Mechanistic Evaluation of AASHTO Flexible Pavement Design Equations

GILBERT Y. BALADI AND ANTHONY THOMAS

A total of 243 pavement sections with various layer properties, roadbed moduli, and traffic volumes was designed using the 1986 AASHTO design guide. Mechanistic analyses of each pavement section were also conducted, and the mechanistic responses in terms of deflection, stresses, and strains were calculated and are presented and discussed. Mechanistic evaluation of the AASHTO design procedure was conducted. The evaluation addressed three features of the AASHTO design method: the structural number, the layer coefficient, and the main design equation. It is shown that the role of the roadbed resilient modulus in the AASHTO design process is not accurate and that, for any pavement layer, its layer coefficient is not a simple function of the modulus value of that layer. It is a function of all layer thicknesses and properties.

The outputs (structural number and layer thicknesses) of the AASHTO design procedure are affected by numerous variables. These variables can be separated into three categories, as follows:

1. Primary material variables that have a significant impact on the AASHTO design outputs. These include the resilient moduli or layer coefficients, the resilient modulus of the roadbed soil, and the traffic volume in terms of an 18-kip single axle load (ESAL) (*1–3*).
2. Secondary material and environmental variables (e.g., drainage coefficients and loss of serviceability because of environmental factors) that have an impact on the AASHTO design outputs (*1,3–9*). Their impacts can be addressed after analyzing the effects of the primary material variables.
3. Other variables, including reliability level, the overall standard deviation, performance period, analysis period, economic factors, initial serviceability index, and terminal serviceability index (*1*).

This paper addresses the impact of the primary material variables on the AASHTO design and mechanistic outputs. The impacts of the other variables are presented under different titles (*9*). Furthermore, a mechanistic evaluation of the AASHTO design procedure was also conducted by using the following four-step procedure.

1986 AASHTO DESIGN PROCEDURE

Step 1: Full Factorial Experiment Design Matrix

Figure 1 depicts the full factorial experiment design matrix. As can be seen the matrix consists of 243 cells (for convenience and easy reference the cells are numbered from 1 to 243). Each cell represents one pavement section. For each cell (pavement section) the resilient moduli assigned to the asphalt surface, base and subbase layers, and roadbed soil and the traffic volume in terms of an 18-kip ESAL are shown in Figure 1.

Step 2: Secondary Material and Environmental Variables

For each cell in Figure 1 the following constant values of the secondary material and environmental variables, design reliability, and standard deviation values were assigned:

1. Loss of serviceability because of environmental factors. It is assumed that the pavement materials experience no loss of serviceability because of frost heave or swelling soil. The evaluation of the concept of loss of serviceability because of frost heave has been presented previously (*9*).
2. Drainage coefficient. A value of the drainage coefficients of the base and subbase materials of 1.0 was assumed. The evaluation of the concept of drainage coefficient has been presented previously (*9*).
3. An analysis and a performance period of 20 years each.
4. A desired level of reliability of 95 percent and an overall standard deviation of 0.45.
5. Initial and terminal serviceability indexes of 4 and 2.5, respectively.
6. A discount rate of zero, a salvage value of $0.0, and material costs of $0.0.
7. No maintenance or rehabilitation cost is allowed.

Step 3: AASHTO Design Parameters (Layer Coefficients)

In step 3 the 1986 AASHTO guide (*3*) was used to convert the resilient modulus of each pavement layer to an equivalent layer coefficient as follows:

1. Figure 2.5 of the 1986 AASHTO guide (*3*) was used to convert the resilient modulus of the asphalt concrete (AC) layer to an equivalent layer coefficient (a_1).
2. The layer coefficients of the base (a_2) and subbase (a_3) materials were calculated by using the following AASHTO equations [see page II-18 of the AASHTO guide (*3*)]:

$$a_2 = 0.249[\log_{10}(E_{\text{base}})] - 0.977 \text{ and}$$

$$a_3 = 0.227[\log_{10}(E_{\text{subbase}}) - 0.839$$

Department of Civil Engineering, Michigan State University, East Lansing, Mich. 48824-1226.

	AC (ksi)	100									300									500								
	Base (ksi)	10			25			40			10			25			40			10			25			40		
	Subbase (ksi)	10	15	25	10	15	25	10	15	25	10	15	25	10	15	25	10	15	25	10	15	25	10	15	25	10	15	25
Roadbed (ksi)	ESAL (10^6)																											
1	5	1	10	19	28	37	46	55	64	73	82	91	100	109	118	127	136	145	154	163	172	181	190	199	208	217	226	235
	10	2	11	20	29	38	47	56	65	74	83	92	101	110	119	128	137	146	155	164	173	182	191	200	209	218	227	236
	20	3	12	21	30	39	48	57	66	75	84	93	102	111	120	129	138	147	156	165	174	183	192	201	210	219	228	237
5	5	4	13	22	31	40	49	58	67	76	85	94	103	112	121	130	139	148	157	166	175	184	193	202	211	220	229	238
	10	5	14	23	32	41	50	59	68	77	86	95	104	113	122	131	140	149	158	167	176	185	194	203	212	221	230	239
	20	6	15	24	33	42	51	60	69	78	87	96	105	114	123	132	141	150	159	168	177	186	195	204	213	222	231	240
10	5	7	16	25	34	43	52	61	70	79	88	97	106	115	124	133	142	151	160	169	178	187	196	205	214	223	232	241
	10	8	17	26	35	44	53	62	71	80	89	98	107	116	125	134	143	152	161	170	179	188	197	206	215	224	233	242
	20	9	18	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153	162	171	180	189	198	207	216	225	234	243

FIGURE 1 Full factorial experiment design matrix for mechanistic analysis of AASHTO flexible pavement design procedure.

where E_{base} is the resilient modulus of the base material, and E_{subbase} is the resilient modulus of the subbase material.

In addition, for the thickness design of all pavement sections of Figure 1, the layered design analysis found on pages II-37 and II-38 of the AASHTO guide (*3*) was used. Hence, unique layer thicknesses were obtained for each of the 243 pavement sections of Figure 1 [i.e., subjective solution of the AASHTO structural number (SN) equation was not allowed].

Step 4: AASHTO Thickness Design

In step 4 the 1986 AASHTO design procedure (DNPS86 computer program) was used for the design of each of the 243 pavement sections of Figure 1. The outputs of the AASHTO design (layer thicknesses and SN) were then tabulated [for details regarding the thicknesses and the SN values, the reader is referred to work by Baladi and McKelvey (*9*)].

MECHANISTIC ANALYSIS

Given the material properties listed in Figure 1 and the layer thicknesses obtained from the AASHTO design procedure for the 243 pavement sections, a mechanistic analysis of each section was conducted by using the linear option of MICHPAVE (a finite-element computer program). Some of the results of the mechanistic analysis were verified by using the CHEVRON5 computer program. It should be noted that in all mechanistic analyses, Poisson's ratios of 0.3, 0.35, 0.4, and 0.45 for the AC, base, subbase, and roadbed soils, respectively, were used. The mechanistic responses (compressive vertical stresses and strains at the top and bottom of the AC, base, and subbase layers and at the top of the roadbed soil, the tensile stress and strain at the bottom of the AC layer, and the deflections at the top of the AC, base and subbase layers, and roadbed soil) were tabulated (*9*).

MECHANISTIC EVALUATION OF AASHTO DESIGN EQUATIONS

To avoid unnecessary repetitions the mechanistic evaluation of the AASHTO design method was accomplished by using the results for nine pavement sections. Table 1 provides a list of the nine pavement sections along with their SN values, total thicknesses, layer thicknesses, and material properties. The nine sections are grouped, relative to the material variables, into four categories, as follows:

1. Sections 60, 141, and 222, in which the only material variable is the AC modulus.

TABLE 1 Structural Number, Layer Thicknesses, and Layer Moduli of Nine Pavement Sections of Figure 1 (Performance Period of 20 years and 20,000,000 18-kip ESAL)

Cell Number	Structural Number	Total Thickness (inch)	Layer Thicknesses (inches)			Layer Modulus (ksi)			
			AC	Base	Subbase	AC	Base	Subbase	Roadbed
141	6.51	38.50	8.41	12.09	18.0	300	40	10	5
114	6.51	39.98	10.04	11.94	18.0	300	25	10	5
87	6.51	31.80	13.8	0.0	18.0	300	10	10	5
141	6.51	38.5	8.41	12.09	18.0	300	40	10	5
150	6.51	34.09	8.41	8.18	17.50	300	40	15	5
159	6.51	28.87	8.41	3.66	16.80	300	40	25	5
141	6.51	38.5	8.41	12.09	18.0	300	40	10	5
60	6.51	47.84	17.75	12.09	18.0	100	40	10	5
222	6.51	37.03	6.94	12.09	18.0	500	40	10	5
156	10.3	52.46	8.41	3.66	40.40	300	40	25	1
159	6.51	28.90	8.41	3.66	16.80	300	40	25	5
162	5.25	21.03	8.41	3.66	8.96	300	40	25	10

2. Sections 87, 114, and 141, in which the only material variable is the base modulus.
3. Sections 141, 150, and 159, in which the only material variable is the subbase modulus.
4. Sections 156, 159, and 162, in which the only material variable is the roadbed modulus.

Furthermore, for the purpose of mechanistic evaluation of the AASHTO design procedure, an engineering criterion was developed and is presented in the next section.

Engineering Criteria for Evaluation of AASHTO Design Equations

Recall that the 243 pavement sections were designed by using the AASHTO design procedure for a total loss of serviceability during the performance period of 1.7 PSI where PSI is present serviceability index. This implies that the 243 pavement sections will receive the same level of protection against damage because of their respective traffic volumes and loads. On the basis of this AASHTO concept, an engineering evaluation criterion was developed. The criterion can be stated as follows: Pavement sections designed by the AASHTO method to carry the same traffic level, to be supported on the same roadbed soil, and to have the same performance period should also experience the same magnitude of stresses, strains, and deflections caused by an 18-kip ESAL. Otherwise, the level of protection is different and the pavements will have variable performance periods. This criterion implies that the magnitude of the mechanistic responses (stresses, strains, and deflections) delivered to a pavement section can be used as a measure of pavement damage. Higher responses cause higher levels of damage. Likewise, higher mechanistic responses indicate a lower protection level from damage because of traffic loading.

Observations of AASHTO Design Outputs

Examination of the AASHTO design outputs (SN and layer thicknesses) of the nine pavement sections listed in Table 1 indicates that the AASHTO design method produces

1. A constant structural number that is independent of the layer properties but dependent on the roadbed soil resilient modulus and the number of 18-kip ESALs.
2. A constant AC thickness that is independent of the moduli of the subbase layer and the roadbed soil.
3. A constant base thickness that is independent of the moduli of the AC layer and the roadbed soil.
4. A constant subbase thickness that is independent of the moduli of the base and AC layers.

Evaluation of AASHTO Design Equations

As stated earlier the 243 pavement sections were analyzed by using the linear option of the MICHPAVE computer program, and the mechanistic responses were obtained and tabulated. The mechanistic responses of the nine pavement sections of Table 1 are summarized in Table 2. For those pavement sections with the same roadbed modulus, the data are plotted in Figures 2 through 9. For those pavements (sections 156, 159, and 162) with different roadbed soil moduli, Figure 10 depicts the variations in the pavement peak deflection. Nevertheless, examination of the range of the AC, base, and subbase layer properties listed in Table 1 and the mechanistic responses (listed in Table 2 and shown in Figures 2 to 9) indicates that for a constant traffic level and for one type of roadbed soil the AASHTO design method produces pavement sections (layer thicknesses) such that

1. The peak surface deflection is almost constant (Figure 2). Hence, the amount of the overall damage delivered to the pavement section (or the overall protection level) is constant and independent of the material properties.
2. The amount of compression and the resulting compressive strains experienced by any one pavement layer vary from one section to another (Figures 3 through 8). These variations are favorable (provide a better protection of the layer in question) for some pavement sections and unfavorable for other sections. Hence, the amount of damage delivered to each layer of the pavement sections varies. This implies that although the AASHTO design procedure ensures that the overall damage of the pavement

TABLE 2 Mechanistic Responses of Nine Pavement Sections of Table 1 Owing to 18-kip ESAL

Cell Number	Deflection at the Top of (mills)				Vertical Compressive Stress at the Top of (psi)			Vertical microstrain at top/bottom of layers				Tensile Stress at the Bottom of the AC layer (psi)
	AC	Base	Subbase	Roadbed	Base	Subbase	Roadbed	AC	Base	Subbase	Roadbed	
141	21.26	20.13	17.10	13.25	15.91	2.88	1.01	30/81	426/198	324/167	201	64.10
114	20.87	19.57	16.54	13.02	9.39	2.52	0.97	42/160	406/195	282/159	191	64.54
87	19.64	N/A	18.03	14.30	N/A	3.20	1.12	68/115	N/A	315/168	201	52.04
141	21.26	20.13	17.10	13.25	15.91	2.88	1.02	30/181	426/198	324/167	201	64.10
150	21.70	20.58	18.22	14.37	15.25	4.58	1.21	26/184	421/238	348/181	240	66.58
159	21.83	20.71	19.43	15.66	14.84	8.59	1.46	25/186	417/309	377/195	283	68.47
141	21.26	20.13	17.10	13.25	15.91	2.88	1.01	30/181	426/198	324/167	201	64.10
60	21.14	15.31	13.58	11.05	7.24	1.71	0.70	63/134	214/123	199/115	138	10.30
222	21.14	20.60	17.51	13.50	16.27	3.02	1.05	28/159	423/206	337/175	209	105.50
156	35.19	34.07	32.79	27.00	15.34	9.44	0.2	31/179	4.16/3.11	3.79/1.09	1.82	64.05
159	21.83	20.71	19.43	15.66	14.71	8.59	1.46	46/186	4.17/3.09	3.77/1.95	2.83	68.47
162	16.93	15.79	14.52	12.03	14.38	8.23	3.25	27/188	4.15/3.07	3.75/2.46	3.14	69.81

N/A = Not applicable, the AASHTO design produced zero thickness for this layer.

sections is the same, the relative damage delivered to each layer is not.

3. The tensile stress induced at the bottom of the AC layer varies from one section to another (Figure 9). Hence, the amount of fatigue damage delivered to each layer of the pavement sections varies. This implies that the performance (or the rate of deterioration) of the various pavement sections is not the same.

For pavement sections 156, 159, and 162 (all variables have a constant value except the roadbed soil resilient modulus) examination of the data listed in the last three rows of Tables 1 and 2 and shown in Figure 10 indicates that the peak pavement deflection at the top of each layer, the compressive stresses and strains, and the tensile stresses are variables. They are a function of the roadbed soil resilient modulus.

On the basis of these observations three features of the AASHTO design procedure are discussed next.

DISCUSSION OF RESULTS

Several important aspects relative to the mechanistic evaluation and calibration of the AASHTO flexible design equations can be inferred from the mechanistic analysis of those equations. These aspects are divided (according to the features of the AASHTO

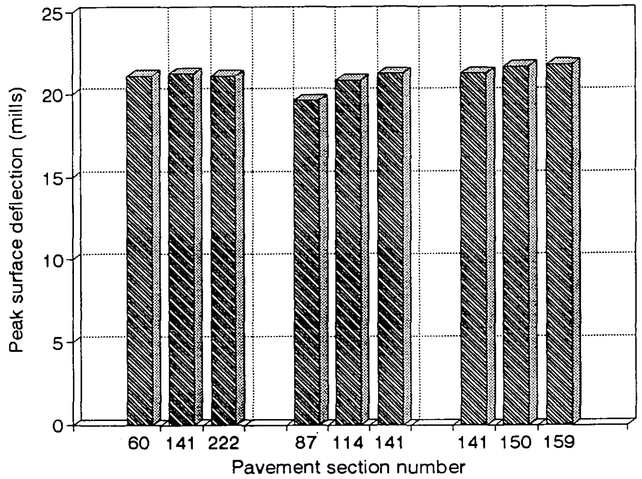

FIGURE 2 Peak pavement surface deflections of pavement sections having same roadbed soil modulus and traffic volume and load.

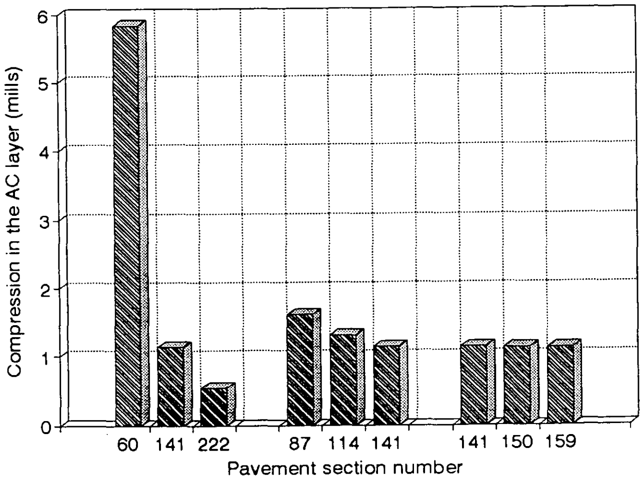

FIGURE 3 Amount of compression in AC layer of pavement sections having same roadbed soil modulus and traffic volume and load.

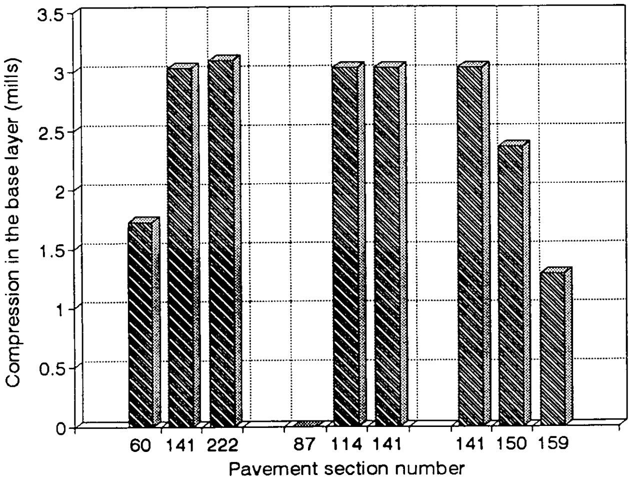

FIGURE 4 Amount of compression in base layer of pavement sections having same roadbed soil modulus and traffic volume and load.

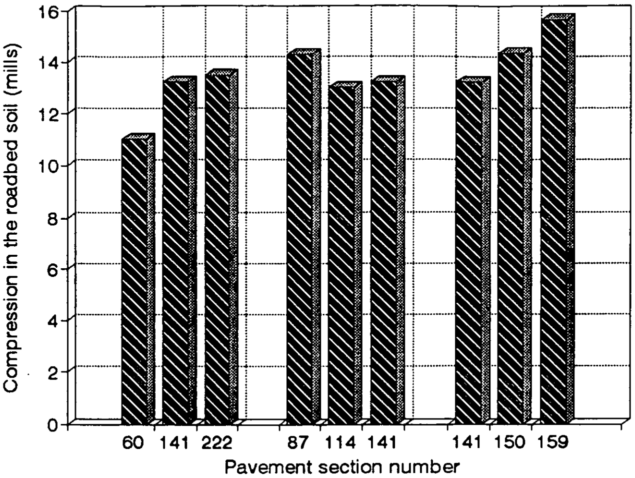

FIGURE 6 Amount of compression in roadbed soil of pavement sections having same roadbed soil modulus and traffic volume and load.

equation) into three categories and are discussed in the following sections.

Features Related to SN Equation

The AASHTO SN equation (the effects of drainage are excluded) can be in two forms, as follows:

$$\mathrm{SN} = a_1D_1 + a_2D_2 + a_3D_3 \quad \text{or} \quad \mathrm{SN} = \mathrm{SN}_1 + \mathrm{SN}_2 + \mathrm{SN}_3$$

The AASHTO concept embedded into the SN equation is that the total SN of any flexible pavement section is the sum of the SNs of its layers. The outputs of the mechanistic analysis support this AASHTO concept. The reason for this is that for pavement sections supported on the same roadbed soil, variations in the layer coefficients or moduli are offset by varying the layer thicknesses, which minimizes their impacts on the pavement peak deflection. Hence, the total structural capacity is the same.

Features Related to AASHTO Layer Coefficient Equations or Nomographs

The AASHTO layer coefficients are related to the layer modulus through nomographs or equations, as follows:

$$a_2 = 0.249[\log(E_{\mathrm{BS}})] - 0.977 \quad \text{and}$$

$$a_3 = 0.227[\log(E_{\mathrm{SB}})] - 0.839$$

On the basis of the SN and layer coefficient equations, the second AASHTO concept can be written as follows: the structural number

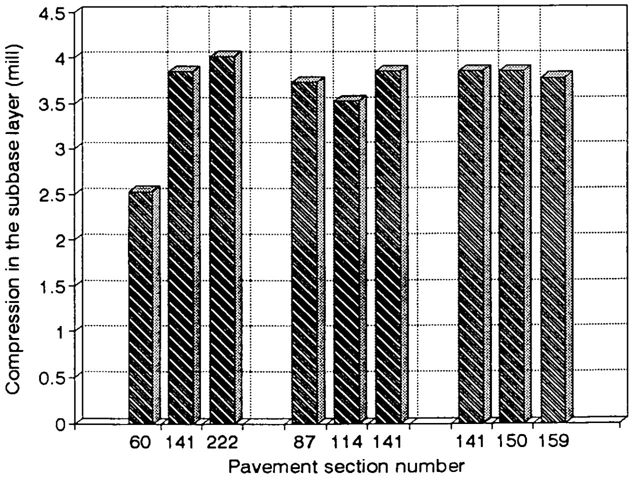

FIGURE 5 Amount of compression in subbase layer of pavement sections having same roadbed soil modulus and traffic volume and load.

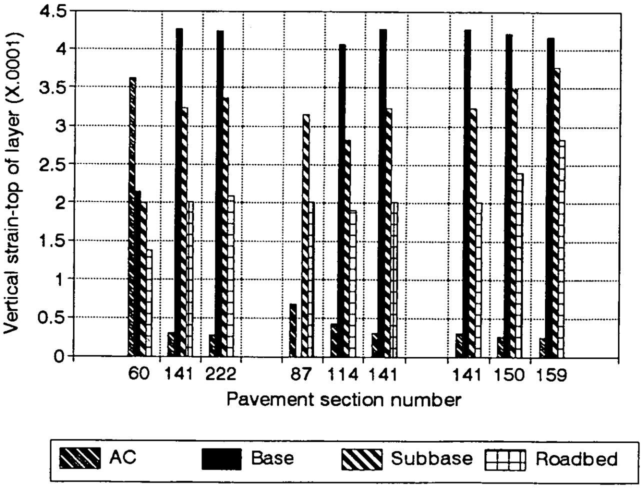

FIGURE 7 Vertical strains induced at top of each layer of pavement sections having same roadbed soil modulus and traffic volume and load.

of any pavement layer is the product of its layer coefficient and thickness, and the layer coefficient is a simple function of the modulus of that layer. The outputs of the mechanistic analysis do not support this AASHTO concept. The reason for this is that (see Figures 2 through 9) the amount of damage delivered to each layer (or the mechanistic response) varies from one pavement section to another. Given that the mechanistic response (amount of damage) in each pavement layer is a function of the properties and thicknesses of all layers, one can conclude that the AASHTO layer coefficient equations and nomographs need to be calibrated so that the amount of damage delivered to each layer because of an 18-kip ESAL remains constant. Such a calibration is a function of the type of distress (damage) being considered and the properties and thicknesses of all pavement layers. Stated differently, for any pavement layer the value or values of its layer coefficients are distress mode dependent. For example, the layer coefficient values required to ensure equal rutting may not be the same as those required to ensure equal fatigue cracking or equal roughness (ride quality).

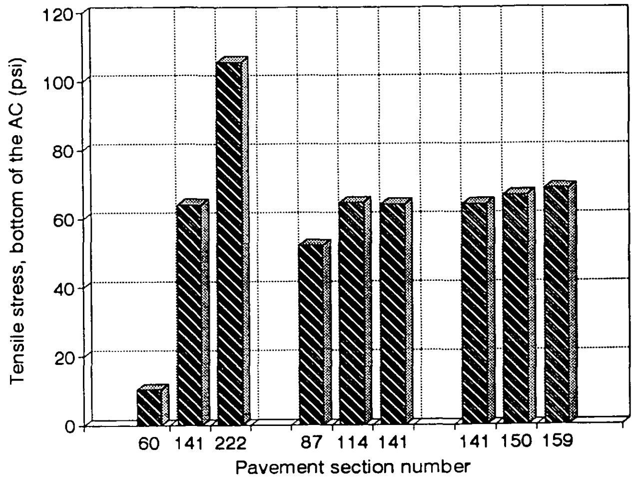

FIGURE 9 Tensile stress at bottom of AC layer of pavement sections having same roadbed soil modulus and traffic volume and load.

Features Related to Main AASHTO Design Equation

The AASHTO main design equation is written in terms of an 18-kip ESAL, design reliability and standard deviation, resilient modulus of the roadbed soil, the serviceability loss, and the required SN of the pavement, as follows:

$$\log(W_{18}) = (Z_R)(S_0) + 9.36[\log(\mathrm{SN} + 1)] - 0.20 + \frac{\log[(\Delta\mathrm{PSI})/(4.2 - 1.5)]}{[0.4 + 1{,}094/(\mathrm{SN} + 1)^{5.19}]} + 2.32[\log(\mathrm{MR})] - 8.07$$

Typically, the number of 18-kip ESALs is used as an input to the equation, and the required SN is calculated. Hence, the AASHTO concept herein is that, for a constant number of 18-kip ESALs and for the same design reliability, standard deviation, and serviceability loss, the required SN of any pavement section is a function of the resilient modulus of the roadbed soil. The results of the mechanistic analysis do not support this AASHTO concept. In reference to Figure 10 pavement sections 156, 159, and 162 were designed by using the AASHTO flexible pavement design procedure. The material properties of the AC, base, and subbase layers for all three sections are the same. All sections were designed to carry 20 million ESALs. The only difference between the three sections is the resilient modulus of the roadbed soil. The layer moduli, the resilient modulus of the roadbed soil, and the AASHTO design outputs (layer thicknesses) for those sections are listed in Table 1. Their mechanistic responses are summarized in Table 2. The mechanistic responses (listed in Table 2 and shown in Figure 10) indicate that

1. The pavement peak surface deflection varies from 35.19 mils for pavement section 156 to 16.93 mils for pavement section 162.

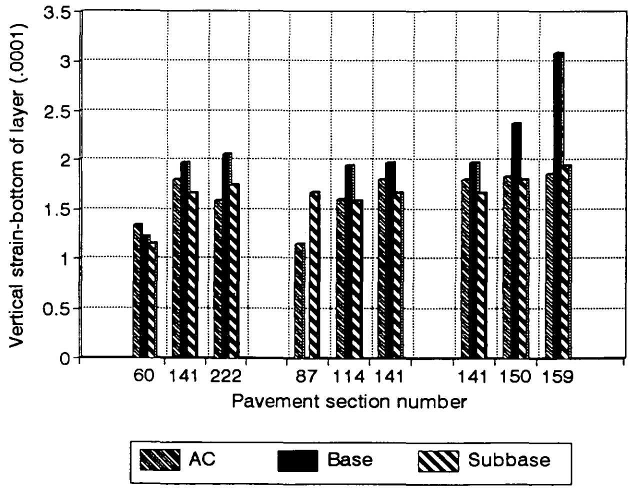

FIGURE 8 Vertical strain induced at bottom of each layer of pavement sections having same roadbed soil modulus and traffic volume and load.

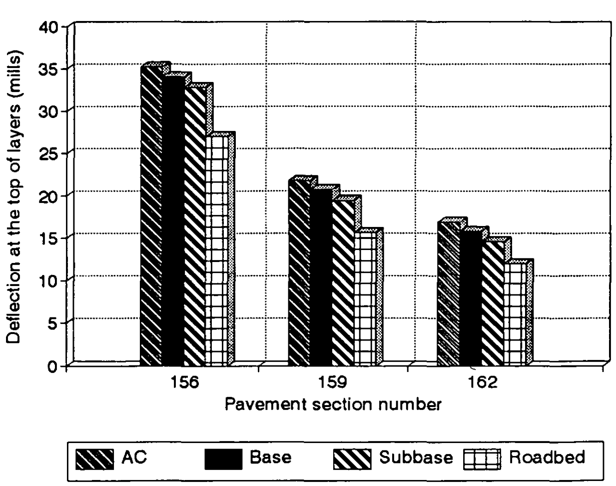

FIGURE 10 Deflection at top of each pavement layer for pavement sections 156, 159, and 162 with roadbed resilient moduli of 1, 5, and 10 ksi, respectively.

This indicates that the overall damage delivered to the pavement sections because of traffic load varies from one section to another. Previously, it was stated that for the same type of roadbed soil and traffic level the AASHTO design procedure produces pavement sections (on the basis of their SN) such that the peak pavement deflection is almost constant. This finding, however, is not true when the roadbed soil is changed from one type to another. The implication here is that the SNs produced by the AASHTO method do not provide the same level of protection to the roadbed soil. Because in the AASHTO main design equation the only factor affecting the calculation of the SN is the resilient modulus of the roadbed soil, one can conclude that the AASHTO main design equation for flexible pavements does not properly account for the effects of the resilient modulus of the roadbed soil on the SNs of the pavement. Hence, its role needs to be calibrated.

2. The values of the deflections at the top of the base and subbase layers and at the top of the roadbed soil (see the last three rows of Table 2 and the data depicted in Figure 10) indicate that the amount of damage received by the pavement sections because of traffic load varies from one section to another. This observation is similar to that reported earlier and confirms the finding that the AASHTO layer coefficient values need to be calibrated.

3. The tensile stress delivered at the bottom of the AC layer also varies from one pavement section to another, indicating various levels of fatigue damage. This is also similar to an earlier observation and confirms the finding that for any pavement layer its coefficient is a function of the thicknesses and moduli of all pavement layers.

One important point that should be noted here is that the AASHTO flexible pavement design procedure is empirical in nature. Its inherent distress mode is serviceability (ride quality). The accuracy of the AASHTO method relative to this mode of distress (pavement serviceability) cannot be verified by using mechanistic analysis at this time. Long-term pavement performance data must be used to address the adequacy of the AASHTO procedure. The observations stated above are related to other distress modes that are not inherent in the AASHTO design procedure. Simply stated, the present form of the AASHTO design procedure cannot be used to design a pavement section with high rut and fatigue cracking resistance.

SUMMARY AND CONCLUSIONS

A full factorial experiment design matrix containing 243 flexible pavement sections was established. Each section was designed by using the AASHTO design procedure. Mechanistic analyses were then conducted, and the mechanistic responses in terms of deflection, stresses, and strains were calculated. On the basis of the analyses, the following conclusions relative to the AASHTO design method are drawn:

1. The impact of the roadbed resilient modulus on the structural number and layer thicknesses is not accurate and needs to be calibrated.
2. For a constant subgrade modulus, pavement sections designed by the AASHTO procedure would have similar peak deflections independent of layer properties.
3. The AASHTO layer coefficients are not accurate and need to be calibrated as a function of the thicknesses and moduli of all pavement layers.

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