of measured surface deflections, computer run time, and theory associated with modeling complex materials). Thus, one must obtain (for example) a single modulus value for the asphalt concrete materials even though such a layer may be composed of different asphalt concrete mixtures, lifts, and hence moduli. Finally, backcalculated and laboratory moduli must show at least modest agreement in order for pavement engineers to become more confident in backcalculation procedures.

When the seed moduli are accurately estimated, the backcalculation process will produce solutions with less error in fewer iterations, thus minimizing the nonuniqueness problem. The seed moduli may be estimated by engineering judgment, temperature-stiffness relationships, and surface deflections, among others. EVERCALC contains internal regression equations (*12*), which are used to estimate the seed moduli (for up to three layers) from deflection basin parameters. This is done in an attempt to minimize nonuniqueness.

To address at least partially the nonuniqueness question for backcalculated solutions, EVERCALC backcalculated solutions were compared with theoretical elastic layer solutions. This was accomplished by calculating "theoretical" surface deflections for preselected layer moduli and thicknesses (for three layer pavements). These calculations were performed with the Chevron N-layer computer program for the following cases, shown in Table 3.

Surface deflections were calculated at six offsets of 0, 8, 12, 24, 36, and 48 inches from the load. The load was assumed to be 9,000 pounds, placed on a circular load plate 11.8 inches in diameter. The cases were excluded in which the asphalt concrete layer was of greater thickness than the base; thus, 384 cases were used. The surface deflections so calculated were then used as inputs into EVERCALC, and moduli for each of the three layers backcalculated. This enabled a straightforward comparison of the known moduli used originally to calculate the surface deflections (via Chevron N-layer program) to the backcalculated moduli obtained from those same surface deflection (via the EVERCALC program).

A maximum of five surface deflections can be used for direct backcalculation with EVERCALC; thus, two separate runs were made for surface deflections at 0, 8, 12, 24, and 36 inches (case A) and those at 0, 12, 24, 36, and 48 inches (case B). These two deflection sensor configurations have been commonly used by the WSDOT and appear to define the deflection basin reasonably. A maximum allowable tolerance of 10% was used for "matching" the deflection basins. The 10% tolerance is an absolute value (i.e., the sum of the absolute differences in surface deflections at all five locations). This tolerance level resulted in three backcalculation iterations or less to procure an "in tolerance" solution for the cases studied. Thus, the backcalculation results reported throughout this paper were obtained in a "production" mode representative of expected, everyday usage of EVERCALC.

The percent differences between the backcalculated and theoretical moduli were determined. The backcalculations performed for surface deflection measurements conforming to case A were slightly better than those for case B (i.e., better agreement between backcalculated and theoretical moduli). This is most likely due to the second surface deflection measurement being only 8 inches from the center of the load plate for case A, as opposed to 12 inches for case B, thus better defining a critical portion of the deflection basin.

A summary of the absolute percent differences (or errors) for the backcalculated and theoretical moduli is shown in Table 4 for case A surface deflection locations (i.e., sign conventions were ignored which result in higher average errors). Overall, the subgrade moduli have the closest agreement (about 1.5%). The base materials have an average difference of about 6.5% and the pavement surfacing (asphalt concrete) about 8.2%. Figure 2 is used to show the cumulative frequency distribution of the errors. Overall, most of the calculated errors were less than 10% for the subgrade moduli. For asphalt concrete and base layers, 82% of the comparisons had less than a 10% error; 90% had less than 20% error; and 95% had less than 30% error. Further, the errors tended to increase for thin, low stiffness (100,000 psi) asphalt concrete layers.

COMPARISON OF BACKCALCULATED AND LABORATORY MODULI

Comparisons between backcalculated (or in situ) and laboratory moduli are difficult because of variability of the materials, sampling, and testing. The results presented in this section will show the results of such an attempt.

Sixteen pavement test sites (Table 5) were used to compare the backcalculated and laboratory moduli. These test sites are typical of flexible pavement sections on the state-maintained route system in Washington. In part, however, they were selected for their apparent uniformity (for example, in construction, distress, and subgrade soils). Surface distress at these sites was observed to be mostly fatigue (alligator) cracking or its usual precursor, longitudinal cracking. Only five of the sixteen test sites were evaluated (for backcalculation pur-

TABLE 3 COMPARISON OF EVERCALC BACKCALCULATED SOLUTIONS WITH THEORETICAL ELASTIC LAYER SOLUTIONS PERFORMED WITH CHEVRON N-LAYER PROGRAM

Asphalt Concrete	**Stiffness (ksi):**	100	300	500	800
	Thickness (in):	3	5	8	
	Poisson's ratio:	0.35			
Base	**Stiffness (ksi):**	10	20	40	
	Thickness (in):	6	12	24	
	Poisson's ratio:	0.40			
Subgrade	**Stiffness (ksi):**	5	10	20	30
	Thickness (in):	semi-infinite			
	Poisson's ratio:	0.45			

TABLE 4 CALCULATED ERRORS FROM COMPARISON OF BACKCALCULATED AND THEORETICAL LAYER MODULI

Surface Thick. (in.)	Layer	Error (%) Theoretical Elastic Modulus (psi) 100,000 Mean	100,000 Std	300,000 Mean	300,000 Std	500,000 Mean	500,000 Std	800,000 Mean	800,000 Std	Average Mean	Average Std
3.0	ACP	18.5	31.8	6.8	12.2	5.0	9.5	5.8	9.8	9.7	13.4
	Base	3.9	6.0	3.7	4.4	4.0	4.8	4.8	6.4	4.6	4.7
	Subgrade	0.7	0.5	0.9	0.9	1.4	1.7	1.4	2.1	1.3	1.2
5.0	ACP	13.5	24.8	6.2	9.4	4.7	7.4	5.5	6.9	7.7	10.4
	Base	6.0	9.6	5.1	6.1	5.1	4.6	6.5	4.8	5.5	5.9
	Subgrade	1.0	0.9	1.1	1.0	1.6	1.5	1.3	1.1	1.2	1.2
8.0	ACP	9.8	24.3	6.2	9.2	3.6	5.2	5.5	11.0	7.2	9.9
	Base	8.6	10.7	8.0	11.3	8.0	7.8	11.0	11.7	9.5	9.4
	Subgrade	2.2	1.7	2.3	1.8	2.4	1.8	2.1	1.6	2.0	2.0

Note 1: Error (%) = $\left|\left(\frac{\text{Backcalculated modulus - theoretical modulus}}{\text{theoretical modulus}}\right)(100)\right|$

poses) as three-layer pavements. The remainder were evaluated as two-layer systems ("full-depth" cases).

The field material sampling required for laboratory testing included obtaining asphalt concrete cores at three locations (stations 0 + 50, 5 + 50, and 9 + 50) within the 1,000-foot-long test sites. This was done to estimate better the asphalt concrete modulus and thickness changes within each test site. Disturbed base course and subgrade soil samples were obtained at the pavement shoulder at approximately the middle of each test site (station 5 + 50). During this sampling in situ, moisture contents were made in the base and subgrade materials.

The laboratory testing of the asphalt concrete cores was conducted in accordance with ASTM D4123 at three temperature levels (41°, 77°, and 104°F) and a loading duration of 100 milliseconds. The base and subgrade materials were recompacted in the laboratory and tested in accordance with AASHTO T274. The remolding moisture content was kept as close as possible to those measured in the field at the time of sampling. The triaxial testing was performed on each sample with confining stresses of 1, 2, 4, and 6 psi and deviator stresses of 1, 2, 4, 6, 8, 10, and 12 psi. All laboratory testing was conducted by the WSDOT at its materials laboratory in Olympia, Washington.

Asphalt Concrete Comparisons

The comparisons of backcalculated (EVERCALC) and laboratory asphalt concrete moduli are shown in Table 6 for all sixteen test sites. All moduli values have been rounded off to the nearest 1,000 psi; however, the percent differences were calculated on the non-rounded values. Further, all backcalculated moduli values were adjusted to a "standard" loading duration (100 milliseconds) and temperature (77°F) to provide better comparisons with the laboratory moduli (for which a large amount of published modulus data is available).

Differences in the backcalculated and laboratory moduli range from being essentially identical to over 400%. Overall, differences of 20% to 50% were common. The largest differences were observed for test site 8, which had extensive, severe fatigue cracking observed at the pavement surface. Thus, the low backcalculated values (40,000 to 100,000 psi) should be expected. Naturally, when this test site was cored, only those cores were obtained which had no cracks. Therefore, the large differences between backcalculation and laboratory moduli are understandable. This same discussion applies to test site 10, since this site has extensive longitudinal cracking. If one views the moduli differences for the remaining test

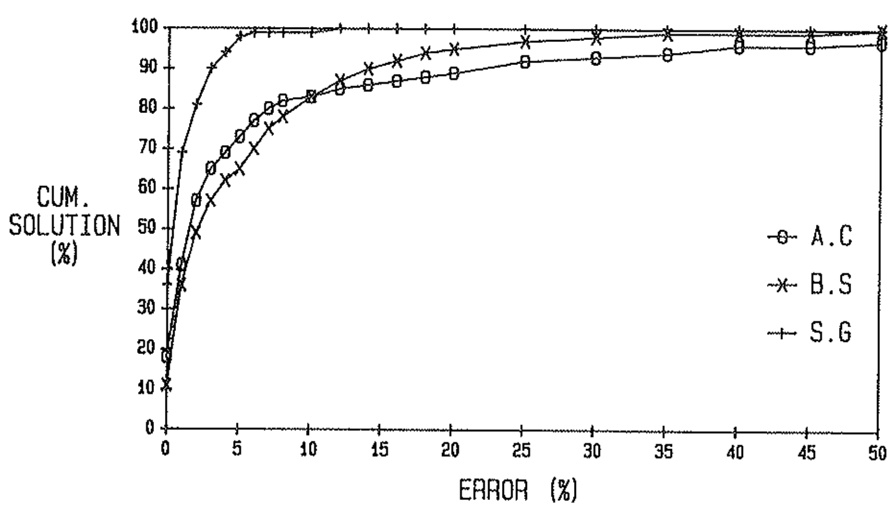

FIGURE 2 Accuracy of backcalculation.

TABLE 5 TEST SITE DESCRIPTIONS

Test Site No.	Route No.	Milepost	Year Original Construction (overlay year)	ACP Thick.	Base Thick.	Observed Surface Distress (if any)
1	SR 11	20.85	72	5.2	28.8	Long. cracking
2	SR 20	53.50	73	4.9	4.8	Long. cracking
3	SR 20	77.50	68 (85)	10.9	6.6	---
4	SR 20	108.20	78	3.5	9.0	---
5	SR 20	140.80	72	3.4	6.6	---
6	SR 167	17.80	68 (80)	11.2	---	---
7	SR 202	30.12	78	13.0	---	---
8	SR 410	9.60	68	7.3	3.6	Fatigue cracking
9	SR 5	35.80	73	16.4	---	---
10	SR 14	18.15	73	9.0	3.6	Long. cracking
11	SR 411	18.05	79	6.8	21.0	---
12	SR 500	3.20	79	6.3	8.4	---
13	SR 90	208.65	73	9.6	8.4	Long. & Trans. crack.
14	SR 90	208.85	73	9.6	8.4	Trans. cracking
15	SR 195	7.24	70 (85)	6.2	11.4	---
16	SR 195	63.80	76	8.5	12.0	---

sites (excluding test sites 8 and 10), then the differences are not alarming.

To put the asphalt concrete moduli differences into greater perspective, the backcalculated moduli for test sites 1 and 3 ("higher" and "lower" moduli test sites) were plotted and shown in Figure 3. The backcalculated moduli were determined from the FWD deflection basins taken every 50 feet within the 1,000-foot test sites. A quick inspection of Figure 3 shows that substantial variations in asphalt concrete moduli can be expected, which suggests the power that NDT pavement evaluation can provide.

Base Course Comparisons

The comparisons of backcalculated and laboratory base course moduli for five of the sixteen test sites are shown in Table 7. These five test sites were judged to have base course thicknesses which would provide for "reasonable" base moduli determination. In general, use of the EVERCALC program has led the authors to conclude (at this time) that the base course thickness should be about 1.5 times thicker (or more) than the surfacing layer in order to attempt a three-layer backcalculation.

The backcalculated and laboratory base course moduli were compared at similar stress states (i.e., the in situ stresses estimated during FWD testing and the laboratory triaxial stresses were similar). Overall, good agreement was found for four of the five test sites. The unusually high laboratory modulus for test site 5 (60,000 psi versus 38,000 psi for backcalculation) may be attributed largely to how the base course material was sampled.

Table 8 is provided to show comparisons between the stress sensitivity coefficients (K_1, K_2) for the backcalculated and laboratory moduli. These coefficients are automatically computed by the EVERCALC program if two or more FWD load levels are used at a test point. Overall, the agreement is modest at best; however, the poorest comparison is again for test site 5. Due to the small number of data points for determining these coefficients from FWD data and backcalculation, one

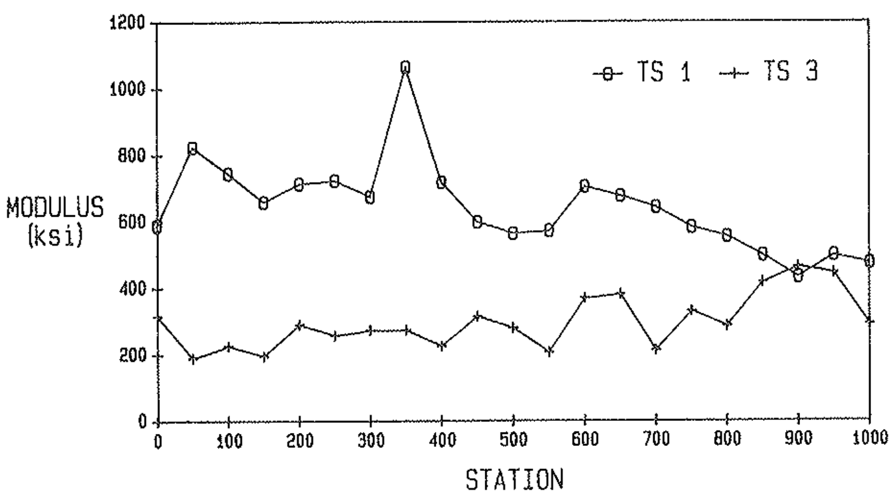

FIGURE 3 Variation of asphalt concrete modulus.

TABLE 6 COMPARISON OF BACKCALCULATED AND LABORATORY ASPHALT CONCRETE MODULI

Test Site No.	Solution Method	Modulus (psi) Station 0 + 50	Station 5 + 50	Station 9 + 50	Average
1	NDT/FWD	868,000	668,000	604,000	713,000
	Lab	426,000	469,000	387,000	427,000
	Difference (%)	-51	-30	-36	-40
2	NDT/FWD	725,000	498,000	487,000	570,000
	Lab	633,000	355,000	234,000	407,000
	Difference (%)	-13	-29	-52	-29
3	NDT/FWD	246,000	373,000	568,000	395,000
	Lab	333,000	557,000	334,000	408,000
	Difference (%)	+36	+50	-41	3
4	NDT/FWD	684,000	472,000	194,000	450,000
	Lab	346,000	215,000	244,000	268,000
	Difference (%)	-49	-54	+26	-40
5	NDT/FWD	531,000	494,000	740,000	588,000
	Lab	357,000	147,000	354,000	286,000
	Difference (%)	-33	-70	-52	-51
6	NDT/FWD	722,000	741,000	510,000	658,000
	Lab	171,000	489,000	464,000	355,000
	Difference (%)	-76	-34	-21	-46
7	NDT/FWD	460,000	577,000	757,000	598,000
	Lab	431,000	596,000	743,000	590,000
	Difference (%)	-6	+3	-2	-1
8	NDT/FWD	102,300	42,000	94,000	79,400
	Lab	200,000	227,000	215,000	214,000
	Difference (%)	+96	+438	+130	+170
9	NDT/FWD	455,000	657,000	578,000	563,000
	Lab	135,000	117,000	181,000	144,000
	Difference (%)	-70	-82	-69	-74
10	NDT/FWD	131,000	289,000	340,000	253,000
	Lab	779,000	687,000	527,000	664,000
	Difference (%)	+495	+137	+55	+162
11	NDT/FWD	215,000	243,000	358,000	272,000
	Lab	344,000	352,000	219,000	305,000
	Difference (%)	+60	+45	-39	+12
12	NDT/FWD	311,000	242,000	270,000	274,000
	Lab	343,000	414,000	380,000	379,000
	Differemce (%)	+10	+71	+41	+38
13	NDT/FWD	264,000	232,000	344,000	280,000
	Lab	198,000	343,000	318,000	286,000
	Difference (%)	-25	+47	-8	+2
14	NDT/FWD	260,000	218,000	256,000	245,000
	Lab	289,000	240,000	188,000	239,000
	Difference (%)	+11	+10	-27	-2
15	NDT/FWD	404,000	262,000	495,000	387,000
	Lab	375,000	605,000	419,000	466,000
	Difference (%)	-7	+131	-15	+20
16	NDT/FWD	307,000	214,000	321,000	281,000
	Lab	202,000	166,000	164,000	177,000
	Difference (%)	-34	-22	-49	-37

should expect a wider range of coefficient values (as opposed to laboratory results).

To view these comparisons against the expected field base course moduli, backcalculated moduli for test site 1 were computed every 50 feet and plotted in Figure 4. Thus, within only 1,000 feet of a pavement structure, these moduli can easily vary by a factor of about 2.

Subgrade Soil Comparisons

The comparisons of backcalculated and laboratory subgrade soil moduli for all sixteen test sites are shown in Table 9. As was done for the base course comparisons, the moduli comparisons shown in Table 9 were made at similar stress states. The observed differences for these subgrade soils are the least

TABLE 7 COMPARISON OF BACKCALCULATED AND LABORATORY BASE COURSE MODULI

Test Site No.	Modulus (psi)			Moisture Content (%)		
	NDT/FWD	Lab	Diff. (%)	Field	Lab	Diff. (%)
1	23,000	23,000	0	3.7	4.7	+1.0
4	45,000	53,000	18	4.4	4.5	+0.1
5	38,000	60,000	60	5.0	4.3	-0.7
11	21,000	25,000	22	4.2	3.9	-0.3
15	22,000	31,000	36	4.4	4.9	+0.5
Average	30,000	38,000	28	4.3	4.5	+0.2
Std.Dev.	10,000	15,000		0.4	0.4	

TABLE 8 BASE COURSE STRESS SENSITIVITY COEFFICIENTS

Test Site No.	Solution Method	Stress Sensitivity Coefficients K_1	K_2	R^2 (%)
1	NDT/FWD	4,680	0.68	98
	Lab	7,350	0.49	91
4	NDT/FWD	1,149	1.16	92
	Lab	11,529	0.48	91
5	NDT/FWD	280	1.44	96
	Lab	14,270	0.42	89
11	NDT/FWD	1,590	1.10	96
	Lab	9,010	0.44	90
15	NDT/FWD	11,700	0.32	2
	Lab	13,000	0.41	92

of the three pavement materials being compared. Overall, the percent differences range from a low of 2% to a high of 84%, with the average being 10%. The average backcalculated moduli for all sites is 29,000 psi, compared with an average laboratory modulus of 26,000 psi. (Recall that the laboratory moduli were for disturbed, or recompacted, samples.) These differences, again, should be viewed against the kind of variation one might expect in a relatively uniform, short length of pavement. Figure 5 shows the backcalculated subgrade soil moduli for FWD tests performed every 50 feet for two 1,000-foot long test sites (test sites 1 and 3). The illustrated subgrade can easily vary by a factor of 2.

Table 10 is provided to illustrate comparisons of the stress sensitivity coefficients (K_3, K_4) for the backcalculated and laboratory moduli. Overall, the agreement is somewhat better than that observed for the base course comparisons.

SUMMARY AND CONCLUSIONS

A backcalculation program (EVERCALC), which is used to determine pavement-layer elastic moduli, has been examined in two fundamental ways in an attempt to verify the results. The first verification approach was to compare theoretical and backcalculated moduli for a range of three-layer pavement systems. This was accomplished by using the Chevron N-layer

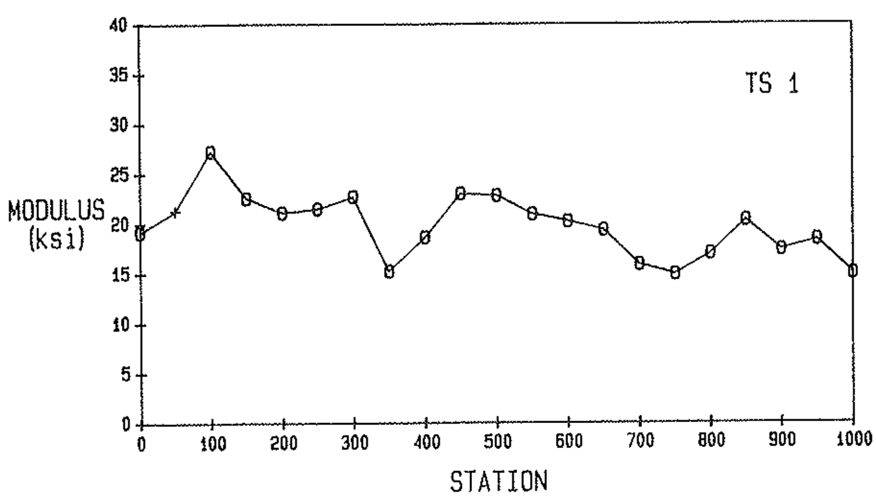

FIGURE 4 Variation of base modulus.

TABLE 9 COMPARISON OF BACKCALCULATED AND LABORATORY SUBGRADE SOIL MODULI

Test Site No.	Modulus (psi)			Moisture Content (%)		
	NDT/FWD	Lab	Diff. (%)	Field	Lab	Diff.
1	26,000	20,000	-21	5.6	7.3	+1.7
2	21,000	16,000	-23	2.4	6.0	+3.6
3	15,000	20,000	+32	3.7	6.4	+2.7
4	27,000	49,000	+84	3.8	4.7	+0.9
5	36,000	32,000	-11	3.5	4.8	+1.3
6	29,000	15,000	-47	9.6	6.0	-3.6
7	39,000	33,000	-14	5.6	5.5	-0.1
8	9,000	5,000	-36	21.5	15.7	-5.8
9	37,000	32,000	-14	12.2	12.6	+0.4
10	39,000	26,000	-32	7.8	9.2	+1.4
11	26,000	28,000	+8	6.9	11.1	+4.2
12	36,000	35,000	-2	8.2	9.0	+0.8
13	36,000	42,000	+17	10.4	8.2	-2.2
14	40,000	42,000	+4	10.4	8.2	-2.2
15	20,000	12,000	-42	13.6	15.1	+1.5
16	20,000	8,000	-59	11.8	12.1	+0.3
Average	29,000	26,000	-10	8.4	8.9	+0.5
Std. Dev.	10,000	13,000		5.0	3.6	

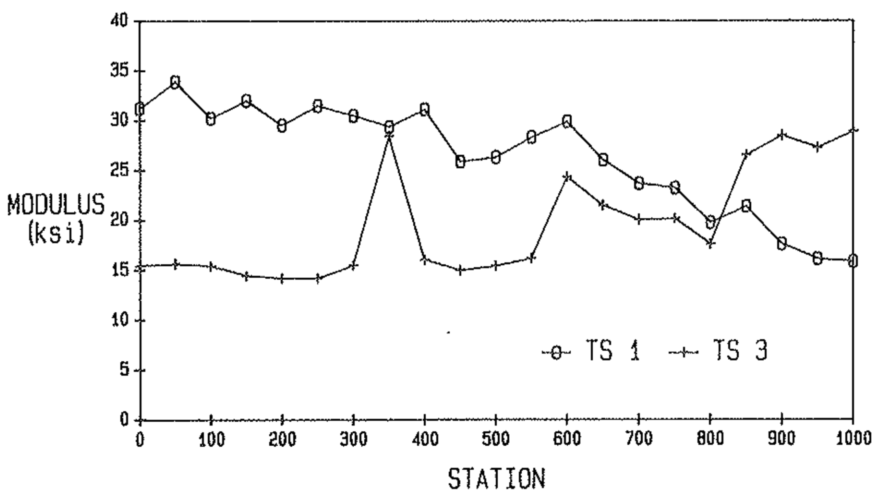

FIGURE 5 Variation of subgrade modulus.

elastic analysis program to generate deflection basins for specified layer moduli and thickness conditions. These comparisons showed modest differences (about 8% for asphalt concrete, 6% for base course, and less than 2% for the subgrade). The largest differences for asphalt concrete were observed for thin surfaces with low stiffness. As the asphalt concrete layer thickness increases, both the base and subgrade moduli differences increased.

The second verification approach was to compare backcalculated and laboratory moduli based on FWD tests and field material sampling along with appropriate laboratory testing. The results show the greatest range of differences for the asphalt concrete layers followed by the base and subgrade materials; however, large differences between backcalculated and laboratory asphalt concrete moduli should be expected for those test sites with extensive cracking. The observed differences between backcalculated and laboratory moduli do not offer a true verification, since laboratory test procedures of disturbed (recompacted) samples do not necessarily provide reference (or true) moduli. Further, these observed differences are generally much less than the variation of moduli expected within relatively uniform, short lengths of pavement (in this case, 1,000 feet).

The following conclusions are offered:

1. The backcalculation of layer moduli from measured pavement deflection basins appears to provide reasonable estimates of in situ pavement moduli. Further, moduli can be estimated for cracked asphalt concrete conditions.
2. The EVERCALC program is a backcalculation procedure which should be of value to the pavement research community and help meet the needs of road-owning agencies.

TABLE 10 SUBGRADE SOIL STRESS SENSITIVITY COEFFICIENTS

Test Site No.	Solution Method	Stress Sensitivity Coefficients		
		K_3	K_4	R^2 (%)
1	NDT/FWD	34,160	-0.24	89
	Lab	16,850	0.17	21
2	NDT/FWD	7,600	0.31	72
	Lab	3,140	0.50	6
3	NDT/FWD	20,610	-0.19	72
	Lab	16,360	0.13	17
4	NDT/FWD	59,050	-0.32	87
	Lab	32,680	0.16	54
5	NDT/FWD	48,710	-0.12	99
	Lab	20,410	0.16	16
6	NDT/FWD	48,670	-0.38	58
	Lab	11,750	0.20	14
7	NDT/FWD	49,176	-0.19	58
	Lab	27,360	0.16	42
8	NDT/FWD	11,910	-0.12	79
	Lab	7,290	-0.10	7
9	NDT/FWD	47,750	-0.21	59
	Lab	24,370	-0.21	68
10	NDT/FWD	37,270	0.02	20
	Lab	11,670	0.17	50
11	NDT/FWD	44,730	-0.44	97
	Lab	23,750	0.15	34
12	NDT/FWD	21,030	0.15	76
	Lab	4,640	0.56	53
13	NDT/FWD	65,390	-0.19	94
	Lab	26,480	0.18	21
14	NDT/FWD	39,260	-0.03	29
	Lab	26,480	0.18	21
15	NDT/FWD	28,760	-0.29	98
	Lab	17,460	-0.32	21
16	NDT/FWD	34,840	-0.30	96
	Lab	8,150	-0.01	21

3. The results of backcalculation analyses based on elastic solutions appear to be influenced by at least the following:
   (a) The backcalculation error is higher for asphalt concrete moduli with relatively thin, low stiffness surfaces.
   (b) The base course thickness should be about 1.5 times (or more) greater than the asphalt concrete surface course in order to achieve reasonable estimates of base moduli.
   (c) The two sensor configurations on the WSDOT FWD did not significantly alter the backcalculated moduli. (One of the two, however, did appear to have slightly smaller errors.)

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