Evaluation of Fly Ash and Lime-Fly Ash Test Sites Using a Simplified Elastic Theory Model and Dynaflect Measurements

SHAH ALAM and DALLAS N. LITTLE

ABSTRACT

The objective of many pavement design studies is to evaluate the long-term structural performance of the pavement layers and, from these evaluations, decide whether to implement new materials or new construction methods. For such studies, the constitutive behavior of the pavements must be identified by characterizing the pavement materials in terms of a stiffness modulus and Poisson's ratio. Presented in this paper is an efficient method for computing the elastic moduli of four types of lime-fly ash stabilized pavement structures from Dynaflect-measured field deflections with reasonable accuracy. This approach is based on a new deflection equation derived from a simplified elastic theory model, and allows analysis of multilayered pavements that utilize simple mathematical computations that permit calculations at a fraction of the cost of multilayered elastic and finite-element models. With this method, a large number of readings can be economically analyzed. The structural model, in the form of a computer program, has unique features and was applied to field measurements of 43 experimental test sections located at 7 sites on Texas highways. These test sections were constructed on low plasticity index (PI) clayey soil and very low PI coarse sandy soil. For low PI clayey soil, the results have shown that fly ash, by itself, was generally ineffective in promoting stiffness gains but provided effective structural improvement when used with lime. For very low PI coarse sandy soil, stabilization with fly ash only was effective.

Dynaflect nondestructive deflection data from seven test sites, summarized in Table 1, were utilized in the study. These sites were constructed by the Texas State Department of Highways and Public Transportation (SDHPT). This study is part of a larger research project concerning the implementation of fly ash in highway construction in Texas. The research was sponsored cooperatively by the SDHPT and the FHWA.

DEFLECTION MEASUREMENT WITH THE DYNAFLECT

The Dynaflect operates on the principle of a vibratory force applied to the pavement surface by two masses rotating in opposite directions. This induces a cyclic peak-to-peak live load of 1,000 lb with a frequency of 8 Hz applied on two steel load wheels in contact with the pavement. The load-induced deflections are measured by five geophones at 12-in.

TABLE 1 Test Site Summary

				Test Site Data			
Test Site No.	County	Highway	Date Completed	No. of Sections	Length of Sections (ft)	Section Construction	Subgrade Soil Type
1	Bowie	FM-3378	Oct. 1979	10	800	One-course surface treatment, 8-in. L-FA base, 8-in. L or FA subbase	Low/medium plasticity silty clay
2	Panola	US-59	Sept. 1979	9	1,000	One-course surface treatment, 2-in. HMAC, 12-in. flexible base, 8-in. L-FA subbase	Low PI silty clay (with sand)
3	Bexar	FM-1604	Dec. 1979	6	800	Two-course surface treatment, 10-in. flexible base, 6-in. L-FA subbase	Low PI Clayey silt
4	Bexar	FM-1604	Oct. 1979	6	800	Two-course surface treatment, 14-in. flexible base, 6-in. L-FA subbase	Low PI clayey silt
5	Bexar	FM-1604	Mar. 1980	8	800	Two-course surface treatment, 12-in. flexible base, 6-in. L-FA subbase	Low PI clayey silt
8	Potter	SH-335	Mar. 1979	6	800	Two-course surface treatment, 1-in. HMAC, 12-in. flexible base, 6-in. L-FA subbase	Medium/low PI clay
12	Wheeler	FM-2697	Nov. 1979	5	900 5,400	Two-course surface treatment, 6-in. FA base	Very low PI sandy soil

Note: L = lime, FA = Fly ash, HMAC = hot-mix asphalt concrete, FM = farm to market, SH = state highway.

intervals (1-3). The measured deflections are indicative of the displacement and shape of the deflected surface, as shown in Figure 1.

The deflection of the pavement structure in response to an induced load has been correlated to structural performance of the pavement layers (4). The shape of the Dynaflect basin is a useful performance indicator and is used in several computer-based methods (5) for predicting stress-strain behavior of pavement layers. In general, these methods rely on the use of multilayered elastic theory models and basin-matching techniques (6) to arrive at reasonably accurate stiffnesses of the pavement layers.

DEFLECTION EQUATION

The basic deflection equation used in the research was postulated by Vlasov and Leont'ev (7). Figure 2 shows the load distribution system of an elastic layer of thickness H resting on a rigid, incompressible layer, where load P is applied to a rigid circular plate of radius r_0. For all radii greater than r, the deflection of the elastic layer can be determined by Equation 1 as follows:

$$w(r, z) = \{(3P/\pi)\ [(1+\nu_1)/E_1 H\Psi_t]\}\ K_0\ (\alpha r)\Psi_1(z) \tag{1}$$

where

$w(r,z)$ = vertical deflection at radius r and depth z,
E_1 = elastic modulus of the layer,
r = radius,
P = applied point load,
z = depth below the surface,
$K_0(\alpha r)$ = modified second-order Bessel function of order 0 with argument r, and
ν_1 = Poisson's ratio of the elastic layer.

The term $\Psi_1(z)$ signifies the distribution of vertical displacement with depth and is assumed to be related to H and z. In thin compressible layers, the principal stress σ_z is assumed to be constant over the depth of the layer and, therefore, the displacement decreases linearly with increasing depth, as shown in Figure 2. The term $\Psi_1(z)$ can be represented as

$$\Psi_1(z) = (H - z)/z \tag{2}$$

For a thick compressible layer, Vlasov and Leont'ev (7) recommended the distribution of $\Psi_1(z)$ as

$$\Psi_1(z) = [\mathrm{Sinh}\ \gamma\ (H - z)]/\mathrm{Sinh}\ \gamma\ H \tag{3}$$

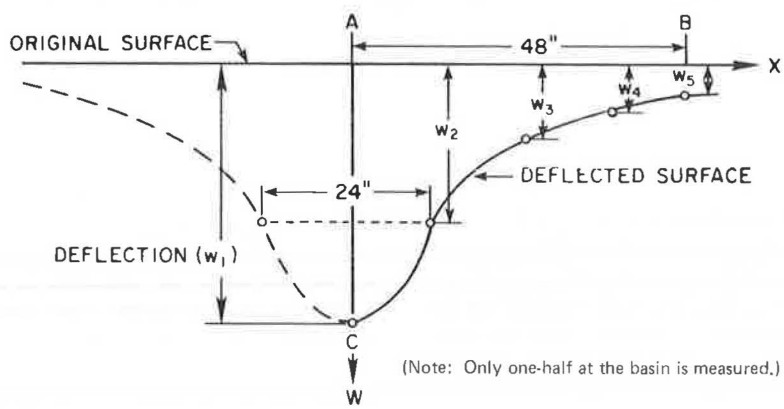

FIGURE 1 Typical deflection basin reconstructed from Dynaflect readings.

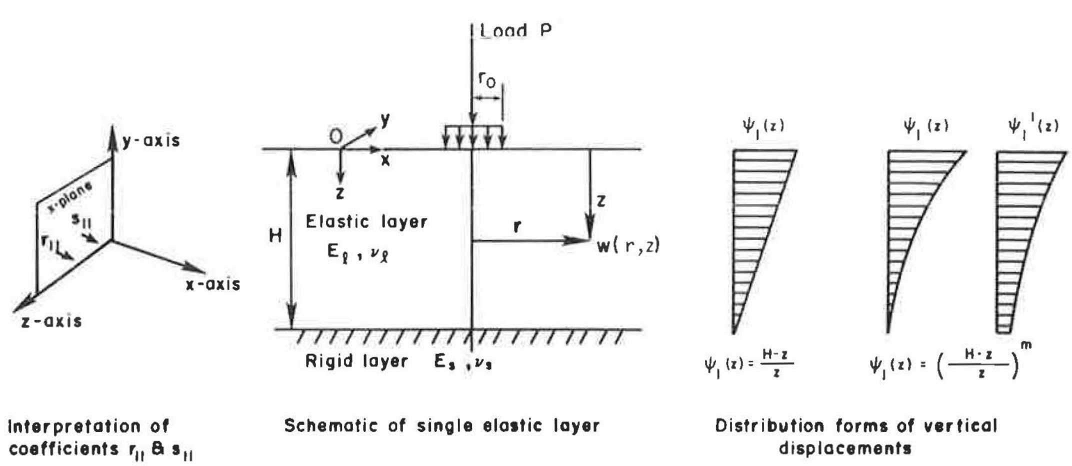

FIGURE 2 Load distribution system of a single elastic layer over a rigid layer.

Gamma is a constant determining the rate of decrease of the displacement with depth. Alpha in Equation 1 is defined as a ratio characterizing the combined effect of compressive strain and shearing strain in the elastic layer and is represented as

$$\alpha = (k/2t)^{1/2} \tag{4}$$

The coefficient k characterizes the compressive strain in the elastic layer and can be expressed as

$$k = E_1\, s_{11}/(1-\nu_1^2) \tag{5}$$

The coefficient t characterizes the shear strain in the elastic layer and can be expressed as

$$t = E_1\, r_{11}/[4(1+\nu_1)] \tag{6}$$

In Equations 5 and 6, S_{11} and r_{11}, are parameters characterizing compressive strain and shear strain, respectively, in the X plane and the X direction. They are defined as

$$S_{11} = K/H = \int_0^H \Psi_1'^2\,(z)dz \tag{7}$$

$$r_{11} = H\,\Psi_t/3 = \int_0^H \Psi_1^2\,(z)dz \tag{8}$$

The terms Ψ_k and Ψ_t are defined as distribution forms of compressive and shear strains, respectively, and are related to $\Psi_1(z)$ and its derivative $\Psi_1'(z)$. The distribution of vertical displacements for a single elastic layer was assumed to be represented as

$$\Psi_1'(z) = [(H-z)/H]^m \tag{9}$$

where m is a constant dependent on the in situ physical properties of the pavement structure. Substituting Equation 9 into Equations 7 and 8 and eventually into Equation 1, Equation 10 is yielded:

$$w(r,z) = (P/\pi)[(1+\nu_1)/E_1]\;[(2m+1)/H]\;J_1\,(dr)\;[(H-z)/H]^m \tag{10}$$

where $J_0(dr)$ is the first-order Bessel function of order 0 and argument αr

$$\alpha = (m/H)\,\{2(2m-1)/[(2m-1)\,(1-\nu_1)]\}^{1/2} \tag{11}$$

[Based on Lytton's findings (8), the $K_0(x)$ Bessel function, originally used by Vlasov and Leont'ev, was substituted for $J_0(x)$.]

Equations 10 and 11 represent deflections in a single elastic layer, whereas all pavements consist of at least two and usually several layers. Odemark's assumption (9) is useful in transforming the thickness of multiple elastic layers to an equivalent thickness of a material with a single-datum elastic modulus. The concept is presented in Figure 3 where H is the distance of the rigid layer from the surface as in Figure 2, and h_k is the thickness of the subgrade layer assumed to behave elastically.

The transformed total thickness of all layers is of the form

$$H' = \sum_{i=1}^{k} h_i\,(E_i/E_0)^n \tag{12}$$

where

- H' = transformed depth of all layers,
- k = number of layers,
- h_1 = thickness of layer i,
- n = exponent to be found by analysis in this study, equal to 0.33 in Odemark's assumption (9),
- E_i = elastic modulus of layer i,
- E_0 = modulus of datum layer, assumed to be the subgrade in this study, and

$$h_k = H - \sum_{i=1}^{k-1} h_i \tag{13}$$

Thus, the concept of Equations 12 and 13 may be applied to compute a transformed depth $\bar{z}$ as follows:

$$\bar{z} = \sum_{i=1}^{L-i} h_i\,(E_i/E_0)^n + \left(Cz - \sum_{i=L}^{L-1}\right) h_i\,(E_1/E_0)^n \tag{14}$$

where L is the number of layers and z is the actual depth. The revised equations for multilayered pavements are

$$w(r,z) = (C/\pi)\,P\;[(1+\nu_0)/E_0]\;[(2m+1)/H]\;J_0\,(\alpha r)\,[(H'-\bar{z})/H']^m \tag{15}$$

$$\alpha = (mB/H)\{[2(2mB+1)]/[(2mB-1)\,(1-\nu_0)]\}^{1/2} \tag{16}$$

where ν_0 is the Poisson's ratio of datum subgrade layers.

For multilayered pavements, the constant B is introduced to correct the value of the power law exponent m, and constant C is introduced to correct the derived deflection value in Equation 16. Equations 16 and 17 are the basis of this study, and

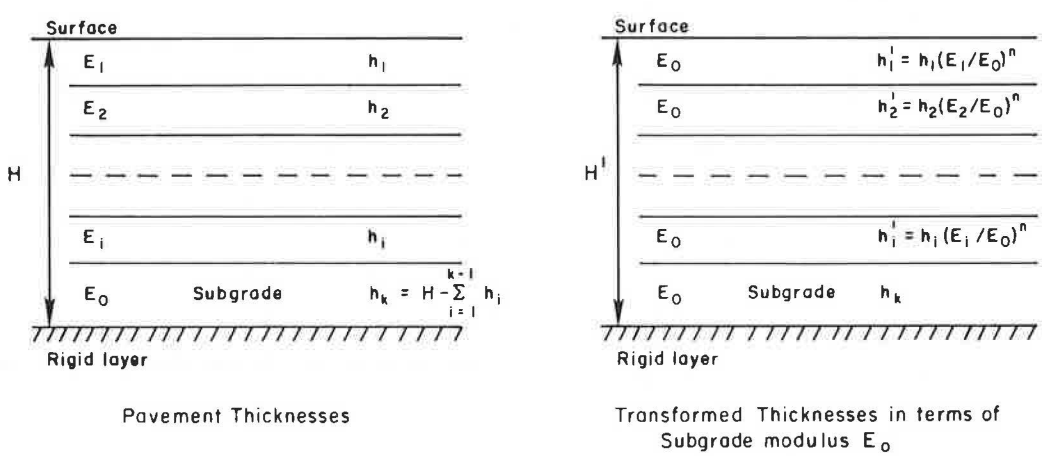

FIGURE 3 Transformed thicknesses of k-layers for multilayered pavements.

constants m, n, C, B, and H were determined for each type of pavement construction by statistical analysis of Dynaflect-measured field data.

STATISTICAL PROCEDURE

The regression analysis procedure that was followed to determine the constants in Equations 15 and 16 assumes a nonlinear relationship between a dependent variable y and an independent variable x. The nonlinear regression model is of the form

$$\hat{y} = \beta_0 \, x^{\beta_1} \tag{17}$$

where $\hat{y}$ is the predicted value of the dependent variable, and β_0 and β_1 are constants derived by regression analysis.

From principles of simple linear regression analysis, the best values of constants β_0 and β_1 can be obtained when a least-squares criterion is employed that minimizes the summed square of differences between an observed y and the predicted $\hat{y}$. To meet assumed conditions of nonlinearity, a method called "pattern search," which was developed by A.R. Letto in a computer program now in use at the Texas Transportation Institute, was incorporated in the overall statistical analysis procedure of the study. The principal steps in the analysis were as follows:

1. Assume a functional relationship between x and y, and write the equation as

$$\hat{y} = f(x) \tag{18}$$

2. Subtract the predicted value of dependent variable $\hat{y}$ from observed value y and obtain the error, ε. The error is squared and added to the errors of all the other observations. This is expressed as

$$\epsilon_j^2 = \sum_{j=1} [y_h - f(x)]^2 \tag{19}$$

where ε_j is the error for the jth observation, and y_j is the jth observation of y.

3. Apply the pattern search technique and determine a set of constants in f(x) that minimizes the sum of squared error in Equation 19.

In summary, the statistical procedure applied in this study in regression analyses 1-3 meets the least-squares criterion typically used in linear regression analysis and employs pattern-search techniques to account for the nonlinearity of relationships.

By utilizing the general forms of deflection Equations 15 and 16 and field-measured data, the statistical procedures were applied to develop relationships for constants for lime-fly ash stabilized layers. The sections were divided into four construction types, described as follows:

1. Lime-fly ash stabilized base over lime or fly ash stabilized subbase.
2. Hot-mix asphalt concrete (HMAC) layer over flexible base and lime-fly ash stabilized subbase.
3. Flexible base over lime-fly ash stabilized subbase, and
4. Fly ash stabilized layer over natural subgrade.

The clarifications according to type of construction are illustrated in Table 2, which also gives the age of data selected for development of the equations for lime-fly ash stabilized layers.

TABLE 2 Summary of Test Sites and Dynaflect Deflection Data Selected for Development of the Deflection Equation for Time-Fly Ash Stabilized Sections

	Selected Sections			
Construction Type	Test Site No.	Section No.	No. of Sections in Construction Type	Deflection Data Age After Construction (months)
1	1	2,3,4,6,7,8,9,10	8	36
2	2	2,3,4,5,6,7,8,9	8	37
3	3	1,2,3,5,6	22	33
	4	2,3,4,5,6		37
	5	1,2,3,4,6,7,8		33
	8b	2,3,4,5,6		26
4	12	1,2,3,4,5	5	22

ANALYSIS AND RESULTS

Deflection Basin Fitting Analysis

The elastic moduli of pavement layers were estimated from Dynaflect deflection measurements by employing the multilayered elastic approach with the aid of the Shell BISTRO computer program in the following steps:

1. Thickness of pavement layers, initial estimates of the pavement layer elastic moduli, the Dynaflect-induced load of 1,000 lb, and the loading configuration were input into the computer program and vertical deflections were analytically computed at the five geophone locations of the Dynaflect. The Poisson's ratios of layers were assumed for the HMAC layer, the flexible base, the lime-fly ash stabilized layers, and the natural subgrade as 0.40, 0.45, 0.15, and 0.45, respectively (1,10).
2. Field-measured deflections were individually compared with the five computed deflections and the overall fit of the basin was determined.
3. The initial layer moduli used in the computer program were adjusted to improve the fit of the computed-to-measured deflection basin.
4. The process was repeated until a reasonable accuracy of fit was achieved.

Observations made in application of the procedure are generally in agreement with the findings of McCullough and Taute (6) on rigid pavements as follows: (a) variations in the elastic moduli of the base or subbase influence sensor-1 deflection significantly but have only a minor effect on sensor-5 deflections, which implies that the slope of the basin is affected; and (b) variations in the elastic moduli of the subgrade significantly affect both sensor-1 and sensor-5 deflections. This effect is generally proportional and thus has a minimal effect on the slope of the basin.

As reported by various researchers, the sensor-5 deflection is a unique indicator of the stiffness of the subgrade and predicts the elastic modulus of the subgrade accurately as shown in Figure 4.

For two-layer pavements, a unique elastic modulus ratio determines the deflection basin shape, and

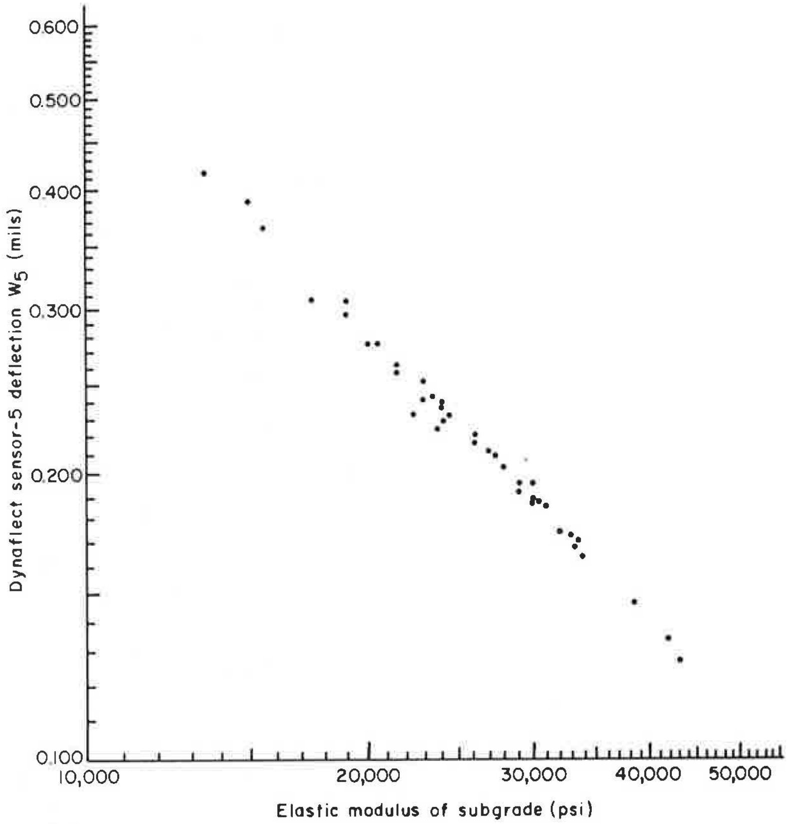

FIGURE 4 Subgrade modulus as a function of sensor-5 reading of the Dynaflect, in the log-log form.

because the subgrade modulus is singularly related to the deflection recorded by deflection sensor 5, both moduli are easily determined. On the other hand, more than one combination of modulus ratios may produce equally accurate predicted deflection basins in multilayered systems. The pavement cross sections evaluated in this study are given in Table 1.

Regression Analysis 1

The first step of this analysis was the determination of the vertical displacement with depth. All sections containing lime-fly ash stabilized layers as summarized in Table 2 were analyzed at Dynaflect sensor 1 for 8 depths selected at the pavement surface, at the interfaces of the layers, and at a 1-ft depth thereafter. The Shell BISTRO computer program was used to determine vertical displacement values.

The pavement sections used in this study were of the same thickness for all construction types except type 3. The following physical properties were investigated as predictors of the constant m: modular ratios K_1, K_2, and K_3 and layer thickness ratio D. The dependence of constant m on these properties was tested by applying the general linear model (GLM) regression procedure, and both linear and log-linear relationships were derived. The results of this analysis are given in Table 3.

A study of the statistical parameters in Table 3 indicates that the mathematical model fits the data well and the independent variables significantly account for the behavior of the dependent variable. Therefore, on the basis of the statistical evaluation, the following log-linear relationships were established for each type of construction:

$$\log_e m = 0.4717 + 0.0684\ K_1 - 1.427\ K_2 \quad \text{(type 1)}$$

$$\log_e m = 0.6713 - 0.0322\ K_1 - 0.3916\ K_2 - 0.1714\ K_3 \quad \text{(type 2)}$$

TABLE 3 List of Regression Coefficients of Linear and Log-Linear Relationships Between Constant m Versus Modular Ratios K_1, K_2, and K_3 and Layer Thickness Ratio D

Construction Type	Dependent Variable	Intercept	Coefficients of Independent Variables K_1	K_2	K_3	D	F-Value	R-Square	Significant Difference at $\alpha = 0.1$
1	m	1.6799	0.0684	-0.1648	-	-	5.19	0.675	Significant
	$\log_e$ m	0.4717	0.0654	-1.427	-	-	6.82	0.732	Significant
2	m	1.2985	-0.0251	-0.2563	-0.0905	-	18.53	0.933	Significant
	$\log_e$ m	0.6173	-0.0322	-0.3916	-0.1714	-	43.86	0.970	Significant
3	m	1.5528	-0.0287	-0.1405	-	-0.1787	63.81	0.914	Significant
	$\log_e$ m	0.7732	-0.0421	-0.1908	-	-0.2324	89.67	0.937	Significant
4	m	1.6541	-0.0103	-	-	-	13.09	0.814	Significant
	$\log_e$ m	0.6125	-0.0092	-	-	-	21.81	0.879	Significant

Note: dashes = data not available.

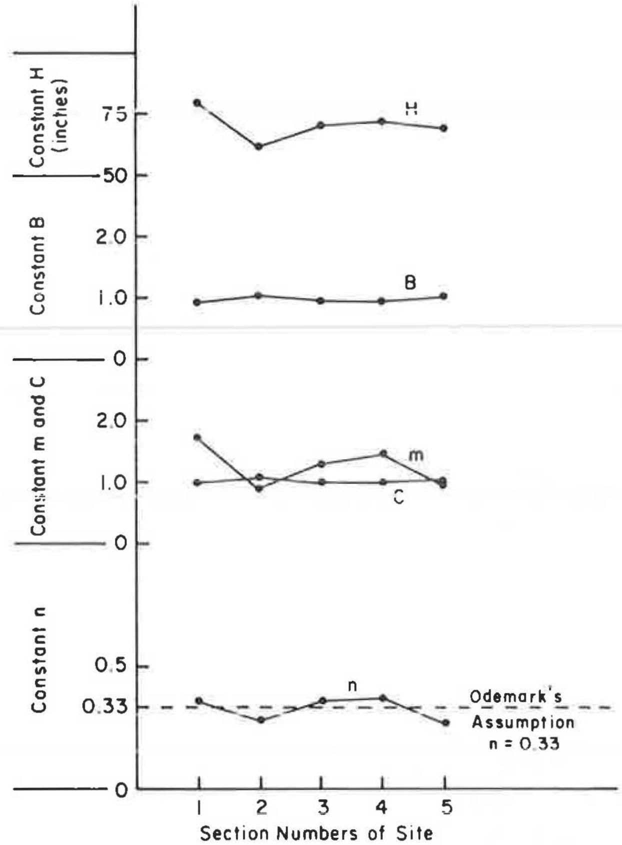

FIGURE 5 Graphic representation of the computed constants m, n, C, B, and H—Site 12.

$\mathrm{Log}_e m = 0.7732 - 0.0421\,K_1 - 0.1908\,K_2 - 0.2324\,D$ (type 3)

$\mathrm{Log}_e m = 0.6125 - 0.092\,K_1$ (type 4)

Regression Analysis 2

The relationships for m as defined previously were utilized in regression analysis 2, and the values of constants n, C, B, and H were derived for each lime-fly ash stabilized test section. The regression procedure utilized elastic moduli values obtained from the basin fitting analysis, the deflection model according to Equations 15 and 16, the error equation (8) and field-measured Dynaflect deflections at all five locations of the geophones.

Figures 5 to 8 show the values of constants determined for the test sections. The computed values of n were observed to be reasonably close to the value of 0.33 used by Odemark (9). Variations were smallest in construction type 2 where values ranged from 0.30 to 0.38 whereas the largest variations in con- struction type 3 ranged from 0.29 to 0.53.

The dependence of constants n, C, B, and H on physical properties was tested by applying the GLM regression procedure. By using the values of n, C, B, and H obtained from regression analysis 2, several linear and log-linear relationships with both single and multiple independent variables were examined. Selected log-linear relationships are summarized in Table 4.

The statistical parameters of Table 4 suggest that a varying degree of correlation exists between the dependent and independent variables for constants n, C, B, and H. The correlation of constant C to the modular ratios and layer thickness ratios was found to be consistently higher than the correlations exhibited by n, B, and H.

Regression Analysis 3

In this analysis, the relationships derived for constants m, n, C, B, and H with modular ratios and layer thickness ratios were utilized to predict deflections and elastic moduli of pavement layers from field deflections. The listing of the computer program developed at Texas Transportation Institute was modified for use in this study for regression analysis (11). The pattern search technique modifications were as follows:

1. The search for elastic moduli of pavement structural layers was restricted to n - 1 layers by eliminating the subgrade modulus from the search. This was based on the knowledge that the subgrade modulus is capable of being accurately determined from the sensor-5 reading of the Dynaflect (Figure 4).
2. The accuracy of the analysis was increased substantially by reducing the incremental amount by which the variables, elastic moduli for layers 1 through n - 1, were incremented during the pattern search process (10).

TABLE 4 List of Regression Coefficients of Log-Linear Relationships Between Constants n, C, B, and H Versus Modular Ratios K_1, K_2, and K_3 and Layer Thickness Ratio D

Construction Type	Dependent Variable	Intercept	Coefficients of Independent Variables K_1	K_2	K_3	D	F-Value	R-Square	Significant Difference at $\alpha = 0.1$
1	$\log_e$ n	-0.6815	-0.0280	-0.0719	-	-	4.01	0.616	Significant
	$\log_e$ C	0.0654	-0.0364	0.0093	-	-	13.26	0.841	Significant
	$\log_e$ B	-0.4738	0.0691	0.0603	-	-	1.79	0.418	Not significant
	$\log_e$ H	4.4239	-0.0008	-0.0233	-	-	2.55	0.505	Not significant
2	$\log_e$ n	-0.7075	-0.0759	-0.1045	0.0107	-	1.23	0.480	Not significant
	$\log_e$ C	-0.1085	0.0053	0.1078	0.0447	-	23.35	0.946	Significant
	$\log_e$ B	-1.0297	0.0409	0.4382	-0.2573	-	19.52	0.936	Significant
	$\log_e$ H	4.1297	0.0248	0.0464	0.0088	-	3.49	0.723	Not significant
3	$\log_e$ n	-0.7355	0.0673	0.0680	-	-0.2535	1.13	0.158	Not significant
	$\log_e$ C	-0.0233	0.0395	0.0757	-	0.0156	16.06	0.728	Significant
	$\log_e$ B	-0.9724	0.0352	0.1740	-	-0.2573	63.05	0.913	Significant
	$\log_e$ H	4.2325	-0.0199	-0.0062	-	0.0686	0.72	0.108	Not significant
4	$\log_e$ n	-0.9438	-0.0045	-	-	-	8.57	0.741	Significant
	$\log_e$ C	-0.0393	0.0014	-	-	-	38.38	0.928	Significant
	$\log_e$ B	-0.1352	0.0019	-	-	-	27.18	0.901	Significant
	$\log_e$ H	4.3631	-0.0024	-	-	-	14.67	0.830	Significant

Note: dashes = data not available.

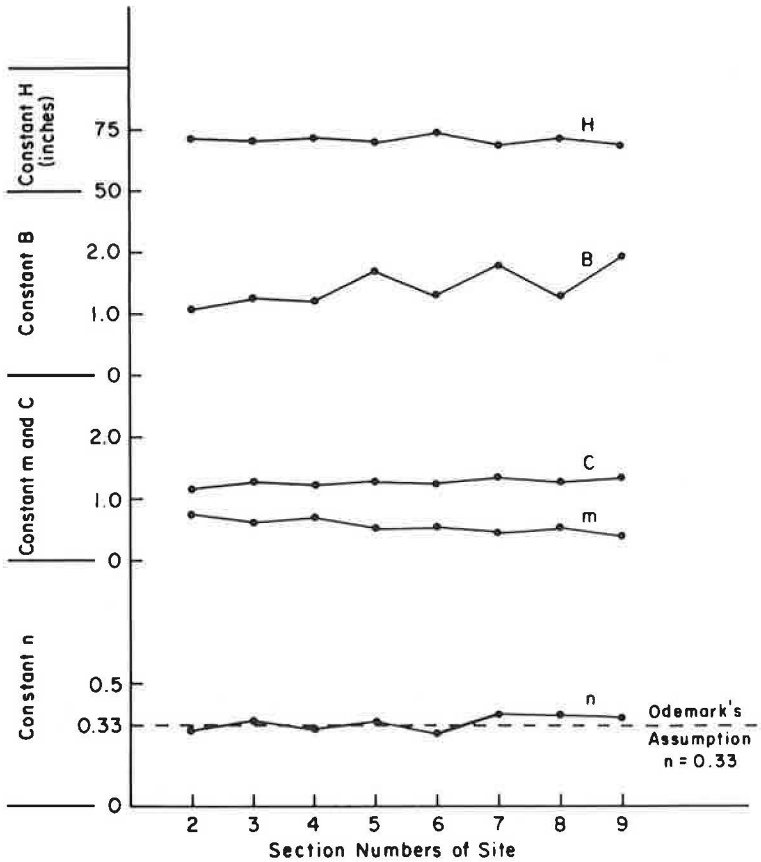

FIGURE 6 Graphic representation of the computed constants m, n, C, B, and H—Site 2.

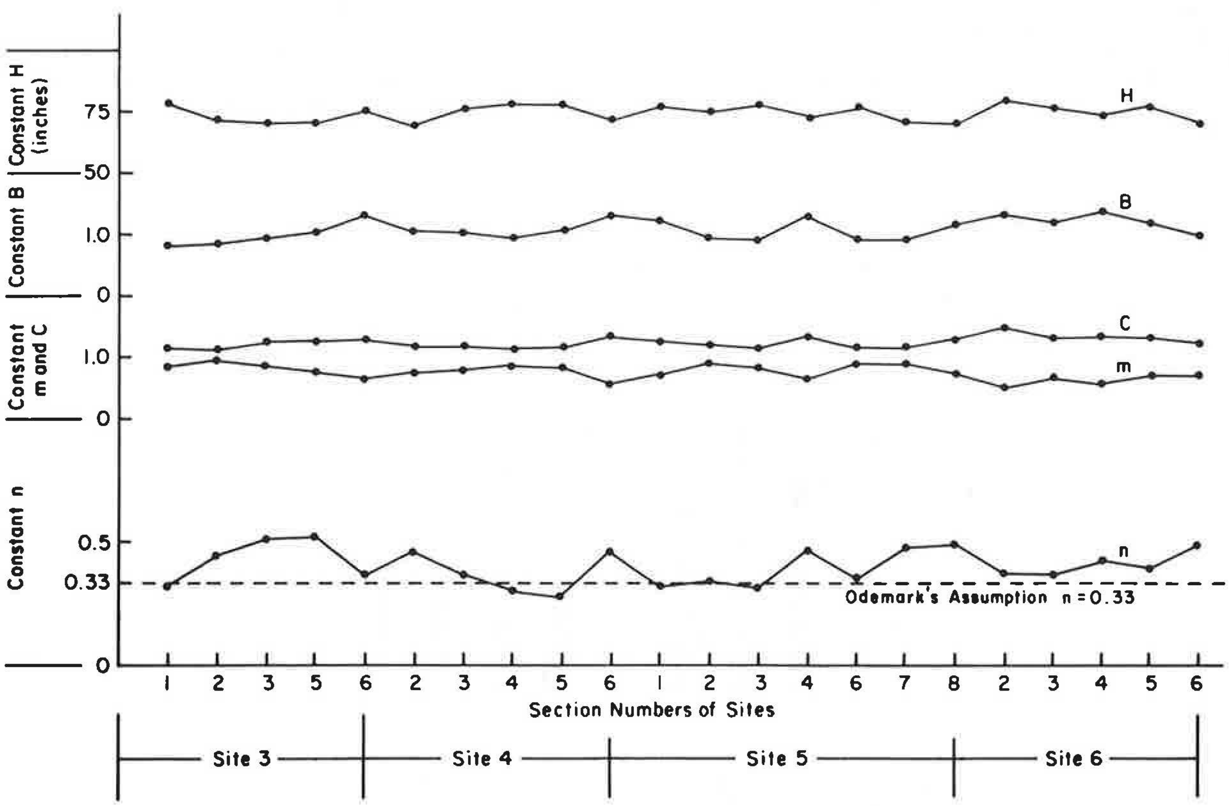

FIGURE 7 Graphic representation of the computed constants m, n, C, B, and H—Sites 3, 4, 5, and 8.

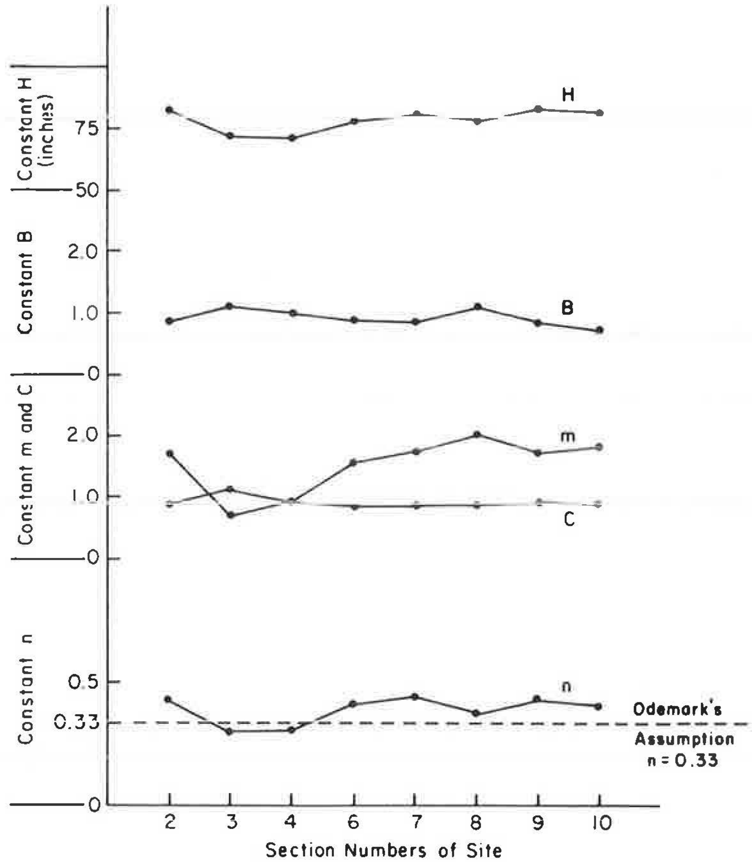

FIGURE 8 Graphic representation of the computed constants m, n, C, B, and H—Site 1.

The elastic moduli of the pavement layers computed by application of regression analysis 3 are shown in Figures 9 through 15.

In general, the computed deflections and elastic moduli were reasonably accurate. Low prediction errors were observed in the majority of computations, and the computed values of the constants m, n, C, B, and H of the simplified elastic theory model were reasonable for all the test sections. Significant savings, in terms of computational costs, were observed in applying the simplified elastic theory model to predict deflections and elastic moduli as

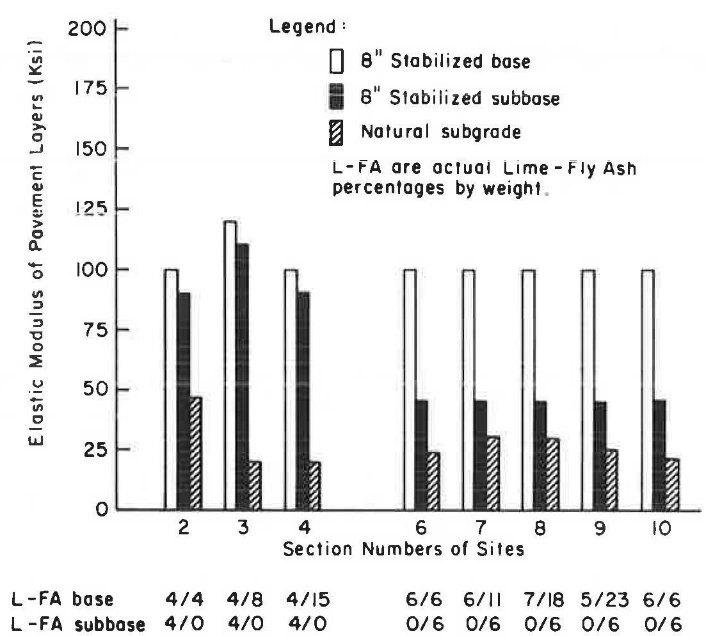

FIGURE 9 Predicted elastic modulus values of pavement layers—Site 1.

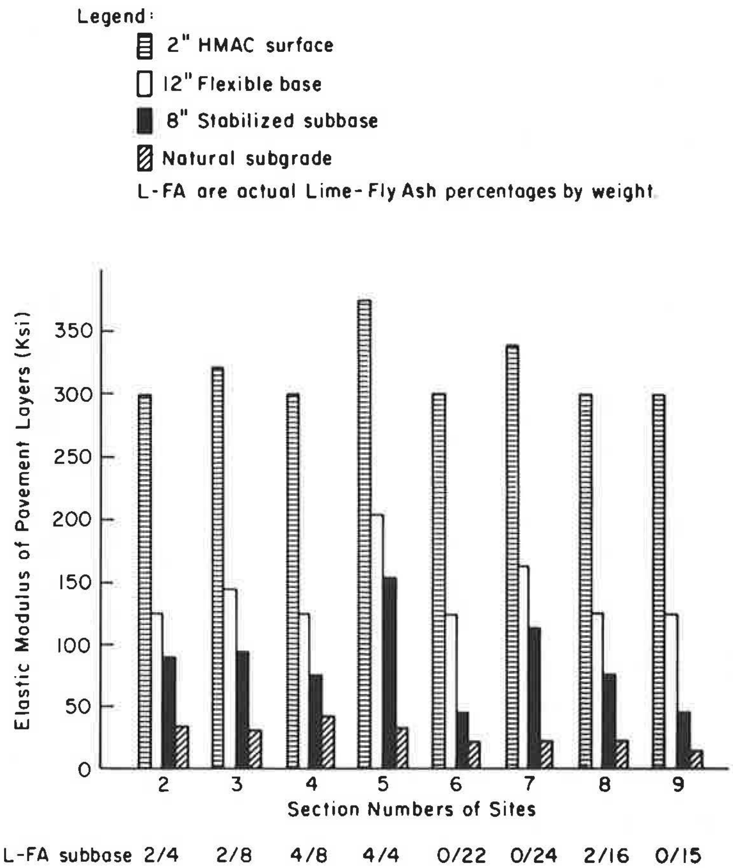

FIGURE 10 Predicted elastic modulus values of pavement layers—Site 2.

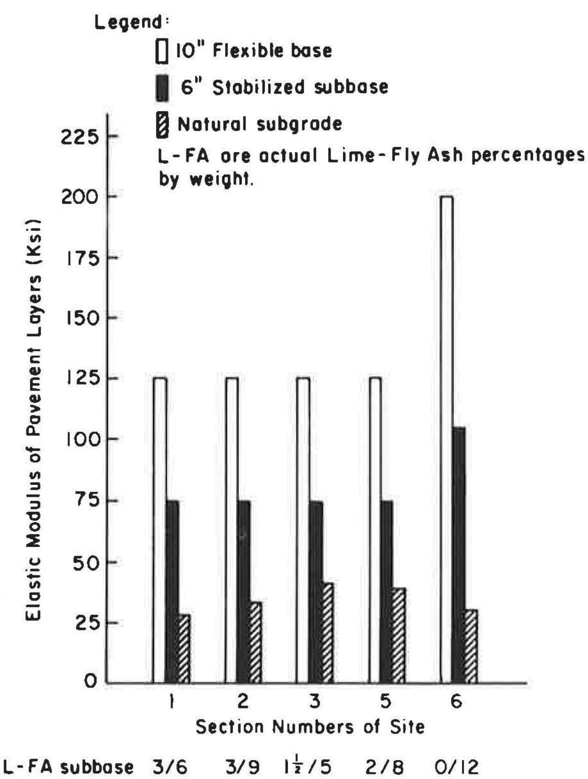

FIGURE 11 Predicted elastic modulus values of pavement layers—Site 3.

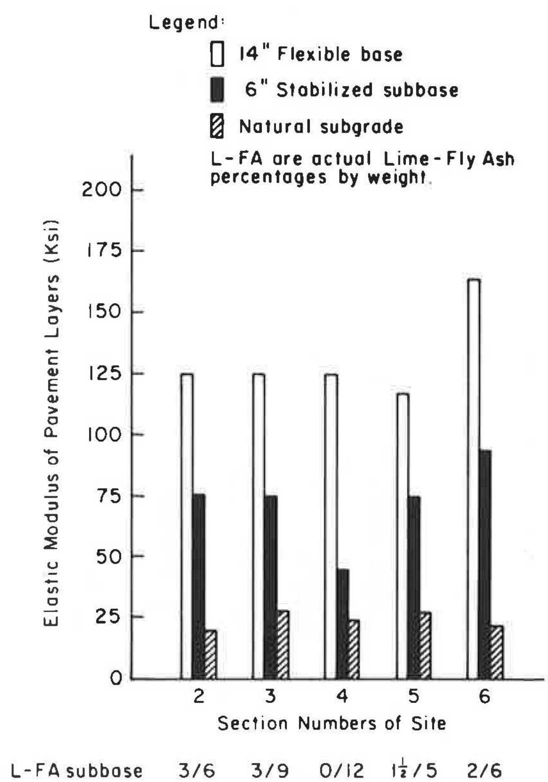

FIGURE 12 Predicted elastic modulus values of pavement layers—Site 4.

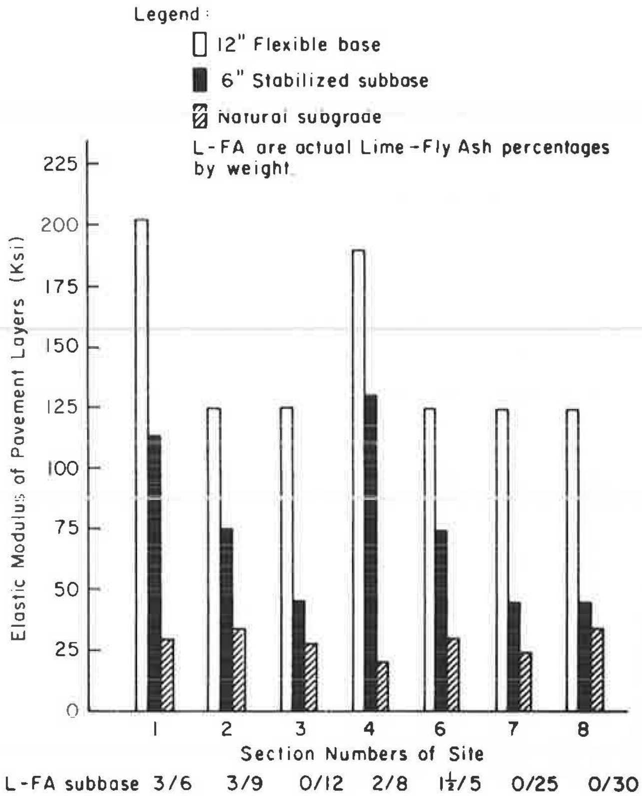

FIGURE 13 Predicted elastic modulus values of pavement layers—Site 5.

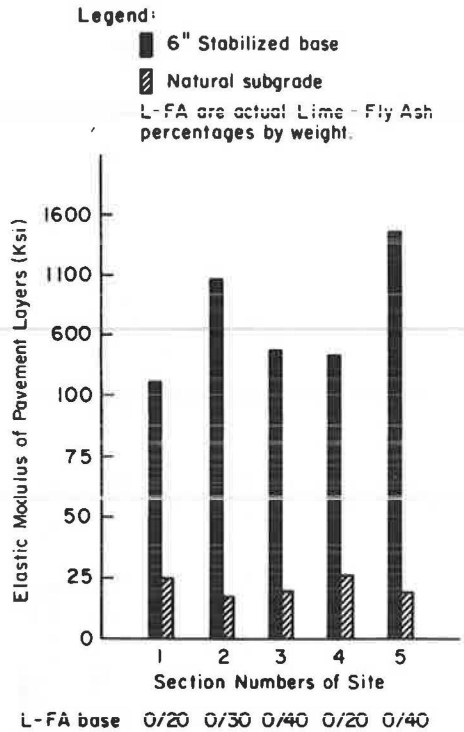

FIGURE 15 Predicted elastic modulus values of pavement layers—Site 12.

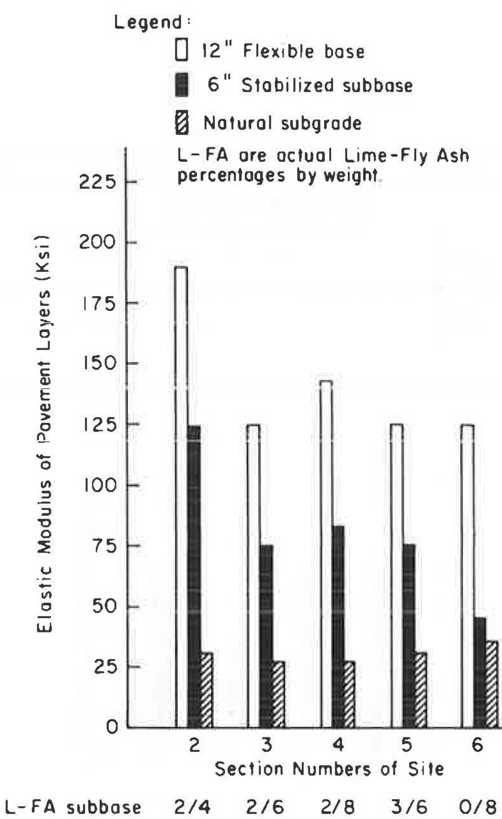

FIGURE 14 Predicted elastic modulus values of pavement layers—Site 8.

compared with the basin fitting technique by using multilayered elastic theory.

Stabilization with only fly ash was found to be generally ineffective in promoting stiffness gains in the low PI clayey soils of Sites 1, 2, 3, 4, 5, and 8 (construction types 1, 2, and 3), but effective stiffness gains were observed in the sections that were stabilized with both lime and fly ash. In comparing the stiffness gains of the test sections constructed on clayey soils, the optimum lime-fly ash ratios appear to be 0.08 to 0.50, using a minimum of 2 percent lime.

Significant stiffness gains were observed in all the sections constructed on the very low PI coarse sandy soil of Site 12 (construction type 4), which indicated that stabilization with 20 to 40 percent fly ash was highly effective for this type of soil.

CONCLUSIONS

The deflection basin matching technique discussed in this paper results in substantial savings in computational costs and affords the ability to analyze a large number of field measurements with good accuracy. This approach is directly applicable as a structural subsystem in a systems approach to pavement design such as the Texas Flexible Pavement System (8).

The structural response of the Texas lime-fly ash test sections was evaluated by the curve fitting technique discussed in this paper and the results were as follows:

1. Fly ash, by itself, was found to be generally ineffective in promoting stiffness gains in low PI clayey soils, but provided effective structural support when used with lime. The only significant exception to this finding was section 6 in Site 3,

which exhibited high stiffness with 12 percent fly ash and no lime.

2. For very low PI coarse sandy soil, stabilization with fly ash only was effective and resulted in substantial stiffness gains in the base layers of all the sections.

3. In comparing the test sections constructed on the low PI clayey soils, the optimum lime-fly ash ratios (yielding the highest stiffnesses) were found to be in the range of 0.10 to 0.50, using a minimum of 2 percent lime.

REFERENCES

1. G.W. Raba. Evaluation of Lime-Fly Ash Stabilized Bases and Subgrades Using Static and Dynamic Deflection Systems. M.S. thesis. Texas A&M University, College Station, Dec. 1982.
2. F.H. Scrivner and W.M. Moore. An Empirical Equation for Predicting Pavement Deflections. Research Report 32-12. Extension of AASHO Road Test Results. Texas Transportation Institute, Texas A&M University, College Station, Oct. 1968.
3. F.H. Scrivner and W.M. Moore. Some Recent Findings in Pavement Research. Research Report 32-9. Extension of AASHO Road Test Results. Texas Transportation Institute, Texas A&M University, College Station, July 1967.
4. N.K. Vaswani. Method for Separately Evaluating Structural Performance of Subgrades and Overlying Flexible Pavements. In Highway Research Record 362, HRB, National Research Council, Washington, D.C., 1971, pp. 48-62.
5. C.H. Michalak, D.Y. Lu, and G.W. Turman. Determining Stiffness Coefficients and Elastic Moduli of Pavement Materials from Dynamic Deflections. Research Report 207-1. Texas Transportation Institute, Texas A&M University, College Station, Nov. 1976.
6. F. McCullough and A. Taute. Use of Deflection Measurements for Determining Pavement Material Properties. In Transportation Research Record 852, TRB, National Research Council, Washington, D.C., 1982, pp. 8-14.
7. V.Z. Vlasov and N.N. Leont'ev. Beams, Plates, and Shells on Elastic Foundation (translated from Russian). Israel Program for Scientific Translations, Jerusalem, 1966.
8. R.L. Lytton and C.H. Michalak. Flexible Pavement Deflection Equation Using Elastic Moduli and Field Measurements. Research Report 207-7F. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1979.
9. N. Odemark. Investigations as to the Elastic Properties of Soils and Design of Pavements According to the Theory of Elasticity. Staten Vaeginstitut, Stockholm, Sweden, 1949.
10. J.F. Meyers, R. Pichumani, and B.S. Kapples. Fly Ash as a Construction Material for Highways. Report FHWA-IP-76-16. FHWA, U.S. Department of Transportation, May, 1976.
11. S.M. Alam. Equations for Predicting the Layer Stiffness Moduli in Pavement Systems Containing Lime-Fly Ash Stabilized Materials. M.S. thesis. Texas A&M University, College Station, May 1984.

Publication of this paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization.

The Effect of Deicing Salt on Aggregate Durability

WENDELL DUBBERKE and VERNON J. MARKS

ABSTRACT

Since 1962, the Iowa DOT has been using the methods of rapid freezing in air and thawing in water to evaluate coarse aggregate durability in concrete. Earlier research had shown that the aggregate pore system was a major factor in susceptibility to D-cracking rapid deterioration. There are cases in which service records indicate that on heavily salted primary roads, concrete containing certain aggregates show rapid deterioration while the same aggregates show relatively good performance on secondary roads with limited use of deicing salt. A five-cycle salt treatment of the coarse aggregate before durability testing has yielded durability factors that correlate with aggregate service records on heavily salted primary pavements. X-ray fluorescence analyses have shown that sulfur contents correlate well with aggregate durabilities with higher sulfur contents that produce poor durability. Trial additives affecting the salt treatment durabilities would indicate that one factor in the rapid deterioration mechanism is an adverse chemical reaction. The objective of the current research is to develop a simple method of determining aggregate susceptibility to salt-related deterioration. This method of evaluation includes analyses of both the pore system and chemical composition.