high-temperature stability and strength plus equivalent or improved low-temperature flexibility are possible by replacing a given conventional asphalt cement with a manganese-modified, softer asphalt cement from the same source. The modification must be based on a thorough study of each asphalt-aggregate combination. In general, if an AC-20 grade is specified, it should be replaced with an AC-5 grade from the same source containing enough modifier to give a 0.06 to 0.08 percent manganese content. The modified system does not require any significant changes in construction procedures and, generally, the modified asphalt will tend to compact with less effort. The use of modified asphalt may decrease energy consumption in compaction and in the hot mix plant by allowing the plant to run at lower than normal temperatures. Future reports on the specifics of property changes in experimental highway projects will be forthcoming.

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Sensitivity of Flexible Pavement Performance to Bituminous Mix Properties

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ABSTRACT

Modulus (stiffness) characterization that may be predicted is a crucial factor in the design of pavement structures. Locally produced and used bituminous materials, when not characterized correctly and statistically within an allowable significant range, will result in pavements of unreliable design thicknesses and performance. Crushed stone-, gravel-, slag-, and sand-asphalt mixes were evaluated by the dynamic modulus laboratory test in the study. Tests conducted in the Civil Engineering Department of the University of Maryland and previous tests conducted by the Asphalt Institute were combined to formulate an extensive data base of 131 different mix types and 1,179 mix-temperature-frequency data point combinations. The variables and coefficients used in the model are both statistically significant and rational from an engineering point of view. On the basis of this modulus model, a sensitivity analysis for the selected variables was done on the typical simulated pavement life models for fatigue, rutting for three layers, and rutting for full-depth sections. Some newly incorporated variables like coarse-grained materials were found to be significant in the sensitivity analysis for both the modulus model and the life models. Because of the extreme ranges in the material types and properties considered in the study, it is believed that the final regression equation is applicable to most commonly used bituminous mixtures. The development of this accurate prediction model should obviate the need for design agencies to use time-consuming and expensive laboratory testing to characterize the dynamic response of bituminous materials in pavement design.

Two general approaches to the design of pavement systems are in practice today: (a) an empirical approach such as the AASHTO method of design, which relies on the experience of the user and subsequent correlation with performance and (b) the rational or mechanistic approach, which is primarily based on theoretical concepts of modeling structural behavior. The modulus characterization of materials is important in both approaches.

One of the major properties of bituminous materials in pavement performance is the dynamic modulus, which is a function of many variables. These include aggregate type, aggregate size and gradation, aggregate shape, asphalt content, asphalt viscosity, void ratio, temperature, and frequency of loading. The development of models to predict performance on the basis of improved material characterization in the laboratory under dynamic load simulation conditions, coupled with field experience, allows for a better understanding of pavement behavior and performance in the design process.

BACKGROUND AND STATEMENT OF PROBLEM

It is current practice in many states to use the AASHTO Interim Guide in the design of pavements for state highway systems (1). In general, each state has developed its own unique material design coefficients (a_i) for local material sources and climatic conditions. A need therefore exists to characterize the specific types of pavement materials that are currently being used by state agencies.

By using existing information and pursuing research for development of a prediction model, the goal of improved pavement design can be achieved. It does require, however, a concerted effort to use research results in the design process. The effort implies a twofold obligation: the researcher must make his efforts palatable to the user, and the user in turn must be willing to assimilate the research and, if appropriate, incorporate it into the design procedure.

OBJECTIVE

It is important to know and be able to characterize accurately specific values of dynamic moduli for various pavement materials. Because recent design and construction practices have led to the use of thicker asphaltic layers in pavements (i.e., deep-strength and full-depth designs), the relative importance of determining correctly the modulus of a layer material and its performance is obvious because these factors may well constitute 50 to 100 percent of the total pavement structure.

The major objective of this study was to formulate a statistical model to predict from laboratory tests the dynamic modulus of a typical bituminous mixture. The following specific tasks were undertaken:

1. An accurate statistical model to predict the dynamic moduli of bituminous materials was developed. All significant predictor variables were considered in this model.
2. Using the results generated in the initial task, a sensitivity analysis of the model variables on (a) dynamic modulus, (b) pavement geometry, and (c) pavement performance was undertaken. The ultimate objective of this task was to assess the sensitivity of mix properties directly on pavement life (performance).

DATA COLLECTION AND GENERATION

At present there are two main bituminous modulus predictive models commonly used: (a) the Shell Oil method (2) and (b) the Asphalt Institute Model (3). The Asphalt Institute method was initiated by Shook and Kallas in 1969 on a limited number of laboratory (dynamic modulus) test results. The equation was subsequently refined from an expanded data base and then further modified by Witczak for calculating design curves. This is the formula currently used in the Asphalt Institute MS-1 Design Guide (3,4).

In 1978 a laboratory study was undertaken at the University of Maryland for the Maryland State Highway Administration (MSHA) to develop dynamic modulus characterizations of typical base and subbase materials used in pavement systems. This comprehensive study resulted in the dynamic modulus evaluation of 90 additional bituminous mixes using crushed stone, bank run gravel, slag, and sand aggregates. The results were used by Miller et al. (5) to develop a regression model.

The same data set is extensively analyzed and a more comprehensive model is recommended in the present study. The combined range of properties of different mix types is given in Table 1. The correlation matrix of all probable predictor variables and the criteria variables are given in Table 2.

Simulated Data for Sensitivity Study of Pavement Life

Failure criteria, which in turn determine the actual performance life of a pavement system, are functions of:

1. Traffic: load (W), tire pressure (P), frequency of load (f);
2. Geometry of pavement: thickness of layers (h_i), number of layers (n), modulus of layers (E_i), Poisson's ratio (μ_i); and
3. Environment: temperature (T), moisture content (m).

It is both time consuming and costly to study all variables and their correlations with pavement life.

TABLE 1 Variable Statistics

No.	Variable Type	Range (crushed stone–sand asphalt)	Mean	Standard Deviation	Coefficient of Variation
1	$P_{a.c.}$	3.0–10.2	6.2672	1.9599	0.3127
2	$P_{eff.}$	6.2–18.95	12.2095	3.3960	0.2781
3	P_{air}	0.0–15.90	6.8755	3.5326	0.5138
4	P_{200}	0.4–10.60	5.4756	2.8045	0.5122
5	$P_{3/4}$	0.0–29.30	7.1817	9.7741	1.3610
6	$P_{3/8}$	0.0–58.00	20.8596	17.0753	0.8186
7	P_4	3.0–67.00	31.8657	17.3298	0.5438
8	$P_{abs.}$	0.0–2.50	0.9788	0.5929	0.6058
9	η	1.3–4.30	1.7533	0.7788	0.4442
10	T	40.0–100.0	69.9999	24.5053	0.3501
11	f	1.0–4.0	7.0000	6.7835	0.9262
12	$P_{opt.eff.}$	6.2–18.75	12.1985	3.2592	0.2672
13	Modulus	0.32–40.60	7.11978	6.6301	0.9312

Note: $P_{a.c.}$ = asphalt content by weight (%); $P_{eff.}$ = effective asphalt content by volume (V_{eb}); P_{air} = percentage air void by volume (V_{air}); P_{200} = percentage passing No. 200 sieve by weight; $P_{3/4}$ = percentage retained on No. 3/4 sieve by weight; $P_{3/8}$ = percentage retained on No. 3/8 sieve by weight; P_4 = percentage retained on No. 4 sieve by weight; $P_{abs.}$ = percentage asphalt absorbed by weight; η = viscosity, poise; T = temperature (°F); f = frequency (Hz); $P_{opt.eff.}$ = percentage effective asphalt content by volume at optimum asphalt content only, adjusted for = ±1% asphalt content from optimum; and Modulus = dynamic modulus test results |E|, *10**5 psi.

TABLE 2 Correlation Matrix Combined (N = 1179)

No.	Variable	$P_{a.c.}$	$P_{eff.}$	P_{air}	P_{200}	$P_{3/4}$	$P_{3/8}$	P_4	$P_{abs.}$	η	T	f	$P_{opt.eff.}$	E
1	$P_{a.c.}$	1.0000												
2	$P_{eff.}$	0.9509	1.0000											
3	P_{air}	0.2549	0.0282	1.0000										
4	P_{200}	−0.2408	−0.2523	−0.0048	1.0000									
5	$P_{3/4}$	−0.4444	−0.3600	−0.4180	0.1212	1.0000								
6	$P_{3/8}$	−0.6528	−0.5531	−0.4428	−0.0089	−0.8441	1.0000							
7	P_4	−0.7755	−0.6465	−0.4591	−0.0354	0.6530	0.8497	1.0000						
8	$P_{abs.}$	0.2033	0.0198	0.3923	0.0163	−0.6495	−0.5677	−0.4331	1.0000					
9	η	−0.1762	−0.1465	0.0027	−0.0198	−0.3250	−0.1722	0.0204	0.3111	1.0000				
10	T	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000			
11	f	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000		
12	$P_{opt.eff.}$	0.9283	0.9630	0.0965	−0.2615	−0.3726	−0.5728	−0.6692	0.0184	−0.1511	0.0000	0.0000	1.0000	
13	E	−0.2112	−0.1752	−0.2621	0.0308	0.2677	0.2755	0.2202	−0.1150	0.0608	−0.7850	0.2194	−0.1806	1.0000

Note: $P_{a.c.}$ = asphalt content by weight (%); $P_{eff.}$ = effective asphalt content by volume (V_{eb}); P_{air} = percentage air void by volume (V_{air}); P_{200} = percentage passing No. 200 sieve by weight; $P_{3/4}$ = percentage retained on No. 3/4 sieve by weight; $P_{3/8}$ = percentage retained on No. 3/8 sieve by weight; P_4 = percentage retained on No. 4 sieve by weight; $P_{abs.}$ = percentage asphalt absorbed by weight; η = viscosity, poise; T = temperature (°F); f = frequency (Hz); $P_{opt.eff.}$ = percentage effective asphalt content by volume adjusted for optimum asphalt content; and E = dynamic modulus *10**5 psi.

Therefore the approach used in this study was to analyze and study the sensitivity of pavement life with respect to certain controllable variables while other variables were held constant within an allowable and acceptable range.

In pavement analysis bituminous fatigue cracking is generally analyzed by the equation of the form:

$$N_f = a(1/\varepsilon_t)^b \qquad (1)$$

where N_f is number of load applications to fatigue failure; ε_t is maximum tensile strain applied; and a and b are coefficients resulting from fatigue tests on asphalt materials modified to reflect in situ performance. One such fatigue performance model, presented by the Asphalt Institute in its MS-1 highway design manual (3), is represented by

$$N = 18.4 \times 10^{\{4.84[P_{eff}/(P_{air} + P_{eff}) - 0.69]\}} \times 0.004325 \times \varepsilon_t^{-3.291} E^{-0.854} \qquad (2)$$

Like the fatigue criteria, the vertical compressive strain criteria can be expressed by an equation of the form:

$$N_f = c(1/\varepsilon_v)^d \qquad (3)$$

where N_f is the number of load applications to a predefined performance level; ε_v is the vertical compressive strain on the subgrade surface; and c and d are coefficients determined from analysis of in situ pavements or sections designed according to some prescribed methodology. The typical values used in the Asphalt Institute MS-1 design manual are c = 0.1365×10^{-8}, and d = 4.477.

Assumed Load, Geometry, and Data Points

In multilayer elastic pavement analysis values of ε_t, ε_v, and $|E^*|$ must be determined to estimate the life of any particular system. In this study the following procedure was used. The theoretical critical strain values were determined for a variety of pavement cross sections and layer properties (h_i, E_i) from the Chevron multilayer elastic theory computer program. Figure 1 shows the three-layer pavement system, load, and pavement layer variables analyzed to predict the critical tensile strain and the vertical compressive subgrade strains.

The Chevron computer program was used to find 750 (= 30 x 25) values of tangential strain under the bituminous layer and the vertical strain at the top of the subgrade. When the 750 values were known on the basis of a 10-ksi subgrade modulus, 3,000 (= 750 x 4) values were generated for three other subgrade modulus values of 5, 20, and 40 ksi using the ratio of the subgrade moduli. When these strains were known, regression equations relating the pavement properties and the layer thicknesses to predicted life until either fatigue cracking or deformation were established. The comparative studies were done on two levels of traffic, high traffic volume (15 to 150 x 10^5 repetitions) and low traffic volume (0.7 to 15 x 10^5 repetitions).

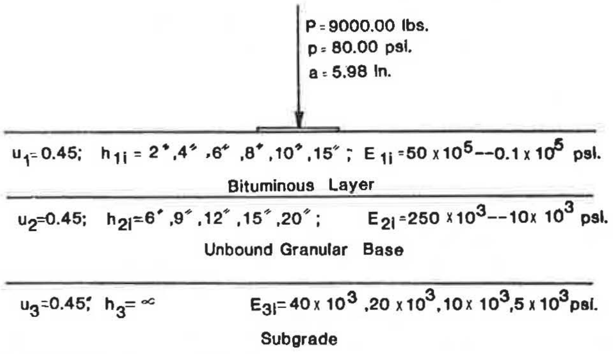

FIGURE 1 Assumed load, geometry, and material properties for simulated data.

RESULTS

The results are presented in three major divisions: development of a dynamic modulus prediction model; development of life prediction models, fatigue and rutting failure criteria on three layers and full-depth pavement system; and sensitivity analysis of the effect of dynamic modulus properties and pavement properties on the life of a pavement system. "Best subset model" analyses were performed to develop these models according to the Biomedical Computer Programs P-Series (6).

Dynamic Modulus Model

Comparisons of the new models and their accuracy of prediction are provided in Table 3 and Figure 2. Model 5 is finally recommended for its convenience in computation and ease of correlation with earlier models.

Life Prediction Models

These models were developed on the basis of generated data points of typical loads and geometries of

TABLE 3 Summary of Analysis of Modulus Prediction Models

		Log Scale		Arithmetic		
No.	Model	R^2	Se	R^2	Se	Remarks
1	Original TAI: $\log E = 0.553833 + 0.028829 * P_{200} * f^{-0.17033} - 0.03476 * P_{air} + 0.070377 * \eta + 0.931757 * f^{-0.02774} + T^{(1.3+0.49825*\log f)} * (0.000005 - 0.00189 * f^{-1.1}) * P_{a.c.}{}^{0.5}$	0.858	0.216	0.821	2.598	Based on 41 samples
2	Original TAI plus Miller's correction *(6)*: $\log E = 0.553833 + 0.028829 * P_{200} * f^{-0.17033} - 0.03476 * P_{air} + 0.070377 * \eta + 0.931757 * f^{-0.02774} + T^{(1.3+0.49825*\log f)} * (0.000005 - 0.00189 * f^{-1.1}) * [(P_{eff.} - P_{opt.eff.} + 8) * 0.483]^{0.5}$	0.877	0.150	0.788	3.063	Based on 131 samples; assumed: $P_{a.c.}$ (by wt.) = $P_{eff.}$ (by vol.) * 0.483
3	A typical log linear model with new variables: $\log E = 2.06171 - 0.0206194 * P_{eff.} - 0.01272698 * P_{air} - 0.00187302 * P_{200} + 0.0102445 * P_{3/4} + 0.00209684 * P_{3/8} - 0.00489546 * P_4 + 0.0131639 * P_{abs.} + 0.0552319 * \eta - 0.0167950 * T + 0.0180509 * f$	0.913	0.127	0.868	2.676	Based on 131 samples; note that some new variables are added
4	A typical polynomial model (with interacting terms): $\log E = 2.468 - 0.1155 * P_{eff.} - 0.0299 * P_{air} - 0.0975 * P_{200} - 0.00963 * P_4 + 0.359 * P_{abs.} - 0.00815 * T + 0.0660 * f - 0.0000618 * T^2 + 0.00253 * P_{eff.}{}^2 + 0.00830 * P_{200}{}^2 - 0.00164 * P_{3/4}{}^2 + 0.000308 * P_{3/8}{}^2 + 0.000204 * P_4{}^2 - 0.105 * P_{abs.}{}^2 + 0.0171 * \eta^2 - 0.00268 * f^2 + 0.00167 * P_{3/8} * P_{eff.} + 0.000709 * P_{3/4} * P_{eff.} + 0.000937 * P_{3/4} * P_4 - 0.00069 * P_{3/8} * P_4 - 0.0031 * P_{3/8} * P_{abs.}$	0.950	0.103	0.905	2.246	More sensitive variables (t-test more than 2.5) were considered; second alternative recommendation
5	Final recommendation models: $\log E = 1.45716 - 0.0256272 * P_{air} + 0.0127921 * P_{3/4} + 0.0627099 * \eta - 0.00837349 * T + 0.147306 * \log f + 0.0000193164 * \log f * T^2 - 0.0000254103 (P_{eff.} - P_{opt.eff.} + 8.0)^{0.5} * T^2 - 0.000149152 * P_{eff.} * P_4 + 0.00591768 * P_{200} * P_{abs.}$	0.934	0.122	0.873	2.339	All variables are sensitive (t-test more than 4.75), see Figure 2
5a	$\log E = 1.42841 - 0.0233473 * P_{air} + 0.013004 * P_{3/4} + 0.0627099 * \eta - 0.008145 * T + 0.146970 * \log f + 0.0000193776 * \log f * T^2 - 0.000073466415 * T^2 - 0.000138513 * P_{eff.} * P_4 + 0.00583715 * P_{200} * P_{abs.}$	0.931	0.125	–	–	For simplicity when $P_{eff.} - P_{opt.eff.} \cong 0$ (i.e., when $P_{eff.}$ is less ± 1% from $P_{opt.eff.}$)

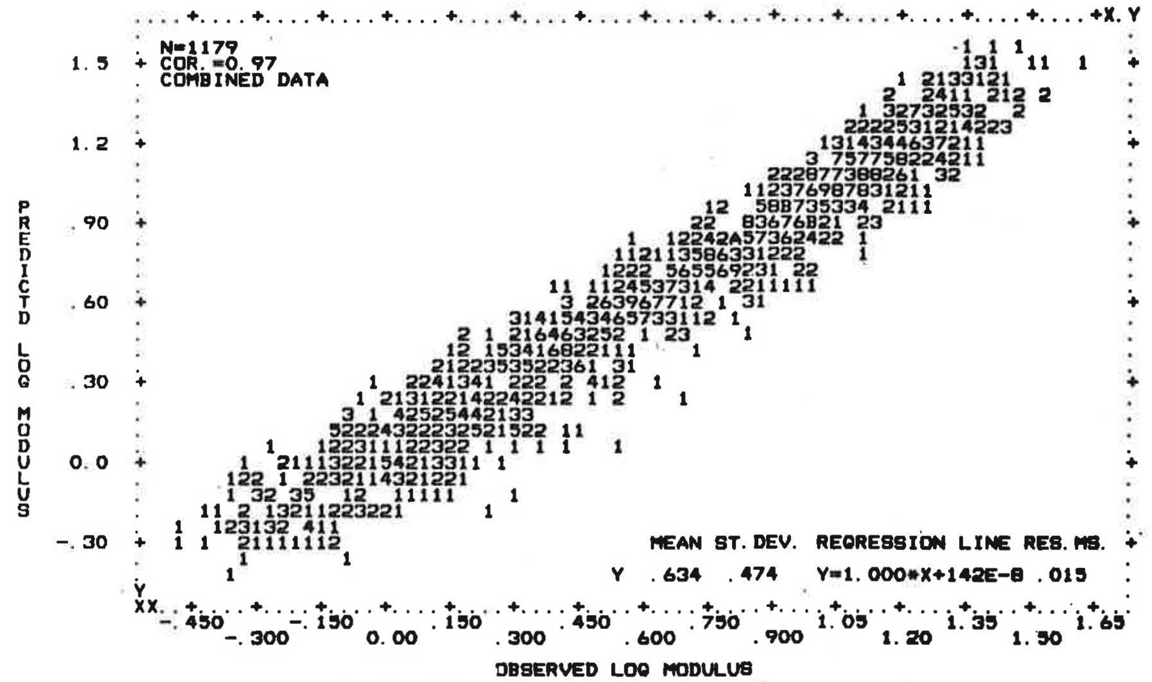

FIGURE 2 Relation between predicted modulus and observed modulus (*10**5 psi) in logscale.

TABLE 4 Summary of Simulated Pavement Life Models

No.	Model	Log Scale (R^2)	Remarks
1	N_f (fatigue life) = 18.4 * $10^{\{4.84*[P_{a.c.}/(P_{air}+P_{a.c.})-0.69]\}}$ * ϵ_f^{**} (–3.291) * (0.004325) * $E1^{-0.854}$ * 0.00001 where ϵ_t = 10** [3.76158 + 1.68109 * log H1 – 0.568424 * log H2 + 0.525136 * log E1 – 1.47607 * log E2 – 1.34128 * log H1 * log H2 + 0.473449 * $(\log H2)^2$ – 0.170227 * $(\log E1)^2$ – 0.215683 * $(\log E2)^2$ – 0.508105 * log H1 * log E1 + 0.578433 * log H1 * log E2 – 0.0636076 * log H1 * log E3 – 0.257907 * log H2 * log E1 + 0.278416 * log H2 * log E3 + 0.440366 * log E1 * * log E2 – 0.0947499 * log E1 * log E3]	0.968	N = 2,866, ϵ_t = 0.0 to 500,000 microinch; t-statistics of all terms >2.5
2	N_f (rutting) = 10** [–11.2799 + 0.721550 * log E1 + 0.626242 * log E2 + 3.18089 * log E3 + 4.21226 * log H2 + 1.62104 * log E1 * log H1 – 0.414480 * log E1 * log E2 – 1.07152 * log E2 * log E3 – 1.29006 * log E1 * log H2 – 0.213647 * log E1 * log E3 – 0.385765 * log H1 * log E3 – 3.013164 * log H1 * log H2 + 0.316417 * $(\log E1)^2$ + 2.44510 * $(\log H1)^2$ + 0.846415 * $(\log E2)^2$ + 2.52927 * $(\log H2)^2$ + 0.632307 * $(\log E3)^2$]	0.970	N = 1,226, N_f = 0.01 * 10^5 to 5000 * 10^5 repetitions; t-statistics of all terms >3.5
3	N_f (full-depth rutting) = 10** [–4.09170 – 7.04070 * log H1 + 3.47788 * log E1 * log H1 – 2.77970 * log E1 * log E2 + 0.42150 * $(\log E1)^2$ + 5.15104 * $(\log E2)^2$ – 0.032375 * $(\log E1)^3$ – 0.929099 * $(\log E2)^3$ + 3.57083 * $(\log H1)^3$ + 0.348792 * $(\log E1)^2$ * log E2 – 1.18682 * $(\log E2)^2$ * log H1 + 1.33166 * $(\log H1)^2$ * log E1 – 0.108265 * log E2 – 1.18682 * $(\log E2)^2$ * log H1 + 1.33166 * $(\log H1)^2$ * log E1 – 0.108265 * $(\log E1)^2$ * log H1 + 0.775561 * $(\log H1)^2$ * log E2 – 1.52762 * log E1 * $(\log H1)^3$]	0.999	N = 246, N_f = 0.01 * 10^5 to 5,000 * 10^5 repetitions; t-statistics of all terms >4.0

pavement systems. A summary of the prediction models is given in Table 4.

Sensitivity Analysis

The change of criterion, which is variable with respect to the change of predictor variable, can be studied using an expanded version of Taylor's Series. The linear terms may be taken to study the approximate relative sensitivity of any variable. This sensitivity analysis was divided into three parts: (a) sensitivity of dynamic modulus with respect to mix properties, (b) sensitivity of pavement life with respect to geometric properties of pavement, and (c) sensitivity of pavement life with respect to bituminous mix properties. The results of the three analyses are given in Tables 5-7 and shown in Figures 3 and 4. The range limitations, the linear relationship, and the percent change of modulus or life in linear approximation of Taylor's Series are shown in the tables. Some examples of calculations follow:

Example 1

Increasing $P_{3/4}$ from 20 to 30 percent for
modulus relative sensitivity (R.S.)
= 0.02945 x 20 - 3.4 x 10^{-9} = 0.589
percent change of modulus improvement
= [(30 - 20)/E_{20}]
= R.S. x {[$P_{3/4(30)}$ - $P_{3/4(20)}$]/$P_{3/4(20)}$}
= 0.589 x 0.50
= 0.2945 ≈ 30 percent

TABLE 5 Sensitivity Analysis: Modulus with Respect to Bituminous Mix Properties

No.	Type of Variable	Range and Limitation	Relative Sensitivity Mean (%)	Standard Deviation	Equation R.S. =	R	Change of Modulus Linear Approximation (%)
1	T	40° F to 100° F	–287.4	1.46	–0.0581 * T + 1.192	–0.976	–50 to +50
2	$P_{eff.}$	6.2 to 18.95%	–81.6	0.49	–0.04979 * $P_{eff.}$ – 0.209	–0.35	–20 to +10.0
3	$P_{opt.eff.}$	6.2 to 18.95%	+69.8	0.496	–0.0579 * $P_{opt.eff.}$ –0.0087	+0.38	+20.0 to +10.0[a]
4	P_{air}	0.0 to 15.9%	–41.0	0.21	–0.059 * P_{air} – 7.0 * 10^{-9}	–1.00	–18.0 to +9.0[b]
5	n	1.31 to 4.43%	+25.3	0.112	–0.1444 * n + 0.000	+1.00	–7.0 to +9.0
6	f	1.0 to 16.0	+25.4	0.07	–1.1 * 10^{-10} * f + 0.254	–1.00	–15.0 to +30.0
7	$P_{3/4}$	0.0 to 29.3%	+21.6	0.288	+0.02945 * $P_{3/4}$ – 3.4 * 10^{-9}	+1.00	–40 to +30.0
8	P_4	0.0 to 67%	–12.6	0.060	–0.0029 * P_4 – 0.02805	–0.84	–9.0 to +3.0
9	P_{200}	0.4 to 10.6%	+7.3	0.061	+0.01406 * P_{200} – 0.0036	+0.651	–1.5 to 3.0
10	$P_{abs.}$	0.0 to 2.5%	+7.3	0.061	+0.06902 * $P_{abs.}$ + 0.006	+0.676	–1.5 to +2.5

Note: $P_{eff.}$ = percentage effective asphalt content by volume, $P_{opt.eff.}$ = percentage effective asphalt content at optimum. See also notes to Tables 1 and 2.

[a] Sensitivity is opposite that of $P_{eff.}$ because of the adjustment factor.

[b] See Figures 3 and 4.

TABLE 6 Sensitivity Analysis: Life with Respect to Pavement Geometric Properties

			Relative Sensitivity				Change of Life Linear Approximation (%)
No.	Variable	Range and Limitation	Mean (%)	Standard Deviation	Equation R.S. =	R	
Fatigue Criteria							
1	H1	HTV	232.9	2.166	$+0.5754 * H1 - 0.982$	+0.76	−75 to +675
		LTV	134.0	2.362	$+0.733 * H1 - 1.943$	+0.76	−30 to +240
		H1: 2-15 in.					
2	E2	HTV	181.8	0.959	$+0.0037 * E2 + 1.566$	+0.16	−150 to +250
		LTV	129.0	1.044	$+0.0187 * E2 + 0.831$	+0.23	−70 to +140
		E2: 10-250 ksi					
3	E1	HTV	44.2	0.982	$+3.92 * 10^{-4} * E1 - 0.112$	+0.61	−120 to +120
		LTV	72.2	1.034	$+4.58 * 10^{-4} * * E1 + 0.0598$	+0.71	−120 to +120
		E1: 10-500 ksi					
4	H2	HTV	30.3	0.393	$-0.034 * H2 + 0.72$	−0.43	−50 to +36
		LTV	29.6	0.407	$-0.0334 * H2 + 0.70$	−0.39	−50 to +36
		H2: 6-20 in.					
5	E3	HTV	10.5	0.240	$+8.96 * 10^{-4} * E3 + 0.117$	−0.04	−27 to +27
		LTV	9.7	0.253	$-2.72 * 10^{-4} * E3 + 0.100$	−0.01	−27 to +27
		E3: 5-40 ksi					
Rutting on Subgrade Criteria							
1	H2	HTV	418.2	1.666	$+0.246 * H2 + 1.2508$	+0.68	−240 to +240
		LTV	427.9	1.566	$+0.236 * H2 + 1.738$	+0.60	−180 to +180
		H2: 6-20 in.					
2	H1	HTV	384.8	1.930	$+0.399 * H1 + 1.651$	+0.59	−200 to +500
		LTV	349.6	1.865	$+0.4674 * H1 + 1.55$	+0.61	−150 to +750
		H1: 2-15 in.					
3	E3	HTV	174.5	0.582	$+0.035*E3 + 1.30$	+0.59	−100 to +400
		LTV	179.2	0.560	$+0.04204*E3 + 1.367$	+0.53	−75 to +225
		E3: 5-40 ksi					
4	E2	HTV	152.5	0.780	$+0.0087*E2 + 0.777$	+0.72	−100 to +250
		LTV	140.3	0.753	$+0.0096*E2 + 0.748$	+0.72	−60 to +300
		E2: 10-250 ksi					
5	E1	HTV	111.4	0.752	$+2.19*10^{-4}E1 + 0.862$	+0.41	−150 to +375
		LTV	106.5	0.714	$+2.48*10^{-4}E1 + 0.759$	+0.51	+120 to +420
		E1: 10-500 ksi					
Rutting on Second Layer (full depth) Criteria							
1	H1	HTV	589.3	1.764	$0.288*H1 + 3.804$	+0.46	−300 to +300
		LTV	494.5	2.776	$+0.5668*H1 + 1.702$	+0.53	−250 to +500
		H1: 2-15 in.					
2	E2	HTV	191.0	0.866	$0.0324*E2 + 1.139$	+0.46	−100 to +150
		LTV	215.9	1.111	$+0.063*E2 + 0.664$	+0.69	−120 to +150
		E1: 10-40 ksi					
3	E1	HTV	136.1	0.945	$+2.18*10^{-4}*E1 + 1.103$	+0.37	−150 to +225
		LTV	82.6	1.383	$+3.16*10^{-4}*E1 + 0.393$	+0.38	−180 to +120
		E1: 10-50 ksi					

Note: HTV = high traffic volume = 15 to 150 x 10^5 repetitions; LTV = low traffic volume = 0.7 to 15 x 10^5 repetitions; H1 = thickness 1, bituminous material; E2 = modulus 2, granular material; E1 = modulus 1, bituminous material; H2 = thickness 2, granular material; E3 = modulus of subgrade material; P_{200} = percentage passing No. 200 sieve by weight; $P_{abs.}$ = percentage asphalt absorbed by weight; $P_{opt.eff.}$ = percentage effective asphalt by volume at optimum; $P_{eff.}$ = percentage effective asphalt content by volume; P_{air} = percentage air void by volume.

[a] R.S. slope is negative because of adjustment factor; negligible sensitivity.

Example 2

Increasing $P_{3/4}$ from 20 to 30 percent for pavement life relative sensitivity (R.S.)

$= 0.05464 \times 20 + 0.07226 = 1.16506$

percent change of pavement life improvement

$= [(N_{30} - N_{20})/N_{20}]$

$= R.S. \times \left(\left\{[P_{3/4(30)}] - [P_{3/4(20)}]\right\}/P_{3/4(20)}\right)$

$= 1.16507 \times 0.50$

$= 0.5825 \simeq 58$ percent

The approximate graphic representation is also shown in Figures 5-8.

CONCLUSIONS

The result of the prediction model for dynamic modulus has shown that three new variables, which do not appear in previous regression models found in the literature, are primarily responsible for the increased predictive accuracy of the models developed in this study. They are (a) the percentage retained on No. 3/4 sieve, (b) the percentage retained on No. 4 sieve, and (c) the percentage of asphalt absorbed (by weight). These three variables have been incorporated in the final recommended model and are also present, along with percentage retained on No. 3/8 sieve, in the alternative recommended model (Table 3).

One of the major findings of the study is that gradation (distribution of aggregate sizes) plays an important role in defining the dynamic modulus of asphalt mixtures. Each form of the two models was found to have rational coefficients.

The sensitivity analysis of the dynamic modulus with respect to all variable properties proved the significance of all variables in the model. By using linear approximations of the Taylor Series (Figures 3 and 4) the range of relative sensitivity of each parameter was ascertained. The ranking of variable sensitivity, from highest to lowest, is shown in Table 5. The most significant variable affecting the dynamic modulus is the temperature of the mix. The

TABLE 7 Sensitivity Analysis: Pavement Life with Respect to Bituminous Mix Properties

			Relative Sensitivity				Change of Life Linear Approximation (%)
No.	Variable	Range and Limitation	Mean (%)	Standard Deviation	Equation R.S. =	R	
Fatigue (strain criteria)							
1	P_{air}	HTV P_{air}: 2.85-15.90%	−308	1.107	$-0.04748 * P_{air} - 2.756$	−0.14	−30.0 to +30.0
		LTV P_{air}: 3.5-15.90%	−328	1.330	$+0.00467 * P_{air} - 3.327$	+0.01	−25.0 to +25.0
2	$P_{eff.}$	HTV $P_{eff.}$: 6.20-18.10%	+116	1.83	$-0.160 * P_{eff.} + 2.97$	−0.29	−25.0 to +25.0
		LTV $P_{eff.}$: 7.2-18.95%	+88.7	1.58	$-0.1578 * P_{eff.} + 2.671$	−0.27	−50.0 to +50.0
3	η	HTV η: 1.40-4.43	+51.1	0.64	$+0.198 * \eta + 0.147$	+0.28	−50.0 to +50.0
		LTV η: 1.31-4.43	+54.6	0.49	$0.1816 * \eta + 0.212$	+0.24	−17.0 to +17.0
4	$P_{3/4}$	HTV $P_{3/4}$: 0.0-29.3%	+52.2	0.92	$0.0546 * P_{3/4} + 0.072$	±0.57	−45.0 to +30
		LTV $P_{3/4}$: 0.0-29.3%	+47.0	0.86	$0.08223 * P_{3/4} - 0.0183$	+0.78	−75.0 to +75.0
5	P_4	HTV P_4: 3.0-62.30%	−24.7	0.281	$-0.0048 * P_4 - 0.077$	−0.28	−9.0 to +9.0
		LTV P_4: 9.0-65.60%	−23.4	0.240	$-0.0071 * P_4 - 0.0304$	−0.49	−7.0 to +15.0
6	P_{200}	HTV P_{200}: 2.0-10.6%	+12.7	0.19	$+0.01636 * P_{200} + 0.033$	+0.21	−6.0 to +6.0
		LTV P_{200}: 2.0-10.6%	+16.6	0.21	$+0.0235 * P_{200} + 0.0295$	+0.31	−7.5 to +7.5
7	$P_{abs.}$	HTV $P_{abs.}$: 0.0-2.5	+12.7	0.19	$+0.0658 * P_{abs.} + 0.0694$	+0.19	−7.0 to +7.0
		LTV	+16.6	0.21	$+0.0697 * P_{abs.} + 0.0956$	+0.18	−7.0 to +7.5
8	$P_{opt.eff.}$[a]						
Rutting on Subgrade Criteria							
1	$P_{eff.}$	HTV $P_{eff.}$: 7.2-18.9%	−86.4	0.67	$-0.0526 * P_{eff.} - 0.222$	−0.26	−15.0 to +15.0
		LTV $P_{eff.}$: 7.2-18.9%	−89.4	0.70	$-0.0465 * P_{eff.} - 0.307$	−0.22	−15.0 to + 15.0
2	P_{air}	HTV P_{air}: 0.0-14.1%	−48.4	0.38	$-0.0676 * P_{air} - 0.0665$	−0.65	−12.5 to +12.5
		LTV P_{air}: 0.0-10.45%	−45.5	0.35	$-0.0619 * P_{air} + 0.0137$	−0.68	−15.0 to +7.5
3	η	HTV η: 1.4-4.43	+28.7	0.21	$+0.1805 * \eta - 0.0187$	+0.62	−12.5 to +12.5
		LTV η: 1.4-4.43	+25.0	0.22	$+0.0999 * \eta + 0.0738$	+0.50	+17.5 to −17.5
4	$P_{3/4}$	HTV $P_{3/4}$: 0.0-29.3%	+25.8	0.41	$+0.03639 * P_{3/4} - 0.0109$	+0.84	0.0 to +40.0
		LTV $P_{3/4}$: 0.0-29.3%	+19.1	0.35	$+0.0333 * P_{3/4} - 0.009$	+0.87	0.0 to +30.0
5	P_4	HTV P_4: 3.0-62.30%	−12.9	0.10	$-0.003 * P_4 - 0.0348$	−0.52	−6.0 to +6.0
		LTV P_4: 3.0-62.30%	−17.2	0.08	$-0.00428 * P_4 - 0.024$	−0.59	−7.5 to +3.5
6	P_{200}	HTV P_{200}: 0.4-10.6	+5.52	0.054	$+0.0104 * P_{200} - 0.0023$		−1.75 to +1.75
		LTV P_{200}: 2.0-10.0%	+5.50	0.05	$+0.0108 * P_{200} - 0.0054$		−2.0 to +2.0
7	$P_{abs.}$[b]						
8	$P_{opt.eff.}$[c]						
Rutting on Second Layer (full depth) Criteria							
1	$P_{eff.}$	HTV $P_{eff.}$: 7.39-12.38%	−186.6	0.86	$-0.1498 * P_{eff.} - 0.431$	−0.26	−18.0 to +18.0
		LTV $P_{eff.}$: 7.5-12.38%	−206.5	1.03	$+0.2336 * P_{eff.} + 1.042$	−0.52	−12.5 to +12.5
2	$P_{3/4}$	HTV $P_{3/4}$: 0.0-29.3%	+169.0	1.21	$+0.113 * P_{3/4} - 0.077$	+0.98	−40.0 to +260.0
		LTV $P_{3/4}$: 0.0-29.3%	+143.5	0.97	$+0.09795 * P_{3/4} - 0.117$	+0.97	−17.5 to +245.0
3	P_{air}	HTV P_{air}: 2.79-14.80%	−123.6	0.56	$-0.183 * P_{air} - 0.114$	−0.95	−25.0 to +25.0
		LTV P_{air}: 2.99-13.20%	−109.6	0.48	$-6.4959 * P_{air} - 0.244$	−0.84	−17.5 to +17.5
4	η	HTV η: 1.4-2.64	+75.6	0.19	$+0.3923 * \eta + 0.1625$	+0.78	−9.0 to +9.0
		LTV η: 1.4-2.64	+59.6	0.14	$+0.166 * \eta + 0.3525$	+0.38	−6.0 to +12.0
5	P_4	HTV P_4: 23-62.3%	−47.5	0.17	$-0.00945 * P_4 - 0.04$	−0.82	−10.0 to +15.0
		LTV P_4: 31.3-65.6%	−40.9	0.14	$-0.0061 * P_4 - 0.1155$	−0.64	−17.5 to +14.0
6	P_{200}	HTV P_{200}: 7.39-12.38%	+16.9	0.163	$+0.03057 * P_{200} - 0.068$		−3.52 to 5.25
		LTV P_{200}: 2.3-10.6%	+10.5	0.105	$+0.02001 * P_{200} - 0.0298$		−1.75 to 5.25
7	$P_{abs.}$[d]	HTV $P_{abs.}$: 0.20-2.50%					
		LTV $P_{abs.}$: 2.50-3.0%					
8	$P_{opt.eff.}$[c]						

Note: HTV = high traffic volume = 15 to 150 x 10^5 repetitions; LTV = low traffic volume = 0.7 to 15 x 10^5 repetitions; P_{air} = percentage air void by volume; $P_{eff.}$ = percentage effective asphalt content by volume; η = viscosity (poise); $P_{3/4}$ = percentage retained on No. 3/4 sieve by weight; P_4 = percentage retained on No. 4 sieve by weight; P_{200} = percentage passing No. 200 sieve by weight; $P_{abs.}$ = percentage asphalt absorbed by weight; $P_{opt.eff.}$ = percentage effective asphalt content by volume.

[a] R.S. slope is negative because of adjustment factor. Negligible sensitivity.
[b] Very negligible sensitivity.
[c] R.S. slope is not rational because of adjustment factor.
[d] Negligible sensitivity.

next major set of variables is composed of factors influencing the amount and type of asphalt in the mix (asphalt content, asphalt viscosity, and the air void percentage of the mix). The frequency of load (f) is the next most significant variable. This parameter, reflecting the rate of vehicle loading on the mix, is a variable that, like temperature, cannot be controlled by the mix properties. The final set of significant variables reflects the gradation of the aggregate ($P_{3/4}$, P_4, and P_{200}).

Influence of Pavement Geometric Properties on Life

The models given in Table 4 were developed on the basis of a simulated data base of typical axle loading and typical geometric properties of three layers for normal highway pavements. The range of variation for the dynamic modulus of the bituminous (first) layer was kept within that of the experimental dynamic modulus. From the sensitivity analysis (Table 6), it is observed that the thickness of the bituminous layer is the single most important variable in all failure modes. The next important variable is the granular modulus in fatigue life and the subgrade modulus in rutting failures. The modulus of the bituminous material is third in importance in fatigue life and last in rutting failures. The percentage change of life in linear approximation more or less follows the same order except in the three-layer rutting analysis. This indicates that the material characterization of bituminous and granular layers and the thickness of the bituminous layer are significant.

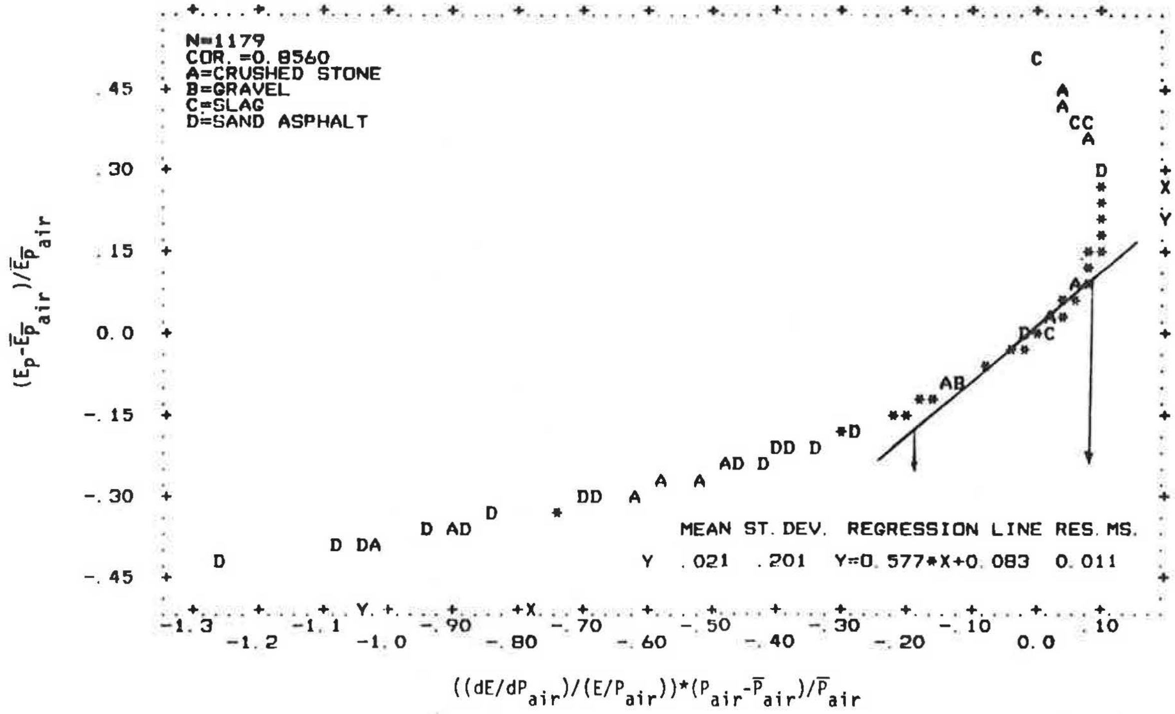

FIGURE 3 Relation between ratio of change of relative sensitivity and modulus with respect to percent air void by volume.

Influence of Modulus Properties on Life

The sensitivity analysis of the life of a typical pavement (simulated geometric and pavement properties) with respect to the properties of the first bituminous layer (equivalent to experimental samples) is given in order of relative sensitivity in Table 7. Both air void and effective asphalt content are consistently more significant in all modes of failure among all the variables except temperature and frequency (excluded), as shown in Table 7. The relative sensitivity of effective asphalt content is positive in fatigue failure but negative in rutting failure. The percentage retained on No. 3/4 sieve ($P_{3/4}$) is next to viscosity in fatigue life and three-layer rutting but second in full-depth rutting. The relative sensitivity is positive in all cases, which indicates that its addition will en-

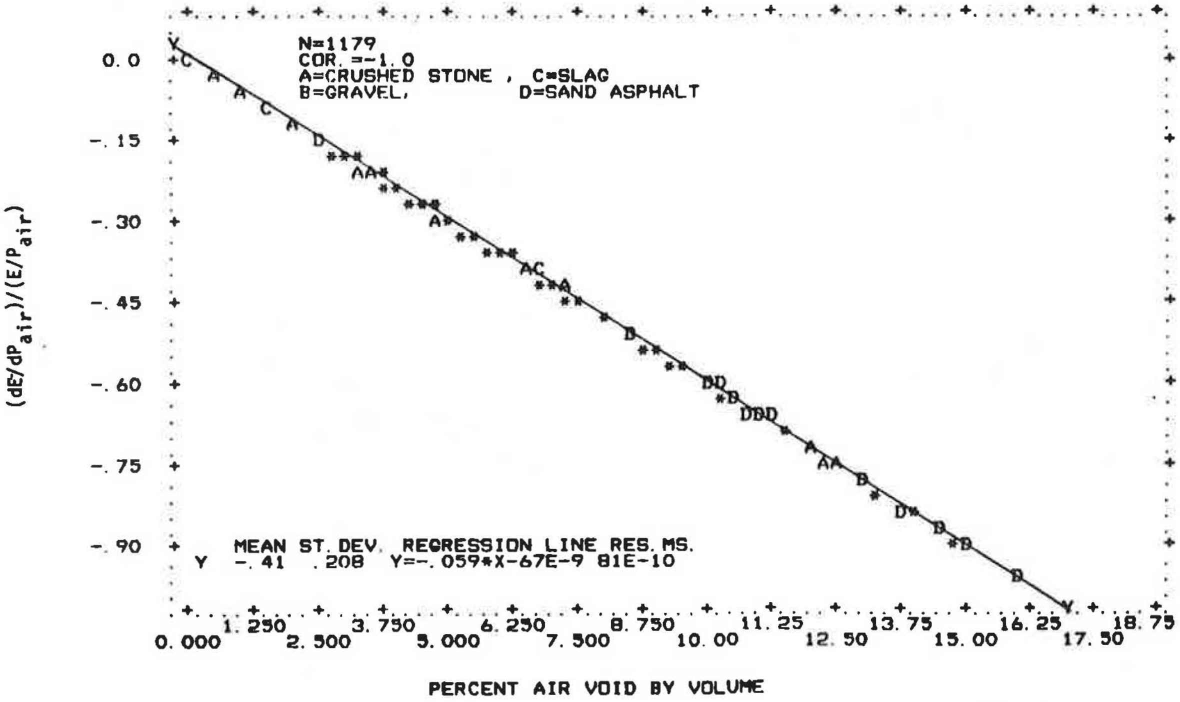

FIGURE 4 Relation between air void and relative sensitivity of modulus with respect to percent air void by volume.

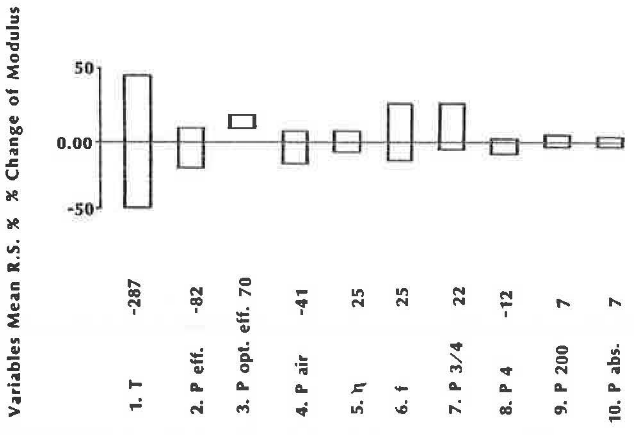

FIGURE 5 Sensitivity of modulus with respect to variables (range of percentage change of dynamic modulus with respect to mix properties).

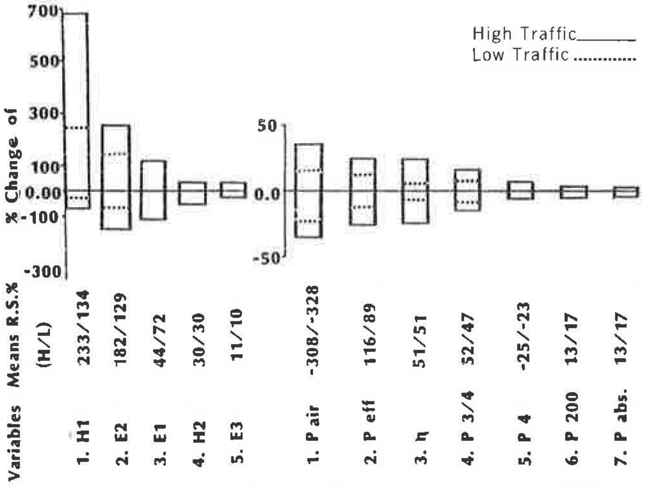

FIGURE 6 Sensitivity of fatigue failure with respect to variables (range of percentage change of life with respect to geometry and mix properties–fatigue).

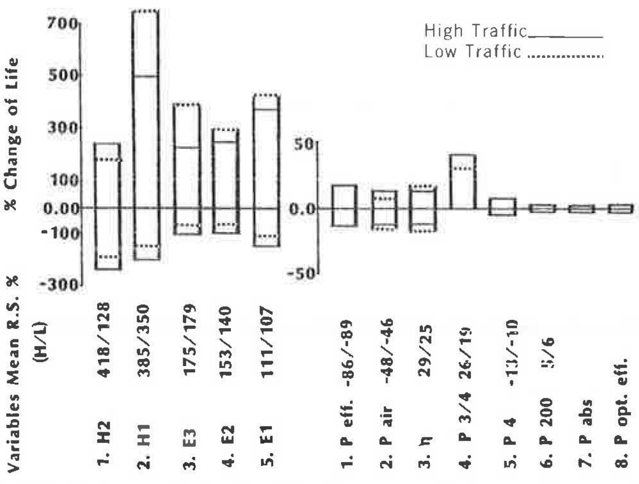

FIGURE 7 Sensitivity of rutting (three layers) failure with respect to variables (range of percentage change of life with respect to geometry and mix properties–rutting, three layers).

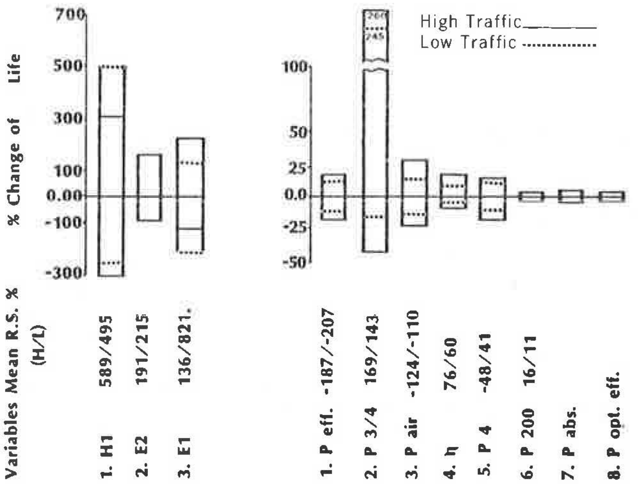

FIGURE 8 Sensitivity of rutting (full depth) failure with respect to variables (range of percentage change of life with respect to geometry and mix properties–rutting, full depth).

hance the life of pavement in all modes of failure. The percentage retained on No. 4 sieve (P_4) has negative relative sensitivity, but the percentage passing No. 200 (P_{200}) has positive sensitivity in all modes of failure. The percentage of asphalt absorbed ($P_{abs.}$) is positive in fatigue failure but negative in rutting distress. All of the variables except the adjusted form of asphalt content of optimum ($P_{opt.eff.}$) appear to give rational signs in the sensitivity analysis. This particular term was chosen from Miller et al. (5). Further analysis is required to determine whether this term should be kept in the final model or the second recommended model should be used (7).

Proper material characterization and the use of appropriate layer material and thicknesses will undoubtedly improve road (pavement) performance. The use of these models should facilitate a more statistically accurate prediction of bituminous modulus and pavement life for fatigue and rutting deformation distresses.

RECOMMENDATION FOR FUTURE RESEARCH

Analyzing and evaluating pavement performance is a complex procedure because so many variables contribute to the final performance or pavement life. With the introduction of new, sophisticated material testing devices and more efficient statistical computer approaches, the precise influence of actual in situ material properties and the environment may be easily and economically simulated in the laboratory. Nevertheless, the comparison and correlation of laboratory data with field performance data must be kept continuous and updated so that performance predictions from laboratory studies and actual field performance agree. To achieve this objective, a critical and comprehensive statistical analysis must be done to verify each variable for its individual and combined contribution and for its correlation with other variables. The reliability of the model and rationality of each term should also be satisfied.

In a study (7), the following items are recommended for further investigation:

1. Effect of coarse aggregate (aggregate sizes larger then 3/4 in.). In this study, almost all mixes investigated except sand asphalt had coarse aggregate particles larger than 3/4 in. The contribution of this size of aggregate toward a higher

predicted modulus, and hence longer life performance, indicates that the presence of coarse aggregate is desirable in bituminous mixtures to enhance the performance of pavement systems. It is also evident from general trends in the material performance of fine (sand asphalt), intermediate (medium), and coarse aggregate mixes that the presence of coarse material definitely makes the mix stiffer or more resistant to impact loads. This study finding needs further investigation with more laboratory samples that contain this particular variable.

2. Effect on economy of using coarse aggregate. The use of more coarse aggregate entails less energy for crushing and less time for processing. In addition, these mixes require less asphalt to coat the aggregates. This advantage may be offset by the fact that they are less convenient to handle in the manufacturing process. Also, uniform mixing of coarse aggregate might take more time and energy and require more personnel resources on the part of the manufacturer. There is a definite need, therefore, to study the cost efficiency of using large aggregate sizes in bituminous mixes.

3. Percentage retained on No. 4 Sieve (P_4). This study indicated that the percentage retained on No. 4 sieve contributed negatively to the dynamic modulus and life of the pavement. In other words, the "gap-graded mix" appeared to have beneficial effects on the modulus and life of the pavement. To verify and substantiate this hypothesis, new laboratory testing on gap-graded dense aggregate mixes should be carried out. This type of mix might also be difficult to manufacture, manipulate, and consolidate in place efficiently and within a reasonable time. However, when stage construction is contemplated and traffic volume is not too high, this mix may be preferable to conventional, dense, well-graded mixtures. In the United States, gap-graded mixes have seldom been used. In contrast, they have found increased usage in other parts of the world (e.g., Europe, Africa, and Asia).

4. Correlations of temperature and frequency. In the correlation analysis of variables it was found that temperature and frequency are independent of all variables. Thus no correlation exists between them, and they have a direct relation with the dynamic modulus only. Future models should reflect this phenomenon.

5. Adjusted effective asphalt content ($P_{eff.} - P_{opt.eff.} + 8$). This term is almost a constant in the present model, although its presence in models for mixes with asphalt contents that differ from optimum is important. In this study it was recommended that, when the deviation of effective asphalt content is less than ±1 percent of the optimum asphalt content, the term may be reduced to the constant value of +8 for simplicity. Furthermore, use of this term as an interactive product of temperature (T^2) may not be rational, as noted in item 4. Therefore investigations should be carried out to devise a more suitable form for expressing a large deviation of asphalt content from the optimum asphalt content.

In summary, although the purpose of this recommendation is to increase the overall efficiency and rationality of the dynamic modulus predictive equations developed in the study, it is apparent that these models also provide an extremely accurate procedure for predicting moduli from routine physical mix properties. Such an accomplishment greatly diminishes the need for design agencies to conduct expensive, time-consuming, and sophisticated dynamic tests for a wide range of routine mixtures used throughout the world today.

REFERENCES

1. AASHTO Interim Guide for Design of Pavement Structures, 1972. AASHTO, Washington, D.C., 1972.
2. X. Nair and C.Y. Chang. Flexible Pavement Design and Management, Material Characterization. NCHRP Report 140. HRB, National Research Council, Washington, D.C., 1973.
3. Thickness Design--Asphalt Pavements for Highways and Streets. Manual Series 1. Asphalt Institute, College Park, Md., Sept. 1981.
4. M.W. Witczak. Development of Regression Model for Asphalt Concrete Modulus for Use in MS-1 Study. Asphalt Institute, College Park, Md., Jan. 1978.
5. J.S. Miller, J. Uzan, and M.W. Witczak. Modification of the Asphalt Institute Bituminous Mix Modulus Predictive Equation. In Transportation Research Record 911, TRB, National Research Council, Washington, D.C., 1983, pp. 27-36.
6. Biomedical Computer Programs P-Series. University of California, Los Angeles, 1981.
7. G.F. Akhter. The Sensitivity of Bituminous Mix Properties Upon Flexible Pavement Performance. Ph.D. dissertation. University of Maryland, College Park, 1984.

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