Determination of Layer Moduli Using a Falling Weight Deflectometer

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The increasing popularity of nondestructive pavement evaluation methods, based on interpretation of surface deflections, has prompted the development of several different types of nondestructive testing (NDT) devices. One such device is the falling weight deflectometer (FWD), which was used in the evaluation of layer moduli of three pavement sections. Several methods are currently available to interpret the FWD deflection data and backcalculate the layer moduli. Four methods selected for analysis of the deflection data included VESYS, ELMOD, OAF, and MODCOMP2. A comparison of the material properties determined in the laboratory and the backcalculated values indicated that two of the four methods, namely, VESYS and ELMOD, had great potential for pavement evaluation.

The failure of a pavement before the end of its designed life generally results from loss of strength in one or more layers in the pavement's structure. One method of identifying the weakened layer is to evaluate the material properties of existing in-service pavements.

There are two possible methods for evaluating the material properties. The first is to conduct laboratory testing on either laboratory-compacted specimens or undisturbed samples taken from the pavement. This method is tedious, time consuming, and destructive to the pavement structure. In addition, coring often delays traffic, which is usually unacceptable to the public. Furthermore, it is difficult, if not impossible, to simulate exact states of stress in the laboratory testing of pavement materials.

The second method of evaluating the material properties is by means of nondestructive testing (NDT). NDT consists of making nondestructive measurements on a pavement's surface and inferring, from these measurements, in situ characteristics related to the structural adequacy or loading behavior. Such evaluation of highway pavements is of particular importance to those responsible for the operation and maintenance of these facilities. Providing a quantitative basis for evaluating the pavement's structural condition at any stage of its life is one of the main objectives of nondestructive testing of flexible pavement.

Among the different load responses (stresses, strains, and deflections), the only practical measurements are deflections. Deflection is a basic response of the whole system to the applied load. Also, surface deflection measurements are rapid, relatively inexpensive, and nondestructive. All these factors make NDT attractive and useful.

The increasing popularity of structural evaluation methods based on interpretation of surface deflections has prompted the development of several different types of NDT devices. One such device is the falling weight deflectometer (FWD). It is believed that the FWD provides realistic deflection basin parameters that can be used as an input into a mechanistic pavement model to quickly and adequately determine the structural condition of a given pavement.

RESEARCH APPROACH

In order to evaluate the pavement performance and pavement structural condition at any stage of its life, engineers must be able to reliably predict pavement behavior at any time. Several methods for predicting pavement behavior are currently in use *(1–4)*. Based on the deflection data, these methods predict the pavement modulus. In order to evaluate the reliability of these methods, a group of three pavement sections out of primary roads in North Carolina were selected for analysis.

Material samples were taken from the pavement sections for laboratory testing. In the laboratory, the mechanical properties of the pavement materials were determined by subjecting specimens to a series of dynamic laboratory tests under different environmental conditions.

NDT of the pavement sections was conducted with the aid of the FWD. Using the prediction models, the measured deflection basin was interpreted and characterized properly in order to backcalculate the properties of the layer materials. These backcalculated values were then compared with those determined in the laboratory.

FIELD AND LABORATORY TESTING PROGRAM

In order to test a wide variety of pavement configurations while assuring maximum uniformity of materials and construction procedures, three sections of primary roads across North Carolina were selected as the test sites. Furthermore, two subsections were selected in each of the sections and the test pits (approximately 2 by 5 ft) were excavated across the wheel path of the traffic lanes at selected locations. Subsection 01 represented a section with poor performance, and Subsection 11 represented a section with relatively better performance. Where performance throughout a section was poor, the two Subsections 01 and 02 were selected for the purpose of getting representative materials. After removing the asphalt surface, base course, and 2–4 in. of subgrade, a soil moisture cell was installed to monitor the variation of moisture in the subgrade. Samples of subgrade soil were collected for moisture determination in the laboratory.

Cores from the asphaltic surface layers were removed for laboratory testing. The actual layer thicknesses in each of the selected test subsections are given in Table 1.

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TABLE 1 DESIGN THICKNESS OF TEST SUBSECTIONS

Section No.	Subsection No.	Pavement Layer Thickness (in.)			
		I_2	H	H–B	ABC
US–64	01	3	3	–	7.5
	11	2.80	3	–	7.5
I–40	01	2	3	3	10.0
	02	2	3	3	9.5
US–19	01	2	2	–	13.0
	11	2	2	–	13.0

NOTE: I_2 = asphaltic surface course;
H = asphaltic binder course; H–B = asphaltic base course; ABC = aggregate base course.

FWD Testing Procedures

The FWD used in this study was obtained from Dynatest Consulting, Inc., Ojai, California. The FWD provides an impact load to the pavement. A mass is dropped from an operator-selected height onto a plate that is connected to a base plate by springs *(5)*. FWD deflections are measured with velocity transducers. One of these sensors is located at the center of the loading plate. Six additional sensors are movable and can be placed at any desired distance away from the center of the place. During this testing program, the FWD sensors were placed at 7.87, 11.8, 23.3, 39.3, 55.1, and 70.8 in. away from the center of the loading plate.

At four selected points, closed to the test pits, a complete load sweep test was performed at two different dates. The FWD was operated at three load magnitudes ranging from 6,000 to 12,000 lb.

The air temperature was measured during the testing. The Witczak formula was used to determine from the air temperature the mean pavement temperature at the upper third point of the asphalt layer *(6)*.

The FWD deflection basin is characterized by the following equation:

$$Area = \frac{1}{2}\left(\frac{D_0 + D_1}{D_0}\right)(7.87) + \left(\frac{D_1 + D_2}{2}\right)(3.93) + \left(\frac{D_2 + D_3}{2}\right)(11.8) + \left(\frac{D_3 + D_4}{2}\right)(15.7) + \left(\frac{D_4 + D_5}{2}\right)(15.8) + \left(\frac{D_5 + D_6}{2}\right)(15.7) \qquad (1)$$

where

D_0 = maximum deflection (at the center of the plate);
D_1, D_2, D_3, D_4, D_5, and D_6 = deflections at 7.87, 11.8, 23.6, 39.3, 55.1, and 70.7 in. from the center of the load plate, respectively; and
$Area$ = normalized deflection basin area (in.^{2}).

Laboratory Testing

Laboratory testing was performed to determine the resilient modulus of each layer of the pavement test sections. Asphalt concrete samples cored from the pavement sections were 4 in. in diameter, with a height equal to the pavement's thickness. A diamond saw was used to cut and slice the cores into sections corresponding to the structure of the layer. The resilient modulus values in the indirect tension mode were determined at temperatures of 0°F, 30°F, 50°F, 70°F, 90°F, and 120°F.

Cylindrical samples of base course and subgrade soil were recompacted and tested under dynamic load in a triaxial cell. The resulting characterization was a stress-dependent resilient modulus for different moisture contents. The test procedures are described by Khosla *(7)*.

MODULI CALCULATION METHODS

Four procedures were used to backcalculate the modulus values. The procedures involve the initial calculation of deflection parameters using the measured deflection profile. Then the estimation of in situ stiffness of pavement layer is carried out using a graphical solution or a computer program. In the following section, various procedures for backcalculating the resilient modulus of the pavement layers are discussed.

Graphical Procedures

The VESYS program was used as part of this research to develop a graphical procedure for backcalculating the pavement parameters. The VESYS model incorporates the viscoelastic and fatigue properties of the pavement materials. For the analysis of existing pavement systems, algorithms were developed that can be used with measured load deflection data and known material thickness or properties.

The algorithms were developed by applying statistical regression analysis techniques to the VESYS-generated response data. The same principle of developing nomographs was used by Hoffman and Thompson *(3)*, except that their nomographs were based on data generated by the finite element program ILLI-PAVE. VESYS data were generated for 1,920 pavement configurations. These included pavements with asphalt concrete (AC) thickness (T_{AC}) of 2, 3.5, 5, 6, and 8 in. Granular base thicknesses (T_{base}) were 5, 7, 9, 11, 13, and 16 in. These thicknesses are representative of the range of typical flexible pavement designs. Four levels of subgrade moduli of resilience (MR_{soil}), (1,000, 3,000, 7,000, and 11,000 psi), four levels of AC modulus of resilience (MR_{AC} = 100,000, 250,000, 500,000, and 1,000,000 psi), and five levels of base course modulus (MR_{base} = 15,000, 20,000, 25,000, 30,000, and 35,000 psi) were evaluated for different group combinations of granular base resilient moduli and asphalt concrete granular base thicknesses.

A constant load of 9,000 lb was maintained throughout the study to account for one-half of the 18-kip, single-wheel load commonly used for design. In mathematical representation, the load was applied on top of the upper layer and uniformly distributed over a circular contact area of 6-in. radius the same as the loading plate on the FWD.

The predictive equations were developed based on multiple regression techniques relating the dependent variables (D_0, *Area)* to the four independent variables (MR_{AC}, MR_{soil}, T_{AC}, and T_{base}). The regression equations were optimized to yield good predictive equations. The following groups were obtained (see Table 2):

1. Group A for pavements with base course moduli in the 15,000–20,000 psi range.
2. Group B for pavements with base course moduli in the 20,000–25,000 psi range.
3. Group C for pavements with base course moduli in the 25,000–30,000 psi range.
4. Group D for pavements with base course moduli in the 30,000–35,000 psi range.

Each group was divided into four subgroups according to asphalt concrete and base course thicknesses as follows:

- Subgroup 1 includes pavements with AC layers between 2 and 3.5 in. thick and base course layer thicknesses of 11 in. and less.
- Subgroup 2 includes pavements with AC layers between

TABLE 2 VESYS DEFLECTION BASIN ALGORITHMS

Dependent Variable	R^2	σ	O	A	B	$C \times 10^{-3}$	$D \times 10^{-3}$
Group A Subgroup A1: $2 \leq T_{AC} \leq 3.5$ and $5 \leq T_{base} \leq 11$							
Log D_0	0.8947	0.00660	2.54302	–0.07690	–0.01536	–0.00152	–0.05650
Area	0.8926	3.20000	18.62890	2.35430	0.23410	0.00485	–1.14756
Subgroup A2: $3.5 \leq T_{AC} \leq 6$ and $5 \leq T_{base} \leq 13$							
Log D_0	0.8919	0.00711	2.46114	–0.05649	–0.01102	–0.00021	–0.05643
Area	0.9165	2.61170	20.82290	1.74453	0.01079	0.00687	–1.13039
Subgroup A3: $3.5 \leq T_{AC} \leq 6$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8876	0.00709	2.42531	–0.05493	–0.00883	–0.00021	–0.05530
Area	0.9060	2.85970	22.04200	1.70225	0.00829	0.00678	–1.12581
Subgroup A4: $5 \leq T_{AC} \leq 8$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8823	0.00770	2.35864	–0.04227	–0.00770	–0.00023	–0.05632
Area	0.8917	2.98400	24.88840	1.11373	–0.02676	0.00735	–1.03941
Group B Subgroup B1: $2 \leq T_{AC} \leq 3.5$ and $5 \leq T_{base} \leq 11$							
Log D_0	0.8859	0.00660	2.51110	–0.07018	–0.01804	–0.00014	–0.05709
Area	0.9067	2.75080	19.43320	2.27395	0.27868	0.00465	–1.16114
Subgroup B2: $3.5 \leq T_{AC} \leq 6$ and $5 \leq T_{base} \leq 13$							
Log D_0	0.8933	0.00705	2.42912	–0.05270	–0.01256	–0.000192	–0.05730
Area	0.8878	3.35700	21.84990	1.62080	0.09244	0.00668	–1.09810
Subgroup B3: $3.5 \leq T_{AC} \leq 6$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8886	0.00705	2.38590	–0.05080	–0.00984	–0.00019	–0.05624
Area	0.8886	3.21870	22.71080	1.56320	0.02731	0.00675	–1.08740
Subgroup B4: $5 \leq T_{AC} \leq 8$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8838	0.00767	2.31880	–0.03834	–0.00860	–0.00021	–0.05723
Area	0.8851	2.99180	25.24160	0.96940	0.02407	0.00737	–1.00560
Group C Subgroup C1: $2 \leq T_{AC} \leq 3.5$ and $5 \leq T_{base} \leq 11$							
Log D_0	0.8973	0.00650	2.48875	–0.06582	–0.01986	–0.00013	–0.05746
Area	0.9072	2.73640	20.49120	2.07104	0.32778	0.00420	–1.18234
Subgroup C2: $3.5 \leq T_{AC} \leq 6$ and $5 \leq T_{base} \leq 13$							
Log D_0	0.8926	0.00710	2.40620	–0.04934	–0.01402	–0.00018	–0.05730
Area	0.9195	2.26060	23.03600	1.44380	0.13460	0.00621	–1.11380

TABLE 2 *continued*

Dependent Variable	R^2	σ	O	A	B	$C \times 10^{-3}$	$D \times 10^{-3}$
Subgroup C3: $5 \leq T_{AC} \leq 8$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8879	0.00710	2.36110	−0.00047	−0.01109	−0.00018	−0.05652
Area	0.9185	2.19200	24.36950	1.36618	0.02819	0.00627	−1.09390
Subgroup C4: $5 \leq T_{AC} \leq 8$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8829	0.00770	2.30230	−0.03654	−0.00977	−0.00020	−0.05745
Area	0.9066	2.24470	26.54050	−0.89392	−0.00352	−0.00688	−0.99435
Group D Subgroup D1: $2 \leq T_{AC} \leq 3.5$ and $5 \leq T_{base} \leq 11$							
Log D_0	0.8981	0.00650	2.46624	−0.06146	−0.02164	−0.00012	−0.05780
Area	0.9096	2.60990	21.43700	1.91125	0.36021	0.00398	−1.18420
Subgroup D2: $3.5 \leq T_{AC} \leq 6$ and $5 \leq T_{base} \leq 13$							
Log D_0	0.8927	0.00713	2.3840	−0.04644	−0.01537	−0.00017	−0.05790
Area	0.9116	2.37410	23.9829	1.33270	0.12955	0.00589	−1.09118
Subgroup D3: $3.5 \leq T_{AC} \leq 6$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.888	0.00716	2.33571	−0.04432	−0.01213	−0.00017	−0.57017
Area	0.9135	2.19490	25.16870	1.26623	0.03536	0.00592	−1.06948
Subgroup D4: $5 \leq T_{AC} \leq 8$ and $7 \leq T_{base} \leq 16$							
Log D_0	0.8833	0.00776	2.28040	−0.03442	−0.01071	−0.00019	−0.05792
Area	0.8951	2.36660	27.14670	0.81903	−0.00324	0.00657	−0.96330

NOTE: Equation of the form: Dependent variable = O + $A\ T_{AC}$ + $B\ T_{base}$ + $C\ MR_{AC}$ + $D\ MR_{soil}$.

3.5 and 6 in. thick and base course layer thicknesses of 13 in. and less.

- Subgroup 3 includes pavements with AC layers between 3.5 and 6 in. thick and base course layers between 7 and 16 in.
- Subgroup 4 includes pavements with AC layers between 5 and 8 in. thick and base course layers between 7 and 16 in.

The equations in Table 2 for Groups A through D are reproduced in nomographical form. A typical set of nomographs is shown in Figures 1 and 2.

The resilient modulus of the granular base course is relatively insensitive to moisture content and temperature when compared with the resilient modulus of asphalt and the subgrade. Therefore, the VESYS model was used to backcalculate MR_{AC} and MR_{soil}, while prediction equations were developed to determine the MR_{base}. Regressions were performed on the re-

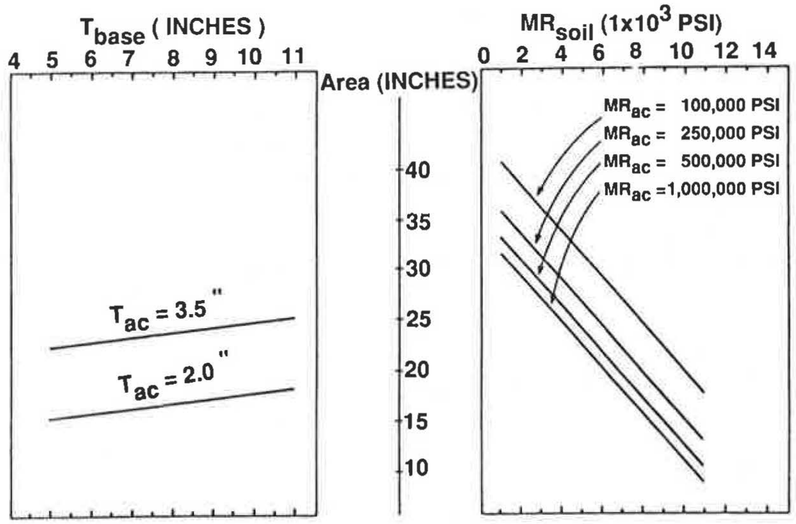

FIGURE 1 Nomograph based on area—Group A1.

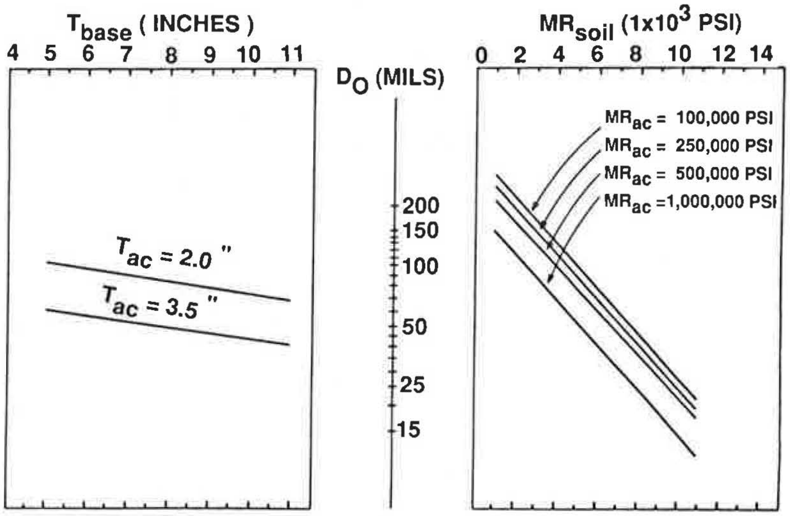

FIGURE 2 Nomograph based on D_0—Group A1.

silient modulus values of the base course to determine the constants of the following relationship for different seasons:

$$\log (MR) = A + B \log \theta \qquad (2)$$

where

MR = resilient modulus,
θ = sum of principal stresses, and
A, B = constants.

The values of the regression constants to predict MR_{base} are shown in Table 3.

Moduli Calculation Using Computer Programs

The FWD load deflection was analyzed using the ELMOD computer program. ELMOD is capable of determining the moduli of the asphalt layer, base course, plus the surface modulus, and the nonlinear parameters C_0 and N of the subgrade *(4)*.

The surface modulus is given by the following relationship:

$$E_0 = c_0 \left(\frac{\sigma}{\sigma'}\right)^N \qquad (3)$$

where

E_0 = surface modulus,
σ = major principal stress,
σ' = a reference stress, and
C_0, N = constants.

The surface modulus (the modulus of the half-space that would give the same surface deflection as the multilayer structure) is calculated at distance r for the known loading conditions and the measured deflection value of $d(r)$ as follows:

$$E_0 = \frac{(1 - r^2)\, \sigma_0 a^2}{r\, d(r)} \qquad (4)$$

where

r = Poisson ratio,
σ_0 = contact stress, and
a = radius of the loaded area.

Using Equation 3 and the following equations, the resilient modulus of the subgrade MR can be calculated.

$$MR = C \left(\frac{\sigma}{\sigma'}\right)^N \qquad (5)$$

$$c = \left(\frac{C_0}{1 - 2N}\right) \qquad (6)$$

The OAF program has been developed to accommodate the

TABLE 3 SUMMARY OF REGRESSION RESULTS

Section No.	Winter		Spring		Summer		Fall	
	A	B	A	B	A	B	A	B
US–64	3,950.0	0.495	4,470.0	0.450	5,750.0	0.412	3,050.0	0.567
I–40	2,900.0	0.5775	3,350.0	0.522	3,800.0	0.510	1,200.0	0.633
US–19	6,500.0	0.356	6,060.0	0.357	8,300.0	0.350	5,500.0	0.416

deflection results from FWD. The procedure is required to measure deflection at 0, 30, 60, and 100 cm from the applied load.

Layer moduli are determined for a specific site by inputting the following information into a computer program making use of the ELSYM program for stresses and deformations in multilayer elastic systems *(1)*:

1. Surface deflection measurements and load configurations,
2. Base type,
3. Layer thickness,
4. Poisson ratio for all layers, and
5. Asphalt concrete modulus at test temperature.

Essentially, the program solves for the moduli of the various layers by attaining compatibility between measured and computed deflections at the locations for which deflection data were acquired in the field.

The MODCOMP2 program can handle up to eight surface deflections for each load level, measured at various radial distances from the center of the load *(2)*.

1. Surface deflection and radial distances of geophones from the center of the load,
2. Load values,
3. Poisson ratio,
4. Base and soil type, and
5. Seed modulus for the pavement layers.

The computed deflections are compared with measured deflection, and the seed moduli are adjusted as a function of the magnitude of the difference in deflections. This process is repeated until agreement between the difference of the computed and measured deflection is within the specific tolerance. The tolerance specified for this analysis was 5 percent.

VERIFICATION PROCEDURE

All of the six subsections were used to validate and verify the four procedures discussed in the previous section. Each location had the conventional flexible pavement design consisting of an AC surface, granular base, and a fine-grained subgrade.

A comparison of the backcalculated material properties with laboratory values was used in the validation procedure.

The resilient modulus of the base course depends upon the state of stress and moisture content. The resilient modulus corresponding to a representative moisture content and 50 psi of bulk stress was determined. A value of 50 psi represents the state of stress in the field as determined by the CHEV5L multilayer elastic computer program.

The resilient modulus of fine-grained subgrade depends upon the deviator stress and moisture content. The resilient modulus corresponding to the representative moisture content at the time of testing and the deviator stress of 6 psi were selected.

From both laboratory and backcalculated results summarized in Tables 4–9, the following observations could be made:

1. From the backcalculated MR_{AC} values and the pavement temperature at the time of deflection testing, it is evident that the modulus values increase with a reduction in temperature values. Thus, there is a logical trend in the variation of MR_{AC} with the temperature values.

2. From the backcalculated MR_{soil} values by VESYS and the soil moisture condition, it is evident that the modulus values increase with a reduction in moisture content. Thus, there is a logical pattern in the variation of MR_{soil} with the moisture content.

3. The backcalculated MR_{AC} values ranged from 119,750 to 600,200 psi, depending on the testing time and prediction method. There was a significant variation in backcalculated MR_{AC} as determined by different approaches.

TABLE 4 SUMMARY OF FIELD MEASUREMENTS AND LABORATORY-RESILIENT MODULUS VALUES FOR US-64 SECTION

		Field Measurements			Laboratory Resilient Modulus Values (psi)		
Sub-section No.	Date of Testing	Pavement Temp (°F)	Base Moisture (%)	Soil Moisture (%)	Asphalt-Concrete	Base	Soil
01	April '85	93	5.3	20.1	258000	26000	6700
	Aug '85	90	4.6	19.17	263000	27000	7500
11	April '85	100	5.3	18.9	200000	26000	4600
	Aug '85	93	4.6	17.9	258000	27000	6500

TABLE 5 SUMMARY OF BACKCALCULATED RESILIENT MODULUS VALUES FOR US-64 BY USING VESYS, ELMOD, MODCOMP2, AND OAF MODELS

		Backcalculated Resilient Modulus Values (psi) Using											
		ELMOD			VESYS			MODCOMP2			OAF		
Sub-section No.	Date of Testing	Asphalt Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil
01	April '85	165000	34500	6295	240000	26000	9100	126320	10099	20025	150370	3980	36145
	Aug '85	175000	49500	6785	350000	28000	9500	193000	6260	24720	172970	3990	42840
11	April '85	119750	18000	4370	250000	26000	6000	187900	11380	5870	185350	1760	13740
	Aug '85	143750	32750	4970	300000	28000	7300	314150	5460	9460	251300	2605	18025

TABLE 6 SUMMARY OF FIELD MEASUREMENTS AND LABORATORY-RESILIENT MODULUS VALUES FOR I-40 SECTION

		Field Measurements			Laboratory Resilient Modulus Values (psi)		
Sub-section No.	Date of Testing	Pavement Temp (°F)	Base Moisture (%)	Soil Moisture (%)	Asphalt-Concrete	Base	Soil
01	May '85	78	5.6	10.0	577300	25000	9200
	Sept '85	86	4.8	11.0	384000	26000	7800
02	May '85	90	5.6	18.5	223900	25000	4300
	Sept '85	83.5	4.8	20.4	319000	26000	2500

TABLE 7 SUMMARY OF BACKCALCULATED RESILIENT MODULUS VALUES FOR I-40 BY USING VESYS, ELMOD, MODCOMP2, AND OAF MODELS

		Backcalculated Resilient Modulus Values (psi) Using											
		ELMOD			VESYS			MODCOMP2			OAF		
Sub-section No.	Date of Testing	Asphalt Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil
01	May '85	455250	24500	10250	600000	25800	9800	*	*	*	600200	2730	29880
	Sept '85	426250	29250	9500	450000	27400	9200	691230	1423	10104	225880	2650	13840
02	May '85	290250	32000	5500	300000	25800	5800	*	*	*	383000	4630	11110
	Sept '85	350000	29250	3500	400000	27400	5200	425450	48600	3740	515680	2190	13700

*MODCOMP2 could not backcalculate the resilient modulus values from the deflection data because the program would not converge within the tolerance limit (5 to 10%).

TABLE 8 SUMMARY OF FIELD MEASUREMENTS AND LABORATORY RESILIENT MODULUS VALUES FOR US-719 SECTION

		Field Measurements			Laboratory Resilient Modulus Values (psi)		
Sub-section No.	Date of Testing	Pavement Temp (°F)	Base Moisture (%)	Soil Moisture (%)	Asphalt-Concrete	Base	Soil
01	May '85	95	6.2	18.4	345000	23500	4000
	Sept '85	88	5.8	18.0	454000	24500	5100
11	May '85	87	6.2	14.8	454600	23500	5200
	Sept '85	85	5.8	15.0	516500	24500	3700

4. The backcalculated resilient moduli of the pavement layers by the ELMOD and VESYS models and laboratory values, for test locations 01 and 11 at different times of testing, were in good agreement.

5. It can be seen that OAF and MODCOMP2 backcalculated lower values of resilient moduli for the base course (MR_{base}) than for the soil, conflicting with the principle of flexible pavements.

CONCLUSIONS

The following conclusions are based on the summary of *MR* methods given in Table 10.

1. ELMOD and VESYS models exhibited greater agreement with the principles of flexible pavement behavior than did OAF and MODCOMP2.

2. In general, backcalculated MR_{AC} values using the four models followed a logical trend in their variation with temperature.

3. The backcalculated MR_{soil} values using the VESYS, ELMOD, and MODCOMP2 models followed a more logical trend in their variation with moisture content as compared with the values arrived at by using the OAF model.

4. The backcalculated *MR* values using the VESYS model had the least variation from laboratory values with the ratio MR_{lab}/MR_{pred} range between 0.48 and 1.08 and most values between 0.77 and 0.97. The values for ELMOD varied between 0.54 and 1.56, with most values between 0.80 and 1.26. The largest variations in the ratio of MR_{lab}/MR_{pred} were exhibited by those values predicted by MODCOMP2 and OAF models. The ratio of MR_{lab}/MR_{pred} for MODCOMP2 ranged from 0.1 to 18.2 with most of the values between 0.55 and 5.61. The MR_{lab}/MR_{pred} ratio for OAF ranged between 0.18 and 14.80, with most values between 0.32 and 9.80. It is possible that developers of these programs could tailor their input in the program to give better results. Perhaps keeping the specified tolerance limit to a low level such as 1 percent or lower, instead of 5–10 percent, could improve the accuracy of the predicted modulus values.

5. From the preceding, it can be seen that VESYS and ELMOD are more suitable for prediction of pavement layer moduli.

TABLE 9 SUMMARY OF BACKCALCULATED RESILIENT MODULUS VALUES FOR US-19 BY USING VESYS, ELMOD, MODCOMP2, AND OAF MODELS

		Backcalculated Resilient Modulus Values (psi) Using											
		ELMOD			VESYS			MODCOMP2			OAF		
Sub-section No.	Date of Testing	Asphalt Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil	Asphalt-Concrete	Base	Soil
01	May '85	338250	22000	4029	355000	25000	6100	584013	7650	7040	500320	5440	9860
	Sept '85	502400	25500	4825	500000	27900	6000	986320	4360	14685	913810	6330	12800
11	May '85	472500	27750	4871	450000	25000	7500	1118170	1415	51440	650800	5795	11165
	Sept '85	535250	34750	4244	500000	27900	6700	918340	4360	14945	952780	3870	15970

TABLE 10 SUMMARY OF BACKCALCULATED *MR* METHODS

			US 64		I-40		US 19	
			01	11	01	02	01	11
ELMOD	In accordance with the principles of flexible pavement behavior[a]		Yes	Yes	Yes	Yes	Yes	Yes
	Logical backcalculated MR_{ac} versus temperature trend[b]		Yes	Yes	Yes	Yes	Yes	Yes
	Logical backcalculated MR_{soil} versus moisture content[c]		Yes	Yes	Yes	Yes	Yes	Yes
	Range of ratio MR_{lab}/MR_{pred}[d]	Min. Ratio	.54	0.82	0.82	.73	0.90	0.71
		Max. Ratio	1.56	1.80	1.26	0.91	1.06	1.07
VESYS	In accordance with the principles of flexible pavement behavior[a]		Yes	Yes	Yes	Yes	Yes	Yes
	Logical backcalculated MR_{ac} versus temperature trend[b]		Yes	Yes	Yes	Yes	Yes	Yes
	Logical backcalculated MR_{soil} versus moisture content[c]		Yes	Yes	Yes	Yes	Yes	Yes
	Range of ratio MR_{lab}/MR_{pred}[d]	Min. Ratio	0.74	0.77	0.85	0.48	0.65	0.55
		Max. Ratio	1.08	1.00	0.97	0.97	0.97	1.03
MODCOMP2	In accordance with the principles of flexible pavement behavior[a]		No	No	No	Yes	No	No
	Logical backcalculated MR_{ac} versus temperature trend[b]		Yes	Yes	N/A	N/A	Yes	No
	Logical backcalculated MR_{soil} versus moisture content[c]		Yes	Yes	N/A	N/A	Yes	Yes
	Range of ratio MR_{lab}/MR_{pred}[d]	Min. Ratio	.23	.68	0.55	0.53	.35	0.1
		Max. Ratio	4.31	4.94	18.2	0.73	5.61	16.6
OAF	In accordance with the principles of flexible pavement behavior[a]		No	No	No	No	No	No
	Logical backcalculated MR_{ac} versus temperature trend[b]		Yes	Yes	Yes	Yes	Yes	Yes
	Logical backcalculated MR_{soil} versus moisture content[c]		Yes	Yes	Yes	No	Yes	No
	Range of ratio MR_{lab}/MR_{pred}[d]	Min. Ratio	0.18	0.33	0.32	0.18	0.40	0.24
		Max. Ratio	6.76	14.80	9.80	11.90	4.32	6.33

[a] Flexible pavements consist of a layered load-distributing system with the highest quality (stiffest) materials uppermost.

[b] Since AC is a thermoplastic material, the logical trend for MR_{ac} is inversely proportional to increasing temperature.

[c] The modulus of resilience for fine-grained soils is inversely proportional to increasing moisture content.

[d] The ratio $MR_{lab}/MR_{predicted}$ gives an indication of over/underestimation of the different procedures. Values closest to unity indicate greatest agreement.

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