tional research is needed to extend the usefulness of the equation to a wider range of subgrade materials. Once additional research has verified or modified these findings, use of this constitutive equation for predicting permanent strain should result in significant saving of laboratory time and equipment because only static triaxial test results are required for its use. Also, rational methods of pavement design, which require characterization of permanent strain behavior, will be more likely to gain quick acceptance by practicing engineers if they have available such a simple means of predicting permanent strain.

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Abridgment

Evaluation of In Situ Elastic Moduli from Road-Rater Deflection Basin

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This paper presents a computer method for evaluating the in situ modulus of pavement layers from road-rater deflection basins. The method that is developed on the basis of the results of a theoretical analysis uses the bitumen-structures-analysis-in-roads (BISAR) computer program and the procedure of successive approximation. The method was used to evaluate the in situ modulus of experimental pavements at the Pennsylvania Transportation Research Facility. The computed modulus values were analyzed statistically to determine the factors that most significantly influence the in situ modulus of each pavement layer. Results indicate that, for the bituminous concrete surface and base materials, the sum of pavement surface temperature and the average five-day air temperature prior to the deflection measurements is the most significant among the factors analyzed. For the subbase material, no single influential factor is identified as significant. The subgrade modulus is influenced most by the subgrade water content, as expected.

One major difficulty in response analysis of pavement structure is to determine the elastic moduli of pavement constituent layers. Two methods are currently available for modulus determination. One method is by means of laboratory testing on specimens either compacted in the laboratory or extracted from the pavement structure; the other method is by nondestructive testing on the pavement surface. Because of its relative ease in data collection in addition to the advantage of nondestruction to the pavement structure, the method of using surface-deflection basins to determine elastic modulus is preferred. Further, of the various instruments available for surface-deflection measurement, the road rater has received increased use due to its relatively high degree of mobility. For these reasons, this paper presents a method for evaluating the in situ elastic modulus from road-rater surface-deflection basins.

Table 1. Variation of surface deflection with layer modulus.

	Surface Deflections [x 10^{-7} in (lb/in^2)]			
Moduli	$\partial\delta_1$	$\partial\delta_2$	$\partial\delta_3$	$\partial\delta_4$
∂E_1	0.009 00	0.000 23	0.000 08	0.000 00
∂E_2	0.019 67	0.004 67	0.000 10	0.000 00
∂E_3	0.006 10	0.004 20	0.001 80	0.000 01
∂E_4	0.510 00	0.470 00	0.410 00	0.326 00

Note: Variations are derived by dividing the surface deflections by the moduli.

THEORETICAL CONSIDERATIONS

The majority of available solutions for evaluating elastic modulus from surface-deflection basins has been limited to two-layer pavement systems (1,2). For three-layer systems, assumptions have been made so that essentially only two modular ratios are unknown (3). Because explicit equations of surface deflection as a function of elastic modulus are available only for a maximum of three elastic layers (4), Burmister's approach (5) is used to formulate such equations for flexible pavements that contain surface, base, subbase, and subgrade.

In the formulation, the pavement is idealized as an elastic system composed of three elastic layers that overlay the elastic half space, and the traffic loading is represented by a uniform circular loading. With this axisymmetrical loading condition, the surface deflection can be determined from the equilibrium and compatibility equations. The general expression contains Airy's stress function (ϕ), which is defined as follows:

$$\phi = J_o(mr)(A_i e^{mz} - B_i e^{-mz} + C_i Z e^{mz} - D_i Z e^{-mz}) \quad (1)$$

where m is a parameter and J_o (mr) is a Bessel function of the first kind of order zero. A_i, B_i, C_i, and D_i are constants that must be chosen to satisfy the boundary conditions and the biharmonic equation $\nabla^4 \phi = 0$. The subscript i refers to the number of layers under consideration; r and z are radial and vertical coordinates.

Equation 1 indicates that there are four unknowns for each layer and, therefore, a total of 16 unknowns for a four-layer system. However, since the stresses and displacements are very small when Z approaches infinity, 2 unknowns equal zero, and the total number of unknowns becomes 14. These 14 unknowns may be solved from 14 equations that can be derived from the following boundary conditions:

1. At the top of the surface layer, the shearing stress equals zero;
2. At the top of the surface layer within the loaded area, the normal stress equals the applied pressure; and
3. At interlayer contacts, a welded bond is assumed (with this assumption, the vertical and radial displacements and vertical and shear stresses above and below the interface must be equal; thus, there are 4 equations at each interface and 12 equations altogether for the three interfaces in a four-layer system).

Details on the formulation of these equations are given by Anani (6). Anani also developed a computer program based on the method of Gaussian elimination to solve the 14 unknowns.

The general equation for the pavement surface deflection at distance r from the loading center is shown below:

$$\delta_{st}(r) = (-1.5\, qa/E_1)\int_o^\infty J_o(mr)(A_1 m^2 e^{-m} - B_1 m e^{m} - C_1 e^{-m} + D_1 e^{m})dm \quad (2)$$

In this equation, A_1, B_1, C_1, and D_1 are functions of elastic moduli and layer thicknesses. The complete functions are given elsewhere (6). As shown, the equation of surface deflection involves nonlinear terms of modulus values.

According to Equation 2, the surface deflections at different radial distances are unique. Therefore, for a four-layer system where the surface deflections at four radial distances are known, the modulus value of each individual layer can be determined theoretically. Because of the extreme complexity of the equation, however, direct solution is not possible at this time. For this reason, instead of seeking direct solutions, these equations are used to investigate the effect of changing the modulus value of one layer on the surface deflections.

SENSITIVITY ANALYSIS

Within the practical range of modulus values, the modulus of each pavement layer is assumed. To determine the rate of change of the deflection at a point [δ(r)] with respect to E_i of one layer, the modulus value is increased and also decreased by the same amount, which is approximately 0.1 percent of the original modulus value. Let E_i' and E_i'' denote the two new modulus values and δ'(r) and δ''(r) denote the corresponding surface deflections when the modulus values of other layers remain unchanged, then the rate of change of surface deflection with respect to the change in layer modulus equals

$$\partial\delta(r)/\partial E_i = [\delta''(r) - \delta'(r)]/(E_i'' - E_i') \quad (3)$$

The analysis is made for a flexible pavement that has layer thicknesses of 1.5, 8, and 8 in for the surface, base, and subbase courses, respectively. The modulus values used are 300 000, 500 000, 45 000, and 30 000 lbf/in², and the Poissons' ratios are 0.35, 0.35, 0.40, and 0.45 for the surface, base, subbase, and subgrade materials, respectively. Surface deflections are computed at four locations: 0, 1, 2, and 3 ft from the center of a circular load. A uniform pressure of 13.0 lbf/in² is used. These distances and pressures correspond to the conditions used in the road-rater deflection measurement.

Table 1 summarizes the results of analysis. As indicated, the rate of change of subgrade modulus has the most-pronounced effect on the deflection basin. The effect of change of surface and base moduli on the surface deflection appears to be noticeable only at distances 0 and 1 ft from the loading center. The deflection at the furthermost point (3 ft from the loading center) seems to be affected solely by the change in the subgrade modulus. According to these results of analysis, the surface-deflection basin can be expressed as a function of elastic modulus as follows:

$$\delta_1 = f_1(E_1, E_2, E_3, E_4) \quad (4)$$

$$\delta_2 = f_2(E_1, E_2, E_3, E_4) \quad (5)$$

$$\delta_3 \simeq f_3(E_3, E_4) \quad (6)$$

$$\delta_4 \simeq f_4(E_4) \quad (7)$$

The last two approximate expressions provide a reasonable degree of accuracy for the range of conditions analyzed. Thus, according to Equation 7, there is only one value of E_4 associated with a deflection value δ_4. Once E_4 is obtained, the unique value of E_3 can be determined from Equation

Table 2. Results of modulus evaluation for section 2.

E_1 (lb/in²)	E_2 (lb/in²)	E_3 (lb/in²)	E_4 (lb/in²)	RRD1 (10^{-6} in)	RRD2 (10^{-6} in)	RRD3 (10^{-6} in)	RRD4 (10^{-6} in)	EAL	ST (°F)	AT (°F)	MC (%)
693 418	860 132	45 803	41 340	324	231	206	143	7 560	61	43	18.1
320 190	486 364	47 350	32 150	608	416	238	117	569 510	109	73	18.8
330 513	584 769	42 165	32 163	542	382	226	138	642 812	110	80	18.8
392 574	792 560	36 861	34 390	472	345	214	117	733 739	80	75	19.4
890 135	1 205 347	47 485	43 175	354	265	198	122	810 241	33	45	17.9
860 337	913 111	32 758	20 470	331	272	202	151	914 134	48	41	20.2
840 947	810 543	36 250	17 831	393	313	223	163	1 031 520	54	37	21.4
390 349	547 584	31 676	28 964	531	336	221	156	1 082 450	89	64	19.1
943 650	870 569	39 596	25 640	455	365	262	196	1 259 840	47	35	19.7
830 930	792 681	40 855	24 765	416	358	231	162	1 366 250	54	37	21.0
717 537	825 756	43 564	25 973	397	332	220	170	1 423 750	40	54	20.7
494 637	603 568	49 137	22 623	425	343	211	179	1 487 650	85	60	19.2
946 567	1 103 765	36 784	22 259	568	409	295	177	1 700 660	34	45	20.0
538 027	798 098	41 422	33 623	531	413	337	220	1 749 950	43	54	21.0
354 930	556 960	34 450	35 360	517	377	227	118	1 959 520	93	76	18.8

6. The determination of unique values of E_1 and E_2 is not as simple because both δ_1 and δ_2 can vary with both moduli. In this study, in order to ensure that the solution for E_1 and E_2 is reasonable, a ratio of E_1/E_2 of 0.7 is used; this ratio is determined from laboratory resilient-modulus testing on core samples.

METHOD OF EVALUATION

The method developed requires the use of the bitumen-structures-analysis-in-roads (BISAR) computer program and the procedure of successive approximation. As the first step in this method, a set of initial values of the modulus is assumed. By using the BISAR computer program, the deflection values δ_1, δ_2, δ_3, and δ_4, which correspond to the assumed modulus values, are calculated. These calculated deflections are compared with the deflections obtained from the four geophones of a road rater, designated here as RRD1, RRD2, RRD3, and RRD4, and the assumed modulus values are corrected.

The correction begins from the subgrade modulus (E_4). To ensure a gradual convergence and also to avoid a drastic correction that might greatly influence the other modulus values, only one-half of the discrepancy is adjusted. Thus, the newly assumed value of E_4 is

$$E_{4_{new}} = E_{4_{old}} \times [(RRD4 + \delta 4)/2]/RRD4 \quad (8)$$

With this new E_4 value and the previously assumed modulus values for other layers, a new set of δ values are calculated. By using the newly computed values of δ, a procedure similar to that described above is followed to adjust the subbase modulus (E_3). The new E_3 value is computed from the previous value by using the following equation:

$$E_{3_{new}} = E_{3_{old}} \times [(RRD3 + \delta 3)/2]/RRD3 \quad (9)$$

Then, the deflection values are computed for the new E_3 and previous E_1, E_2, and E_4 values. By using these computed deflection values, the base-course modulus (E_2) is adjusted as follows:

$$E_{2_{new}} = E_{2_{old}} \times [(RRD2 + \delta 2)/2]/RRD2 \quad (10)$$

After the new set of deflections is calculated, the surface modulus (E_1) is corrected by using the equation below:

$$E_{1_{new}} = E_{1_{old}} \times [(RRD1 + \delta 1)/2]/RRD1 \quad (11)$$

Thus, one complete iteration has been made where new modulus values have been generated. The second iteration begins from the correction of the subgrade E_4 by following the same procedure. This iteration process is repeated until the differences between the calculated and measured deflections for all four sensors (geophones) are within the specified tolerance. A 5.0 percent error is considered allowable for δ_1; however, a 1.0 percent error is the maximum allowed for the other deflections. This difference in the allowable limits is necessary because more iterations are needed to converge on δ_1 than on others. In general, it takes only about 4 iterations for δ_4 and as many as 20 iterations for δ_1 to converge the computed deflections to the measured deflections.

Note that since there are only four geophone readings in a road-rater deflection basin, the procedure is valid only for a maximum of four-layer systems. However, the procedure can be easily adapted for elastic systems that have greater numbers of layers if more sensor readings for a deflection basin are available.

IN SITU MODULUS

The in situ modulus values of experimental pavement at the Pennsylvania Transportation Research Facility are evaluated by using the preceding procedure; the results of modulus evaluation for section 2 are summarized in Table 2. Included with the modulus values are road-rater deflections, surface temperatures (ST), five-day average air temperatures prior to deflection measurements (AT), subgrade moisture contents (MC), and the equivalent 18-kip single-axle loads (EAL). This pavement section has a 2.5-in dense-graded, hot-mixed bituminous concrete surface, 6-in bituminous concrete base, 8-in crushed limestone subbase, and silty clay subgrade. The deflection basins are obtained by using a model-400 road rater operated at 25 Hz vibration frequency. The pavement section is 220 ft long and the sites of deflection measurements are marked on the pavement surface 25 ft apart. The deflection readings are averaged for the test section for each particular date.

The modulus data for other test pavements are documented in a research report (7). Also included in the report are the results of statistical analyses for the variation of the modulus values with various influential factors, such as air and pavement temperatures, subgrade moisture, EAL, layer thickness, and others. Results of the analyses indicate that both the surface modulus and the base modulus are most influenced by the total temperature, which is the sum of the pavement surface temperature and the average five-day air temperature. As expected, both modulus values decrease with an increase in total temperature. The subgrade modulus is only affected by the subgrade moisture content; the higher the water content, the lower the subgrade modulus. For the subbase modulus, no single factor can be considered as significant, namely, the subbase modulus remains almost constant throughout the test facility and the testing period.

SUMMARY

Based on the results of a theoretical analysis, a method for evaluating the in situ moduli of pavement constituent layers from road-rater deflection basins was developed. By using this method, the moduli of pavement layers at the Pennsylvania Transportation Research Facility were evaluated.

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Fabric Use in Low-Deformation Transportation Support Systems

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The feasibility of using fabrics in the construction or rehabilitation of conventional transportation support systems such as secondary roads or track beds was considered. Structural improvement concepts were analyzed. Several theoretical behavior models (ILLI-PAVE, LSTRN3, BISAR, and a simplified confinement model) were used in the structural analyses of soil-fabric-aggregate (SFA) systems. Structural improvement effects, as evidenced by ILLI-PAVE, calculated vertical stress distributions, and vertical deflections in a conventional SFA system are not achieved, thus previous experimental data are confirmed. However, BISAR structural analyses of a typical SFA system indicated the beneficial effects of no slippage conditions at the aggregate-subgrade interface. A simplified confinement model indicated that, if significant permanent deformation is developed in an SFA system, a substantial percentage increase in confinement can be developed. Proposed SFA behavior mechanisms indicated that a stage construction sequence for low-traffic-volume roads and track systems provided for use of the full potential (separation and structural improvement) of fabrics in SFA systems.

Laboratory studies and field performance data have shown that soil-fabric-aggregate (SFA) systems are effective for soft soil (large rut-depth development) applications. Equivalent performance (SFA - conventional aggregate layer construction) can be achieved with a reduced aggregate thickness if a fabric is installed at the soil-aggregate interface.

The success of SFA systems for soft soil applications has led to the development of increasing interest in the potential of fabric use in conventional transportation support systems (e.g., railroads, highway pavements, and airfield pavements). The major difference between conventional transportation support and SFA systems constructed over soft soils is the magnitude of tolerable levels of rut development and surface deflection. Permissible levels of rutting and resilient deflection for conventional transportation support systems are on the order of 1.5 and 0.500 in (38 and 12.7 mm), respectively. Rut depths on the order of 3-5 in (76-127 mm) and resilient deflections in excess of 1 in (25.4 mm) are commonly incurred in SFA systems on soft soils.

The influence of fabric on the structural behavior and performance of low-deformation (SFA) systems is not well established. The purpose of this paper is to investigate potential mechanisms of improvement and thereby determine the feasibility of using fabrics in the construction or rehabilitation of conventional transportation support systems such as primary and secondary roads and trackbeds.

EFFECTS OF STRUCTURAL IMPROVEMENT

Fabrics are thin and exhibit resistance to applied