Dynaflect Evaluation of Layer Moduli in Florida's Flexible Pavement Systems

KWASI BADU-TWENEBOAH, BYRON E. RUTH, AND WILLIAM G. MILEY

Research conducted to investigate the nondestructive testing (NDT) characterization of in-place pavement materials has resulted in the development of a modified sensor spacing for the Dynaflect. The modified testing configuration provides the capability to separate the deflection response contributed by the subgrade, the stabilized subgrade, and the combination of base and asphalt concrete for typical Florida flexible pavement systems. Analysis of Dynaflect data for in-service pavements using an elastic layer computer program resulted in the development of simple power law regression equations to predict layer moduli from modified sensor deflections. This paper presents the development of the simplified layer moduli prediction equations, and the recommended testing and analytical procedures for pavement evaluation investigations. The use of this simplified approach allow a large number of test locations to be analyzed by eliminating the use of computer-iterative programs which are usually time consuming, expensive, and often subject to substantial errors.

Nondestructive testing (NDT) and deflection measurements are now universally recognized methods for the structural evaluation of road and airfield pavements. NDT of pavements has evolved from the very basic Benkelman Beam to the more refined equipment such as Dynaflect, Road Rater, and Falling Weight Deflectometer. The Dynaflect is presently the most commonly used NDT device in the United States for evaluation and design of pavement. Like the Benkelman Beam, a large number of data has been accumulated with the use of this device.

The Dynaflect is a steady-state vibratory device that is instrumented to measure peak-to-peak dynamic deflection on the pavement surface. It applies a load of 1000 lbs., at a frequency of 8 cycles per second, through two steel wheels that are 20 in. apart center to center. The resulting deflection basin is measured by five geophones spaced 12 in. apart, with the first geophone located midway between the loading wheels. These deflection measurements represent the stiffness of the entire pavement section.

Although some significant accomplishments have been made in separating the effects of major parts of the pavement structure, the separation of the effects of all of the various components of the structure with deflection basin measurements has not yet been accomplished. Thus, with the possible exception of the subgrade modulus, the moduli of the other layers are estimated using linear-elastic computer-iterative programs, graphical solutions, or nomographs. The major problems associated with the above solution techniques are that unique solutions cannot be guaranteed, solutions can be time consuming, and the expertise required for interpretation may not be available. The purpose of this paper is to present a simplified approach that would allow a layer-by-layer analysis of the Dynaflect deflection basin. Such a simplified approach would allow a large number of test points to be analyzed and consequently enhance our ability to carry out mechanistic pavement evaluation on a routine basis.

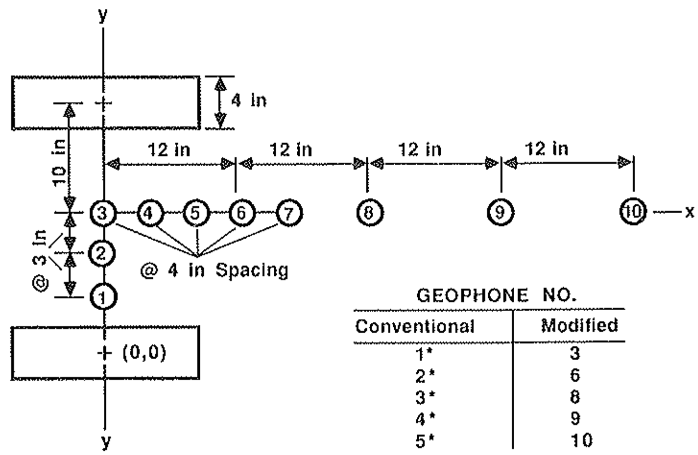
K. Badu-Tweneboah and B. E. Ruth, Department of Civil Engineering, University of Florida, Gainesville, Fla. 32611. W. G. Miley, Bureau of Materials and Research, Florida Department of Transportation, Gainesville, Fla. 32611.

BACKGROUND

The Florida Department of Transportation (FDOT) has for many years been interested in the use of NDT methods for pavement evaluation to typify pavement response and to provide information for structural characterization. The Benkelman Beam was used extensively into the 1970s for research projects and for "troubleshooting" distressed pavement sections. The first Dynaflect unit was purchased by the FDOT in 1966. Initially, it was used as a research tool in combination with Benkelman Beam and plate bearing tests on pavement layers. The Dynaflect evolved as a reliable device for assessment of structural response uniformity for Florida's highway pavement network.

In 1981, the FDOT's Bureau of Materials and Research pavement section under the direction of W. G. Miley developed and adopted a method of predicting the structural subgrade support value from Dynaflect sensor response. This was based on correlations between plate bearing moduli and the measured deflection at the fourth sensor (*1*). Subsequent use of the Dynaflect for pavement evaluation and to determine rehabilitation design thickness requirements has proven valuable to the FDOT. However, determination of layer moduli using elastic multilayered computer programs was time consuming and often yielded moduli that were outside the realm of possibility. Consequently, a research project was initiated in 1984 for the purpose of developing simplified methods for the determination of layer moduli using the Dynaflect.

This investigation involved computer simulation of Dynaflect response using ten different sensor positions (figure 1) for a parametric study of different layer thicknesses and moduli encompassing the range of values encountered in Florida. The results of the study indicated that modified sensor positions provided a unique capability for separation of the deflection response characteristics of asphalt concrete and limerock base from the underlying materials. Also, power law relationships for the fifth sensor was found to be reliable in assess-



GEOPHONE NO.	
Conventional	Modified
1*	3
2*	6
3*	8
4*	9
5*	10

FIGURE 1 Dynaflect modified geophone positions.

ing the subgrade modulus. A series of prediction equations were developed from the computer-generated information for the estimation of the moduli in four layer pavement systems (*2, 3*). Although the prediction accuracy appeared to be good, the complexity of the equations and the dependency upon reasonable estimates of E_1 or E_2 to solve for E_2 or E_1, respectively, indicated that further research to simplify and improve the accuracy of layer moduli predictions would be desirable.

Field tests were conducted on asphalt concrete pavements using the Dynaflect, Falling Weight Deflectometer (FWD), cone penetration test (CPT), Marchetti Dilatometer test (DMT), and plate loading test (PLT). The CPT and DMT data were collected to evaluate the stratigraphy of the subsurface thatis valuable in tuning moduli for elastic layer analyses based on measured deflection basins (*4*). A thin layer of extremely low or high modulus subgrade soil close to the pavement structure can prevent the matching of measured NDT deflections when using the composite subgrade modulus (E_4).

The field test data provided Dynaflect deflection values for standard and modified sensor configurations. Regression analysis of the data, using moduli values that gave analysis program BISAR predicted deflections closely matching the measured deflections, resulted in simplified power law equations for prediction of layer moduli (E_{12}, E_3, and E_4). The composite modulus, E_{12}, of asphalt concrete and base course moduli can provide a direct means for evaluation of the adequacy of the upper pavement layers and separation from the influence of the underlying support layers (E_3 and E_4). The estimation of the asphalt concrete modulus (E_1) from correlations between the constant power viscosity for recovered asphalts and the resilient modulus (E_1) of the mix (*5*) allowed for direct computation of the base course moduli (E_2).

Pavement evaluation is simplified using the Dynaflect and these analysis procedures. This simplified approach enhances our ability to directly determine the adequacy of a pavement structure and to identify structural deficiencies. Also elastic layer analysis can be performed to assess wheel-loading conditions at critical temperatures (*6*) to aid in determining rehabilitation design requirements.

The ensuing discussion presents the results of Dynaflect tests on various pavements, the development of the simplified layer moduli relationships, and the recommended testing and analytical procedures for pavement evaluation investigations. Finally, an application example is provided.

TEST PAVEMENT SECTIONS

Most of the pavement sections used in the study had been scheduled for evaluation by the FDOT. These sections, as listed in table 1, are representative of pavement deflection response, type of construction, and soil moisture conditions. The thickness of the asphalt concrete layer ranges from 1.5 in. to 8.5 in., while the base course thicknesses vary from 6.0 in. to 24.0 in. The subbase thicknesses were generally found to be 12.0 in., except for the SR 24 and SR 80 test sites in which construction drawings indicated thicknesses of 17.0 in. and 36.0 in., respectively.

The base course material consisted of limerock except for SR 12 which was constructed with a sand-clay mixture. In most cases the subbase material was stabilized either mechanically or chemically with lime or cement. This layer is conventionally called stabilized subgrade by the FDOT. The underlying subgrade soils were generally sands with clay-silt layers often encountered at depth, as indicated from the penetration tests (*4*). In certain locations (SR 715 and SR 80), clay and organic soil deposits were the primary subgrade layer. Water table locations inferred from the CPT holes are also listed in Table 1.

Most of the pavement sections were uncracked or had limited (hairline) longitudinal and/or transverse cracking. However, US 441 test section did exhibit block cracking even though the pavement structure was very stiff. Some segments of SR 80, a recently constructed highway, were highly distressed due to construction problems that had resulted in potholes, ponding of water, and cracks in the asphalt concrete surface. Therefore, two segments of this roadway were included in this study: section 1, in which there was no visible surface distress, and section 2, in which cracks and potholes were present.

DESCRIPTION OF TESTING PROCEDURES

Testing with the Dynaflect was accomplished using the standard sensor spacing to identify segments of pavement with

TABLE 1 CHARACTERISTICS OF TEST PAVEMENTS

Test Road	County	Mile Post Number	Year*	Pavement Thickness (in.)		Water Table (in.)
				AC	Base	
SR 26A	Gilchrist	11.8-12.0	1930(1982)	8.0	9.0	62
SR 26B	Gilchrist	11.1-11.3	1930(1982)	8.0	7.5	44
SR 26C	Gilchrist	10.1-10.2	1930(1982)	6.5	8.5	33
SR 24	Alachua	11.1-11.2	1976	2.5	11.0	NE**
US 301	Alachua	21.5-21.8	1966	4.5	8.5	45
US 441	Columbia	1.2- 1.4	1960	3.0	9.0	NE
I-10A	Madison	14.0-14.1	1973(1980)	8.0	10.4	NE
I-10B	Madison	2.7- 2.8	1973(1980)	7.0	10.2	NE
I-10C	Madison	32.0-32.1	1973(1980)	5.5	10.2	NE
SR 15A	Martin	6.5- 6.6	1973	8.5	12.5	65
SR 15B	Martin	4.8- 5.0	1973	7.0	12.0	65
SR 715	Palm Beach	4.7- 4.8	1969	4.5	24.0	NE
SR 12	Gadsden	1.4- 1.6	1979	1.5	6.0	NE
SR 80	Palm Beach	Sec. 1 & 2	1986	1.5	10.5	NE

* Year represents the approximate date the road was built. Dates in parentheses are the latest year of reconstruction--overlay, surface treatment, etc.

** Water table not encountered at depth up to 18 ft. Measurements were made using a moisture meter inserted in the holes produced from cone penetration test (CPT).

TABLE 2 TYPICAL DYNAFLECT DEFLECTION DATA FROM TEST SECTIONS

Test Road	Mile Post Number	Deflections (mils)							
		D_1	D_3	D_4	D_6	D_7	D_8	D_9	D_{10}
SR 26A	11.912	0.87	0.81	0.77	0.68	0.61	0.53	0.45	0.39
SR 26B	11.205	1.28	1.18	1.23	1.12	0.99	0.90	0.77	0.68
SR 26C	10.168	0.89	0.77	0.77	0.62	0.53	0.37	0.24	0.16
SR 26C	10.166	0.90	0.77	0.78	0.68	0.54	0.44	0.27	0.17
SR 24	11.102	0.50	0.51	0.50	0.33	0.28	0.22	0.18	0.15
US 301	21.580	0.56	0.50	0.49	0.37	0.34	0.27	0.20	0.15
US 301	21.585	0.62	0.47	0.46	0.35	0.30	0.25	0.18	0.14
US 301	21.593	0.39	0.43	0.42	0.33	0.27	0.23	0.17	0.14
US 441	1.236	0.65	0.68	0.64	0.52	0.45	0.34	0.26	0.22
US 441	1.241	0.73	0.63	0.57	0.45	0.40	0.32	0.25	0.20
I-10A	14.062	0.30	0.29	0.28	0.18	0.16	0.10	0.07	0.05
I-10B	2.703	0.44	0.46	0.40	0.29	0.25	0.17	0.12	0.09
I-10C	32.071	0.70	0.46	0.43	0.30	0.29	0.22	0.18	0.15
SR 15B	4.811	1.10	1.03	1.04	0.91	0.92	0.82	0.75	0.66
SR 15A	6.549	1.50	1.46	1.48	1.40	1.36	1.27	1.14	1.04
SR 715	4.722	1.37	1.29	1.23	1.08	1.02	0.96	0.89	0.81
SR 715	4.720	1.45	1.38	1.36	1.15	1.19	1.07	1.00	0.91
SR 12	1.485	0.86	0.68	0.65	0.44	0.42	0.36	0.27	0.21
SR 80	Sec 1	2.11	2.02	1.89	1.61	1.48	1.37	1.07	0.85
SR 80	Sec 2	2.41	2.15	2.05	1.61	1.48	1.22	0.96	0.74

* Deflections are for both modified and standard geophone positions.

fairly uniform deflection response. Each segment was tested at 25 ft. spacings until three or more locations provided essentially identical deflection basins. The modified Dynaflect sensor array was then used to obtain deflection measurements. These sensors were positioned by hand at locations designated as 1, 4, 7, and 10 (see figure 1). These positions were derived from the analytical studies (*2, 3*) that provided the best response for layer separation. The initial part of the field testing involved placing the extra sensor at position 9 in the modified system (standard position 4). This procedure was later changed to placing one sensor near each Dynaflect loading wheel and the remaining sensors at modified positions 4, 7, and 10. In the latter case, an average value of D_1 was used in the analysis. Table 2 presents typical Dynaflect deflection data for the different test sections.

Temperature measurements were obtained for the ambient air, the surface of pavement, and in the middle of the asphalt concrete pavement layer using a temperature probe. The mean

TABLE 3 TEMPERATURE MEASUREMENTS OF TEST PAVEMENT SECTIONS

Test Road	Mile Post Number	Test Date	Temperature (°F)		
			Air	Surface	Mean
SR 26A	11.912	10-31-85	79	82	81
SR 26B	11.205	11-05-85	45	48	59
SR 26C	10.168	11-05-85	60	60	82
SR 24	11.102	12-03-85	57	55	57
US 301	21.580	2-18-86	63	65	69
US 441	1.236	2-26-86	51	56	79
I-10A	14.062	3-18-86	84	106	104
I-10B	2.703	3-25-86	80	101	88
I-10C	32.071	3-26-86	82	99	106
SR 15A	6.549	4-28-86	88	110	120
SR 15B	4.811	4-28-86	93	111	127
SR 715	4.722	4-29-86	80	88	111
SR 12	1.485	8-12-86	81	91	102
SR 80	Sec 1 & 2	8-19-86	84	96	94

asphalt pavement temperatures, listed in table 3, were taken using the probe to measure the temperature of motor oil that had been poured into a drilled hole in the pavement. The mean pavement temperature measurements were necessary for correction of prediction of asphalt concrete moduli from low temperature viscosity data of the asphalts recovered from pavement cores (*5*).

TUNING OF LAYER MODULI

Moduli for four layer pavement systems were used as input into an elastic layer analysis program (BISAR) for prediction of the Dynaflect deflection basin. Constant power viscosity (n_j) versus temperature relationships were developed using recovered asphalts tested by the Scheweyer Constant Stress Rheometer. The recovered asphalt viscosity corresponding to the average asphalt concrete pavement temperature during Dynaflect testing was used in previously established equations (*5*) to predict the modulus of the asphalt concrete layer (E_1). Values for E_2, E_3, and E_4 were estimated using equations developed from the analytical studies and reported by Ruth and Badu-Tweneboah (*2*) and Ruth et al. (*3*). These modulus values (E_1, E_2, E_3, and E_4) plus layer thicknesses and Poisson's ratios served as the input data for BISAR. The interface conditions between layers were represented as perfectly rough (complete bonding). The BISAR-predicted Dynaflect deflections were then compared to the measured values to determine if any adjustment of the input moduli was necessary to achieve a suitable match of the measured deflection basin. This process of juggling E values is referred to, in this discussion, as tuning.

Figure 2 illustrates measured and predicted deflection basins for US 441, SR 80, and SR 24 test sites. Most of the test sites gave results similar to that of US 441 and SR 80, although some adjustment in one or more of the layer modulus values was required. However, efforts to achieve a better fit between measured and predicted deflections on SR 24 proved to be fruitless. Evaluation of the stratigraphy using the cone penetration test (cone tip resistance and friction ratio) indicated that either variable foundation soils or nonvisible cracks had influenced the deflection response of the pavement. Tables 4 and 5 give the tuned layer moduli and BISAR predicted deflections, respectively, for each of the test sites.

Regression analyses were performed to evaluate the reliability of the BISAR predicted Dynaflect deflections. Figures 3, 4, 5, and 6 present the results of the regression analyses for deflections at modified sensor locations 1, 4, 7, and 10, respectively. In all cases, the high R^2 value ($R^2 > 0.96$) indicated an exceptionally good correlation between predicted and measured deflections. The regression equations for D_4 and D_7 (figures 4 and 5) provided an almost perfect correlation, with the intercept and slope being within 0.015 mils of zero and 0.018 mils of unity, respectively.

The D_1 values (figure 3) tended to yield a slightly higher intercept (0.065) and slope (1.107) which results in the predicted deflections being slightly greater than those measured. There were four test sites where predicted D_1 values were about 0.2 to 0.3 mils greater than the measured D_1 values. This difference may be due to sensor placement variation, the use of single D_1 measurement in the earlier tests, variation in measured D_1 response according to wheel positioning, or where complete tuning was not achieved (e.g., SR 24).

Except at one site, the D_{10} values provided an excellent, highly reliable relationship (figure 6). However, the slope of 0.95 suggests that predicted deflections are about 5 percent less than measured D_{10} values. The discrepancy occurs because the straight line log-log relationship for predicting E_4 from D_{10} (standard D_5) tends to be a curvilinear (hyperbolic) relationship for E_4 values which fall below 1,000 psi or above 200,000 psi (*2*).

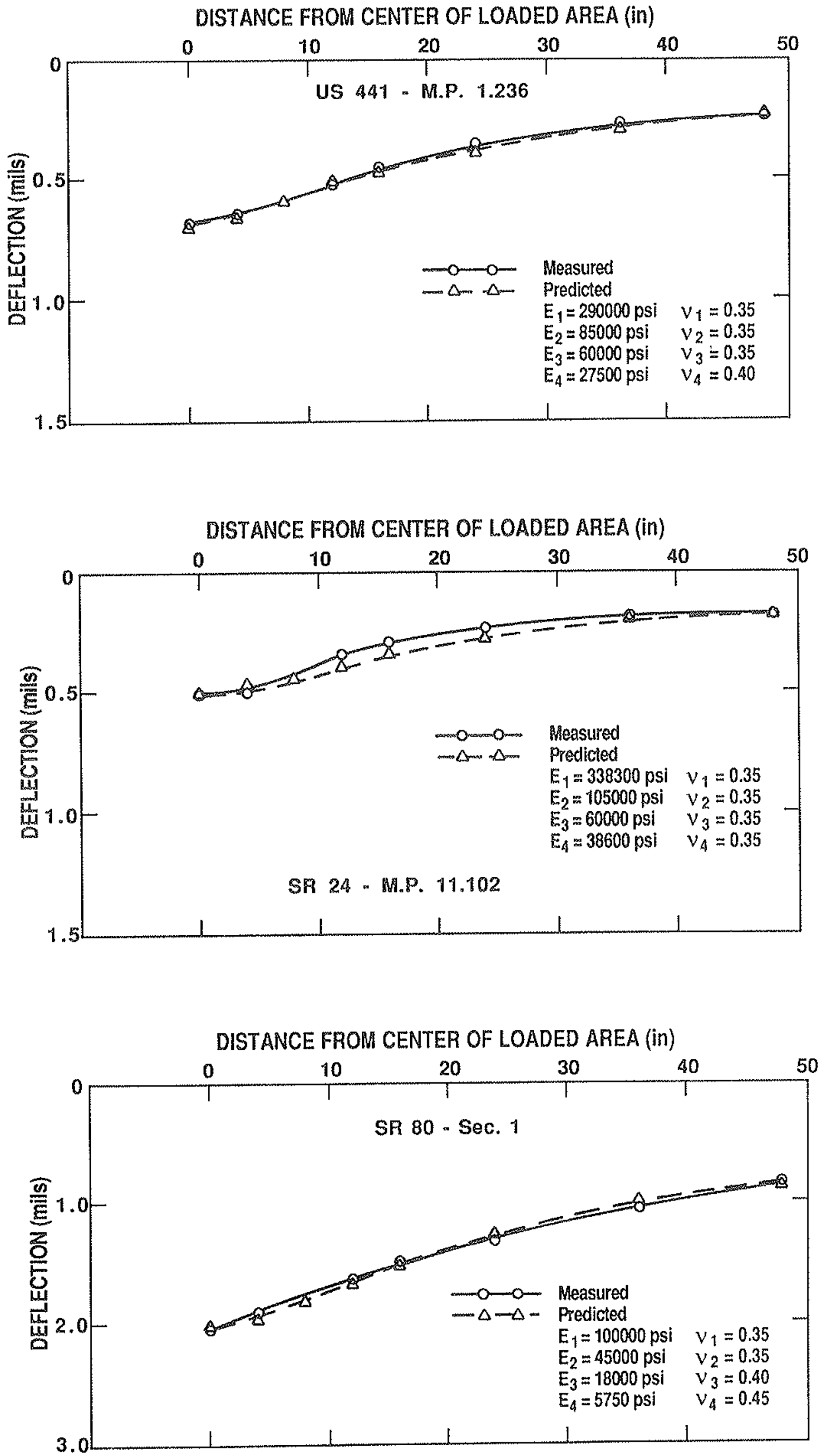


FIGURE 2 Comparison of measured and predicted deflection basins.

TABLE 4 TUNED LAYER MODULI FOR TEST SECTIONS

Test Road	Mile Post Number	Layer Moduli (psi)			
		E_1	E_2	E_3	E_4
SR 26A	11.912	171500	105000	70000	14600
SR 26B	11.205	360000	90000	60000	7900
SR 26C	10.168	171500	55000	35000	28500
SR 24	11.102	338260	105000	75000	38600
US 301	21.580	250000	120000	60000	38600
US 301	21.585	250000	120000	75000	42000
US 301	21.593	250000	130000	80000	44000
US 441	1.236	290000	85000	60000	27500
US 441	1.241	290000	120000	75000	28500
I-10A	14.062	65000	95000	89400	105000
I-10B	2.703	113000	80000	65000	60000
I-10C	32.071	67000	105000	85000	40000
SR 15B	4.811	150000	120000	75000	8100
SR 15A	6.549	150000	120000	40000	4800
SR 715	4.722	92600	75000	50000	6000
SR 715	4.720	92600	65000	45000	5500
SR 12	1.485	400000	120000	75000	26500
SR 80	Sec 1	100000	45000	18000	5750
SR 80	Sec 2	100000	26500	18000	5750

TABLE 5 PREDICTED DEFLECTIONS FROM TUNED LAYER MODULI

Test Road	Mile Post Number	Deflections (mils)									
		D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
SR 26A	11.912	0.95	0.82	0.80	0.78	0.74	0.69	0.64	0.56	0.46	0.38
SR 26B	11.205	1.25	1.19	1.18	1.16	1.12	1.06	1.01	0.90	0.77	0.66
SR 26C	10.168	0.93	0.79	0.76	0.73	0.65	0.56	0.49	0.37	0.26	0.20
SR 24	11.102	0.62	0.50	0.47	0.45	0.40	0.35	0.31	0.25	0.19	0.15
US 301	21.580	0.65	0.54	0.52	0.50	0.45	0.39	0.34	0.27	0.19	0.15
US 301	21.585	0.59	0.49	0.46	0.44	0.40	0.35	0.31	0.24	0.18	0.14
US 301	21.593	0.56	0.46	0.44	0.42	0.38	0.33	0.29	0.23	0.17	0.13
US 441	1.236	0.85	0.71	0.68	0.64	0.58	0.51	0.45	0.36	0.27	0.21
US 441	1.241	0.73	0.62	0.59	0.57	0.52	0.46	0.42	0.34	0.26	0.20
I-10A	14.062	0.70	0.35	0.30	0.27	0.22	0.18	0.15	0.11	0.07	0.05
I-10B	2.703	0.66	0.45	0.42	0.39	0.34	0.28	0.24	0.18	0.13	0.10
I-10C	32.071	0.83	0.50	0.46	0.44	0.398	0.35	0.31	0.25	0.19	0.15
SR 15B	4.811	1.25	1.10	1.07	1.05	1.00	0.96	0.91	0.83	0.72	0.63
SR 15A	6.549	1.71	1.56	1.54	1.52	1.47	1.42	0.36	0.26	0.13	1.00
SR 715	4.722	1.57	1.31	1.27	1.23	1.17	1.10	1.05	0.96	0.86	0.76
SR 715	4.720	1.71	1.45	1.40	1.37	1.29	1.22	1.15	1.05	0.94	0.83
SR 12	1.485	0.87	0.73	0.70	0.67	0.61	0.54	0.48	0.38	0.29	0.22
SR 80	Sec 1	2.49	2.09	2.01	1.94	1.80	1.63	1.49	1.25	1.01	0.85
SR 80	Sec 2	2.92	2.30	2.16	2.07	1.87	1.67	1.50	1.25	1.01	0.86

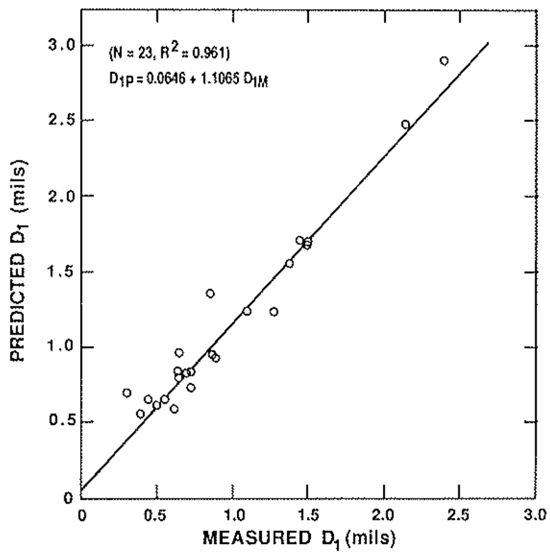


FIGURE 3 Relationship between predicted and measured sensor 1 deflections.

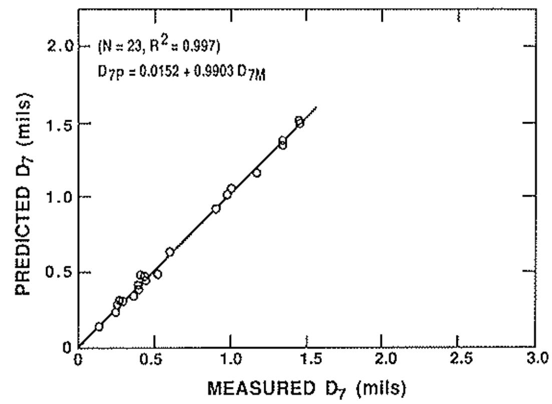


FIGURE 5 Relationship between predicted and measured sensor 7 deflections.

DEVELOPMENT OF SIMPLIFIED LAYER MODULI EQUATIONS

Since the tuned layer moduli provided predicted Dynaflect deflections that correlated exceedingly well with the measured deflections, regression analyses were performed to assess the relationship between

- Composite modulus of asphalt concrete and base course layers (E_{12}) and $D_1 - D_4$.
- Subbase or stabilized subgrade modulus (E_3) and $D_4 - D_7$, and
- Subgrade modulus (E_4) and D_{10}.

As mentioned previously, these sensor deflections were selected from the analytical studies (*2, 3*) because they were related to the moduli of specific layers. It was necessary to combine the asphalt concrete and base course moduli because the analyses had indicated that no sensor location or combination of sensor deflections was suitable for separation of E_1 and E_2. The series of equations (*2, 3*) developed for prediction of either E_1 or E_2 from $D_1 - D_4$, with a reasonable estimate of E_2 or E_1, respectively, albeit their high degree of prediction accuracy, were considered to be too complex for routine evaluation of pavements. Therefore two equations were employed to combine E_1 and E_2 to a composite E_{12} value. The first formula is essentially a weighted average formula, and is of the form

$$E_{12} = \frac{E_1 t_1 + E_2 t_2}{t_1 + t_2} \tag{1}$$

where

E_{12} = composite asphalt concrete and base course modulus,
E_1 = modulus of the asphalt concrete layer,
E_2 = modulus of the base course layer,
t_1 = the thickness of the asphalt concrete layer, and
t_2 = the thickness of the base course layer.

Equation 1, which is a commonly used weighting formula, has been previously utilized by Vaswani (*7*) to combine pavement layers over the subgrade. The second method used to combine E_1 and E_2 follows the approximation suggested by

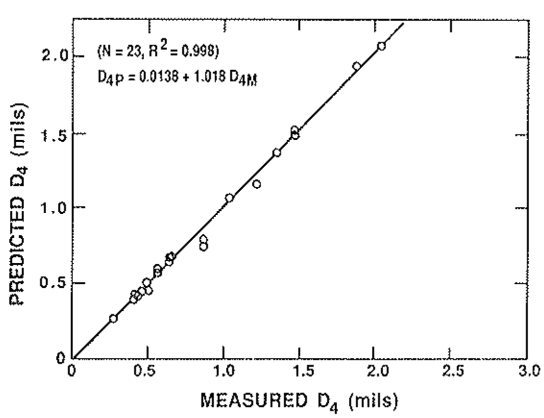


FIGURE 4 Relationship between predicted and measured sensor 4 deflections.

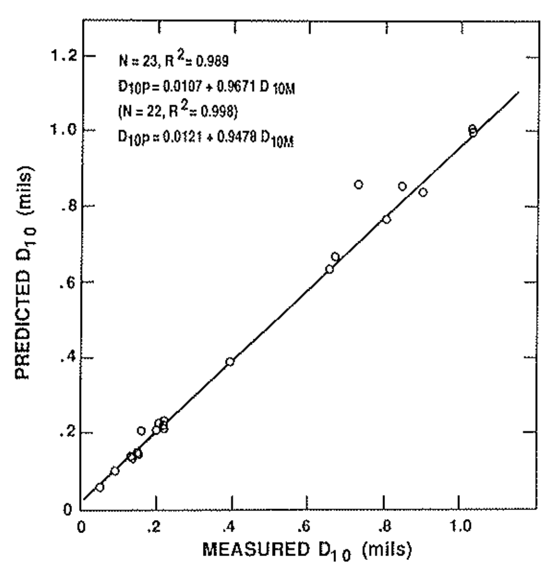


FIGURE 6 Relationship between predicted and measured sensor 10 deflections.

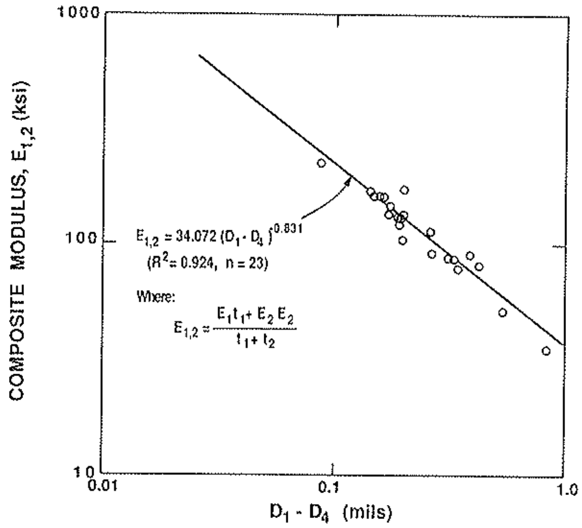


FIGURE 7 Relationship between $E_{1,2}$ (calculated using weighted average formula) and $D_1 - D_4$.

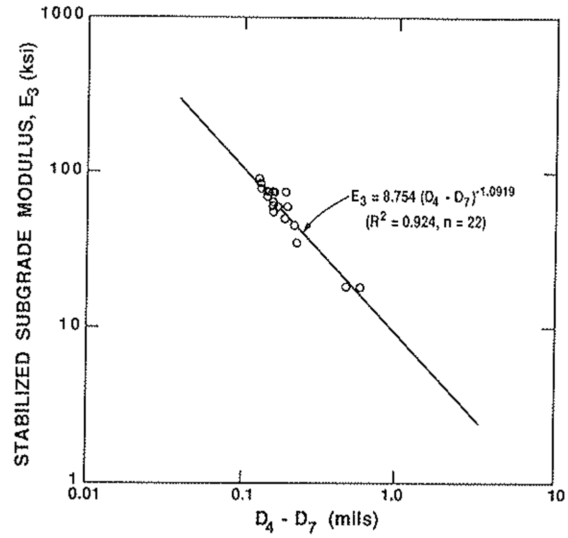


FIGURE 9 Relationship between E_3 and $D_4 - D_7$.

Thenn de Barros (*8*). The equation is of the form

$$E_{12} = \left(\frac{t_1E_1^{1/3} + t_2E_2^{1/3}}{t_1 + t_2}\right)^3 \tag{2}$$

where the variables are as previously defined.

Figures 7 and 8 present the relationships between E_{12} and $D_1 - D_4$ for each of the weighting methods. There is very little difference between modulus deflection relationship for the standard weighting method (Eqn. 1) and the Thenn de Barros formula (Eqn. 2), as shown in figure 7 and figure 8, respectively. It would appear that either method would be suitable for defining E_{12} although the difference between methods is greatest with low E_{12} values and high $D_1 - D_4$ values (e.g., $E_{12} < 34.0$ ksi, and $D_1 - D_4 > 1.0$ mil). As will be shown later, E_2 can be computed directly using E_{12} and either laboratory-measured E_1 values or E_1 values predicted from constant power viscosity (n_j).

The relationship between E_3 and $D_4 - D_7$ is illustrated in figure 9. The results of the regression analysis is fairly good except the range in E_3 values is narrow and limited to only two values below 20 ksi (SR 80). Additional test data in the lower range would be helpful in either verifying the validity of the E_3 prediction equation or modifying the regression equation.

Subgrade modulus prediction equations and the modified Dynaflect sensor 10 deflection values are shown in figure 10. The simplified equation was originally developed using data collected in Quebec, Canada, and Florida (*2*). The results from this earlier study are not included in figure 10. From a practical standpoint, there is very little difference between the E_4 prediction equations. This difference is not significant enough to warrant the use of one equation in preference to the other, except when D_{10} is less than 0.06 mil or much greater than 1.0 mil. Prior analyses (*2, 3*) using the simplified

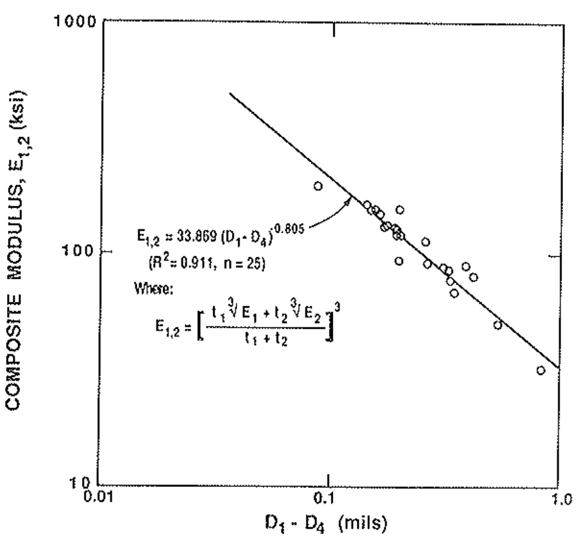


FIGURE 8 Relationship between $E_{1,2}$ (determined using Thenn de Barros' equations) and $D_1 - D_4$.

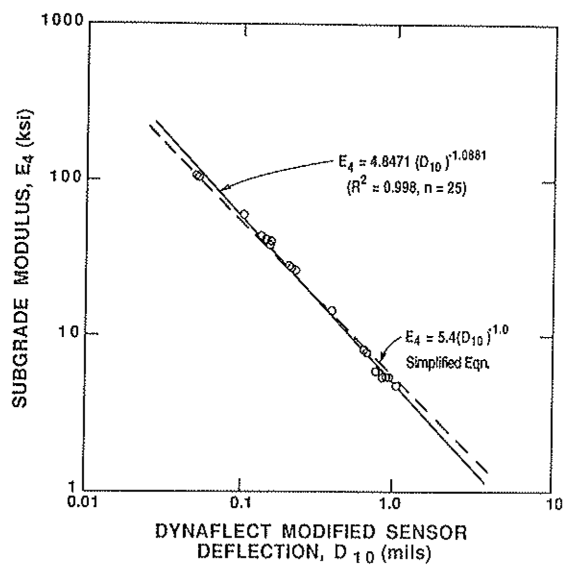


FIGURE 10 Relationship between E_4 and D_{10}.

E_4 prediction equation had indicated overprediction of weak subgrades ($E_4 < 10$ ksi) and underprediction of high or stiff subgrades ($E_4 > 100$ ksi).

The findings from this investigation indicated that separation of loaded areas produces "double bending" which allows for the optimization of sensors to separate layer response. Double bending occurs when two loads are spaced a sufficient distance apart to produce two interacting deflection basins. Proper selection of load and sensor spacing provides deflection measurements that are directly related to the stiffness (modulus) of each pavement layer. Therefore, the unique load-sensor configuration obtained in this study made it possible to develop simplified (power law) equations for prediction of layer moduli. If desired, the predicted layer moduli can be used as "seed moduli" in iterative elastic multilayer computer programs. The results of another investigation demonstrated that predicted E_1 and E_4 values are reliable and seldom require much adjustment or tuning to match the measured deflection basin (*9*). It appears that the most desirable approach in computer simulation is to use E_1 and E_4 as fixed values with predicted E_2 and E_3 values as "seed moduli" for iterative or judgment modified analysis.

RECOMMENDED TESTING AND ANALYSIS PROCEDURES

General testing requirements and procedures for analysis of Dynaflect data for pavement evaluation studies follow:

1. Pavement and air temperature data: Air and pavement surface temperatures can be obtained at suitable intervals during Dynaflect testing using handheld or pocket probe, thermister, thermocouple, or other temperature measuring devices. The mean pavement temperature can be determined by recording the temperature of oil poured into a ⅜- or ½-inch-diameter hole drilled with a masonry bit into the pavement within about a half-inch of the total thickness of the asphalt concrete. One location for a segment of roadway may be sufficient provided that solar radiation and wind effects are fairly uniform and do not vary enough to alter the average temperature more than ±2°F.

It is recommended that conventional pavement response measurements (e.g., Dynaflect) be obtained when pavement temperatures are between 30°F and 85°F. High pavement temperatures may affect the deflection measurements and make it difficult to achieve reliable results. This is particularly true where binder viscosity and E_1 are very low, resulting in excessive volume changes near the loaded area and erroneous deflection measurements.

2. Conduct Dynaflect tests at the desired interval (longitudinal distance) with the sensors at locations conforming to those shown in figure 11. Due to the potential for eccentric loading and variations in pavement response for sensors 1 and 2, it is required that the average value be used in the analysis.

3. Check whether measured deflections are within these limits:

$0.56 \leq D_1$ or $D_2 \leq 2.92$ mil

$0.27 \leq D_3 \leq 2.07$ mil

$0.15 \leq D_4 \leq 1.50$ mil

$0.05 \leq D_5 \leq 1.00$ mil

and also that the following criteria are met:

$0.09 \leq D_1 + D_2 - 2D_3 \leq 0.85$ mil

$0.12 \leq D_3 - D_4 \leq 0.57$ mil

These criteria conform approximately to the following range of layer moduli and thicknesses:

$65.0 \leq E_1 \leq 400$ ksi	$1.5 \leq t_1 \leq 8.5$ in.
$26.0 \leq E_2 \leq 130$ ksi	$6.0 \leq t_2 \leq 24.0$ in.
$18.0 \leq E_3 \leq 90.0$ ksi	$12.0 \leq t_3 \leq 36.0$ in.
$5.0 \leq E_4 \leq 105$ ksi	t_4 = semi-infinite

Note that for the prediction equations, E_i is in ksi, t_i in in., and D_i in mils. Also extremely high or low D_5 values, outside the stipulated range, may be used for estimates of E_4 from 1.0 to 200 ksi.

4. If the above conditions are satisfied proceed to step 5. If not, check deflection measurements and then go to step 3. If the checked deflections do not meet conditions in step 3, proceed to step 5 considering that the predictions may be approximate or significantly in error.

5. Obtain pavement layer thicknesses from construction drawings or by coring.

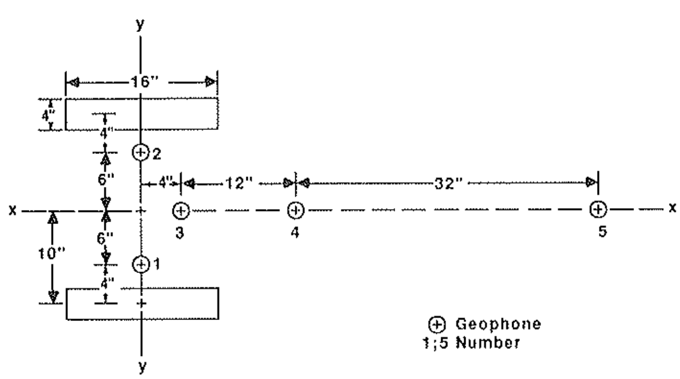


FIGURE 11 Schematic of Dynaflect loading and sensor positions in the modified system.

6. Calculate composite modulus, E_{12} using Equations 3 and 4.

$$E_{12} = 60.611(D_1 + D_2 - 2D_3)^{-0.831} \quad (3)$$

$$E_{12} = 59.174(D_1 + D_2 - 2D_3)^{-0.805} \quad (4)$$

7. Estimate E_1 from recovered asphalt viscosity-temperature-modulus relationships or from dynamic indirect tensile tests on pavement cores (*5, 9*). In Florida, E_1 can be estimated using the relationships illustrated in figure 12. The relationship for pavements with no visible cracks can be used to determine E_1 for the average pavement temperature during Dynaflect testing. If the pavement exhibits extensive cracking (e.g., alligator cracking), E_1 will be reduced considerably, even approaching the modulus (E_2) of the granular base course. It may be impossible to estimate a realistic E_1 value that would simulate the measured deflection basin using elastic layer computer programs.

The relationship for considerable cracking in figure 12 can be used when pavement cracks are spaced sufficiently to eliminate their influence on the Dynaflect deflections. This would apply to pavement sections that have uncracked segments within cracked segments. In this situation higher deflections and lower subgrade or stabilized subgrade moduli may cause the overstressing of these cracked segments. Analysis of the cracked pavements using the E_{1max} relation from uncracked segments could be performed using the E_3 and E_4 values predicted for cracked segments to verify high stress levels and the cause of cracking.

8. If E_1 is known, calculate E_2 using E_{12} from Equation 3 and the explicit form of Equation 1 as follows:

$$E_2 = \frac{E_{12}(t_1 + t_2) - E_1 t_1}{t_2} \quad (1a)$$

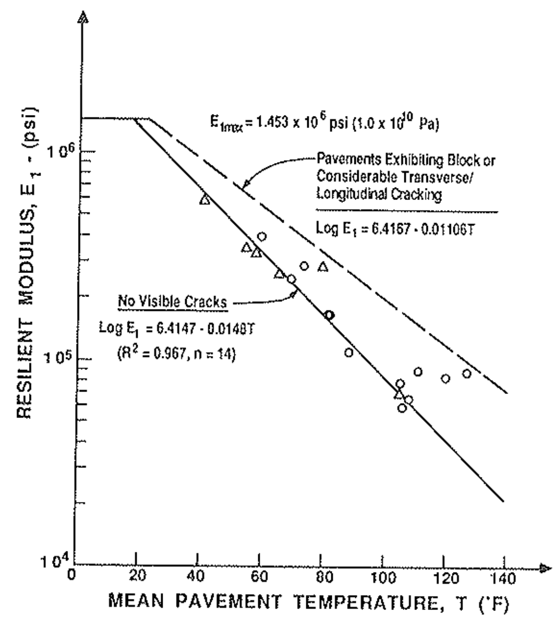


FIGURE 12 Relationship between asphalt concrete modulus E_1 and mean pavement temperature.

9. If E_1 is known, calculate E_2 using E_{12} from Equation 4 and the explicit form of Equation 2 as follows:

$$E_2 = \left[\frac{(t_1 + t_2)(E_{12})^{1/3} - t_1(E_1)^{1/3}}{t_2}\right]^3 \quad (2a)$$

10. Compare E_2 from steps 8 and 9; use an average if possible.

11. If E_1 is unknown, use an average value of E_{12} calculated from Equations 3 and 4, if possible, and $t_1 + t_2$ as composite layer thickness.

12. Calculate E_3 using Equation 5:

$$E_3 = 8.7541\ (D_3 - D_4)^{-1.0919} \quad (5)$$

13. Calculate E_4 from Equation 6:

$$E_4 = 5.40\ (D_5)^{-1.0} \quad (6)$$

Note that in Equations 1 through 6 modulus E_i is in ksi, deflection D_i is in mils, and thickness, t_i in in.

14. Use E_1, E_2, or E_{12}; E_3; and E_4 in an elastic layer computer program to calculate Dynaflect deflections, D_1 through D_5 with coordinates corresponding to that of figure 11. Reasonable values of Poisson's ratio can be assumed without much error on the predicted deflections.

15. Compare measured with predicted deflections; adjust layer moduli to match measured deflections, as required.

The above steps or algorithms have been incorporated into the BISAR elastic layer computer program to perform the iteration after the initial computation of the "seed moduli." The iteration process is interactive and user-specified with respect to the modulus value to be adjusted to achieve the desired tuning.

The FDOT currently has three Dynaflect units, one of which has been modified to meet the system described in this paper. Current plans are to use the standard and modified systems side by side in their research and routine pavement evaluation studies. The Department has also installed microcomputers in the Dynaflect vehicles to allow for on-site assessment of measured data and analysis. With the accumulation of a sufficient data base, it is hoped that the modified system will eliminate the many hassles associated with the interpretation of Dynaflect deflection basins.

APPLICATION EXAMPLE

The following example is provided to illustrate the use of the pavement layer moduli prediction procedures. Dynaflect tests were conducted on SR 24 in Alachua County on January 30, 1987. The air, surface, and mean pavement temperatures during testing were 65°, 62°, and 60°F, respectively. Sensor deflections in the modified system (figure 11) for Milepost 11.122 were 0.83, 0.63, 0.56, 0.32, and 0.16 mils. Pavement layer thicknesses for the asphalt concrete, limerock base, and the stabilized subgrade was determined to be 2.5, 11.0, and 17.0 inches, respectively.

The composite modulus E_{12} was found from Equations 1 and 2 to be 148.6 and 141.0 ksi, respectively, resulting in an average value of 144.8 ksi. The stabilized subgrade and subgrade moduli were computed to be 41.6 ksi and 33.75 ksi, respectively. From figure 12, using a temperature of 60°F, E_1 was

TABLE 6 LAYER MODULI AND PREDICTIONS IN EXAMPLE PROBLEM

a) Layer Moduli

Layer	Modulus (psi)		
	3-Layer*	4-Layer	Tuned
Asphalt Concrete	144790	336000	336000
Limerock Base		108547	95000
Stabilized Subgrade	41587	41587	55000
Subgrade	33750	33750	34000

b) Sensor Deflections

Sensor Number	Measured Deflections	Predicted Deflections (mils)		
		3-Layer	4-Layer	Tuned
1**	0.73	0.755	0.750	0.733
2**	0.73	0.755	0.750	0.733
3	0.56	0.555	0.569	0.534
4	0.32	0.399	0.394	0.365
5	0.16	0.171	0.170	0.167

* Composite modulus, E_{12} is calculated for E_1 and E_2 in the 3-layer case.

** An average value of D_1 and D_2 is used in the analysis.

estimated to be 336.0 ksi. The value of E_2 was then calculated from Equations 1a and 2a to be 105.9 and 111.1 ksi, respectively, with an average of 108.5 ksi being used in the analysis. Table 6 summarizes the layer moduli and BISAR deflection predictions for the calculated or "seed" moduli and the "final" moduli after tuning.

The BISDEF computer program (*10*) was used to compute the moduli of the pavement for comparison purposes. It was not feasible to model the modified sensor configuration (figure 11) in BISDEF, so the corresponding standard array deflections were used. The use of the iterative program required that a rigid layer (E = 1,000,000 psi) be placed at some user-specified depth below the subgrade. The reason for using a finite subgrade thickness, and hence a five-layer system, is to limit the lateral extent of the calculated deflection basins, and presumably it approximates the response of a more realistic subgrade with a modulus of elasticity that increases with depth. Although BISDEF (*10*) recommends a subgrade thickness of 240 in., a value of 999 in. was used in the analysis. It was necessary to simulate the BISAR four-layer solution presented in table 6 as much as possible, and sensitivity analysis (*9*) had shown that there was negligible difference in deflections if a subgrade thickness of 30 ft. or more is used. Also, cone penetration tests (*4*) conducted on that section of highway to a depth of 22 ft. did not indicate the presence of bedrock or a hard layer.

Table 7 lists BISDEF solution using the standard Dynaflect deflections for three input conditions. Case 1, in which BISDEF used its default moduli to determine the four modulus values, predicted unreasonably high E_1 and E_3 values. In case 2, the E_1 value from figure 12 was input into BISDEF and maintained constant, and the iteration process was seeded with the calculated modulus values from the prediction equations for the other layers. The third case is similar to case 2 except that both E_1 and E_4 were kept fixed. It is interesting to note that in all cases, BISDEF predicted higher E_3 than E_2. CPT logs on this site did not indicate any possible weakness of the base course layer.

CONCLUSIONS

A nondestructive testing procedure using a modified Dynaflect sensor configuration has been developed and recommended for flexible pavement evaluation studies in Florida. This technique provides the capability of separating the deflection response of each layer in a four-layer asphalt concrete pavement system. Analyses of Dynaflect data from test pavements with a wide variety of subgrade soils (muck to rock) resulted in the development of simple power law regression equations. The layer modulus prediction equations presented in this paper are applicable to the following range of parameters:

$65.0 \leq E_1 \leq 400$ ksi $1.5 \leq t_1 \leq 8.5$ in.

$26.0 \leq E_2 \leq 130$ ksi $6.0 \leq t_2 \leq 24.0$ in.

$18.0 \leq E_3 \leq 90.0$ ksi $12.0 \leq t_3 \leq 36.0$ in.

$5.0 \leq E_4 \leq 105$ ksi t_4 = semi-infinite

TABLE 7 BISDEF SOLUTION FOR EXAMPLE PROBLEM

a) Layer Moduli

Layer	Modulus (psi)		
	Case 1[(a)]	Case 2[(b)]	Case 3[(c)]
Asphalt Concrete	1000000	336000	336000
Limerock Base	59711	62330	67767
Stabilized Subgrade	150000	80000	80000
Subgrade	28998	35604	34000

b) Sensor Deflections

Sensor Number	Measured Deflections	Predicted Deflections (mils)		
		Case 1[(a)]	Case 2[(b)]	Case 3[(c)]
1	0.55	0.5	0.5	0.5
2	0.35	0.4	0.4	0.4
3	0.23	0.3	0.2	0.3
4	0.19	0.2	0.2	0.2
5	0.16	0.2	0.1	0.2

(a) Using BISDEF's default moduli in the iteration process.

(b) E_1 value fixed and calculated E_2, E_3 and E_4 values (Table 6) used as seed moduli.

(c) E_1 and E_4 fixed, calculated E_2 and E_3 values used as seed moduli in BISDEF.

The advantages of the technique are:

1. An on-board computer (PC) can compute predicted moduli for a four-layer pavement system and print out deflection response and layer moduli profiles superimposed in graphic format for visual interpretation of lineal segments of highway pavement.

2. The deflection response of sensors 1, 2, and 3 (see figure 11) separates the stiffnesses of the asphalt concrete and base course from the underlying support layers. Changes or differences in the average D_1 and D_2 values can be assessed to determine if E_3 or E_4 has produced the change, or if E_{12} indicates stronger or weaker pavement structure.

3. Predicted E_1, E_2, E_3, and E_4 values appear to be more reliable than a four-layer iterative approach.

4. Improved results from iterative procedures seem feasible using predicted layer moduli as "seed moduli" or E_1 and E_4 being fixed with predicted E_2 and E_3 values as the "seed moduli" in the computer iteration process.

REFERENCES

1. H. F. Godwin, and W. G. Miley. Pavement Deflection to Estimate Soil Support Value for Overlay Design. *Proc. First International Symposium on Bearing Capacity and Airfields*, Trondheim, Norway, 1982, pp. 684–691.
2. B. E. Ruth, and K. Badu-Tweneboah. *Non-Destructive Testing for the Structural Characterization of In-Place Pavement Materials*. Final Report: Project 245-D29, Department of Civil Engineering, University of Florida, 1986.
3. B. E. Ruth, E. Puyana, and K. Badu-Tweneboah. Pavement Layer Moduli Evaluation Using Dynaflect. *Proc., Second International Conference on the Bearing Capacity of Roads and Airfields*, Plymouth, England, 1986, pp. 299–308.
4. K. Badu-Tweneboah, J. L. Davidson, B. E. Ruth, and W. G. Miley. Evaluation of Flexible Pavement Substructure. *Proc., VIII Pan-American Conference on Soil Mechanics and Foundation Engineering*, Cartegena, Columbia, 1987, Vol. 3, pp. 27–38.
5. K. Badu-Tweneboah, M. Tia, and B. E. Ruth. Procedures for Estimation of Asphalt Concrete Pavement Moduli at In Situ Temperatures. Presented at 66th Annual Meeting of the Transportation Research Board, Washington, D.C., 1987.
6. B. E. Ruth, M. Tia, and K. Badu-Tweneboah. Factors Affecting the Cracking of Asphalt Concrete Pavements. *Proc., Canadian Technical Asphalt Association*, 1986, Vol. XXXI, pp. 96–109.
7. N. K. Vaswani. Method for Separately Evaluating Structural Performance of Subgrades and Overlying Flexible Pavements. In *Highway Research Record 362*, HRB, Washington, D.C., 1971, pp. 48–62.
8. S. Thenn de Barros. Deflection Factor Charts for Two- and Three-Layer Elastic Systems. In *Highway Research Record 145*, HRB, National Research Council, Washington, D.C., 1966, pp. 83–108.
9. B. E. Ruth, M. Tia, and K. Badu-Tweneboah. *Structural Characterization of In-Place Materials by Falling Weight Deflectometer*. Final Report Project 245-D51. Department of Civil Engineering, University of Florida, 1986.
10. A. J. Bush III, and D. R. Alexander. Pavement Evaluation Using Deflection Basin Measurements and Layered Theory. In *Transportation Research Record 1022*, TRB, National Research Council, Washington, D.C., 1985, pp. 16–28.

Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.