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Structural Analysis of AASHO Road Test Flexible Pavements for Performance Evaluation

DAVID R. LUHR AND B. FRANK McCULLOUGH

The structural analysis of American Association of State Highway Officials (AASHO) Road Test flexible pavements was performed for the specific purpose of developing a pavement performance model that would be implemented in a pavement management system used by the U.S. Forest Service. For this reason, a precise and highly sophisticated structural evaluation was not made. However, it was determined that the nonlinear elastic properties of unbound pavement materials and seasonal material conditions should be characterized. The use of a thin layer BISAR elastic-layer analysis helped to overcome difficulties in the structural analysis associated with the PSAD2A elastic-layer program. An equivalent layer procedure was found to give results similar to the thin layer BISAR analysis. A modified BISAR program was developed that incorporated the equivalent layer procedure and was used in the structural analysis of the AASHO Road Test pavements. Results of the analysis showed that predicted pavement deflections from the structural analysis compared very well with spring and fall deflection measurements taken at the AASHO Road Test. An evaluation of the modulus ratios of adjacent unbound pavement layers led to the conclusion that the modulus ratios are not fixed within a narrow range of values but can vary significantly depending on the state of stress in the pavement layers.

The structural analysis of flexible pavements can involve a wide range of methodologies, which range from sophisticated finite-element modeling that considers nonlinear elastic and viscoelastic properties of pavement materials to relatively uncomplicated elastic-layer techniques that have various simplifying assumptions regarding material properties, loading conditions, etc. Therefore, it is important to choose the appropriate level of sophistication for the particular situation being analyzed.

This paper describes a structural analysis of American Association of State Highway Officials (AASHO) Road Test flexible pavement sections, which was conducted as part of a cooperative research effort by the U.S. Forest Service and the University of Texas at Austin. The objective of the analysis was to calculate pavement response parameters that could be compared with AASHO Road Test pavement performance data. From this information, a pavement performance model would be developed and used to revise and improve an existing pavement management system (1).

The structural analysis in this study was not a precise and highly sophisticated evaluation of the pavement structures. Because of the number of AASHO Road Test sections to be studied, practical restrictions were necessary in the consideration of computer execution time. In addition, since the pavement performance model being developed would be included in a pavement management system, it could be assumed that a similar structural analysis would have to be employed in that system. For these reasons, a relatively simple analysis was favored. However, because of important economic comparisons made among candidate pavement materials in the pavement management system, it was felt necessary to consider the stress-sensitive properties of unbound pavement materials. Because pavement performance varies considerably, depending on climatic and seasonal conditions, it was also determined that the characterization of seasonal material properties was important in the structural analysis. These factors tended to indicate that a more sophisticated evaluation was necessary.

The following sections of this paper discuss the evaluation of different methodologies for performing the analysis. Results from this evaluation are discussed, including results from the structural analysis. A comparison is made between measured and predicted pavement deflections, and the modulus ratios for adjacent unbound pavement layers are studied.

PROCEDURE FOR NONLINEAR ELASTIC ANALYSIS

In the structural analysis of AASHO Road Test pavement sections, the asphalt layer was assumed to have linear elastic properties, whereas the granular base and subbase materials and the fine-grained subgrade were assumed to have nonlinear stress-dependent characteristics. The stress-sensitive nature of the unbound pavement materials was characterized by the following relations. For fine-grained materials,

$$M_R = A\,\sigma_d^B \tag{1}$$

where

M_R = resilient modulus of fine-grained material,
σ_d = principal stress differences ($\sigma_1 - \sigma_3$) or deviator stress (psi), and
A, B = experimentally determined coefficients that define the behavior of the fine-grained material.

For granular materials,

$$M_R = k_1 \theta^{k_2} \tag{2}$$

where

M_R = resilient modulus of granular material,
θ = first stress invariant ($\sigma_1 + \sigma_2 + \sigma_3$) or bulk stress (psi), and
k_1, k_2 = experimentally determined coefficients that define the behavior of the granular material.

Considering the relations described in Equations 1 and 2, where the modulus of an unbound pavement material varies according to the state of stress in the material, the moduli of unbound materials should vary both horizontally and vertically in the pavement structure. This type of two-dimensional variation in material moduli can be satisfactorily represented by using finite-element techniques that model nonlinear elastic material behavior (2). However, as mentioned earlier, the objective of this study was not the precise structural analysis of a layered pavement but rather to calculate pavement response parameters that could be related to pavement performance. The finite-element methodology does not lend itself to this type of objective because (a) it uses a large amount of computer execution time, which would be restrictive in the analysis of all the AASHO Road Test pavement sections; (b) the large amount of variability in pavement performance data may make the structural precision of finite-element methods superfluous in comparison; and (c) finite-element methods are too complex and consume too much computer execution time to be used routinely as part of a pavement management system.

Evaluation of Elastic-Layer Programs

An alternative way to analyze pavement structures by using nonlinear elastic material characterization is through an elastic-layer procedure. In this case, the pavement structure is divided into layers with homogeneous and isotropic material properties. This limits the modulus variation to only the vertical direction, where the modulus may change from one layer to another. A single modulus for each layer is assumed, and the stresses in each layer are determined in an interactive procedure until the relations in Equations 1 and 2 are satisfied. A computer program developed at the University of California at Berkeley [PSAD2A (3)] uses this type of procedure and was examined as a possible method to carry out the analysis of AASHO Road Test pavement sections. The PSAD2A program calculates stresses at seven horizontal locations underneath the loaded area at three depths in each layer. Figure 1 illustrates the 21 locations where stresses are calculated for each layer, with 7 locations for the subgrade. The modulus value for each location where stresses are calculated is computed from the relations in Equations 1 and 2, and the 21 modulus values are averaged to determine the stress-dependent modulus for each layer. The initial assumed modulus is compared with the calculated average modulus, and the procedure is iterated until the two moduli converge.

Two difficulties were apparent when the PSAD2A program was examined. The first involved the development of tensile stresses in the bottom of pavement layers. This is common in elastic-layer analysis, since the layer is treated as a homogeneous isotropic material. Under load, compression develops in the top of the layer and tension at the bottom. However, unbound pavement materials, particularly granular materials, have little or no mobilized tensile strength. Realizing this fact, the PSAD2A program assumes a modulus of zero when the first stress invariant (Θ) becomes negative for a certain location. Often the bottom of a layer will be calculated to be in tension, which results in the seven points in the lower portion of the layer that have a modulus of zero. When the average modulus of the 21 points is calculated, the effect of the 7 moduli with a value of zero is to greatly reduce the average modulus value. This result helps to illustrate the second difficulty: The procedure for averaging the 21 modulus values has the effect of converging the solution for a condition that may not represent the behavior of the layer. The stresses are calculated from one assumed modulus for each layer, yet different modulus values are calculated for 21 points, indicating the intention to consider the two-dimensional variation in moduli for each layer, which cannot be accomplished by using elastic-layer analysis.

In an effort to alleviate the two difficulties stated above, a somewhat different approach than that used in PSAD2A was taken by using the elastic-layer methodology. An examination was made of a typical pavement structure with 7.6-cm (3-in) asphalt, 7.6-cm base, and 10-cm (4-in) subbase. First, no attempt was made to calculate the moduli at different horizontal locations in the unbound layers. Instead, only positions directly beneath the wheel loads were used to calculate stresses for the relations in Equations 1 and 2. This restriction is simply one of the limitations of using elastic-layer theory. Second, the base and subbase layers were divided into thin sublayers of 2.5-cm (1-in) thickness (Figure 2). With this small thickness, the modulus calculated from the stress condition at midlayer is probably an accurate representation of the entire sublayer. This allows the mod-

Figure 1. Locations for stress-dependent modulus calculations in program PSAD2A.

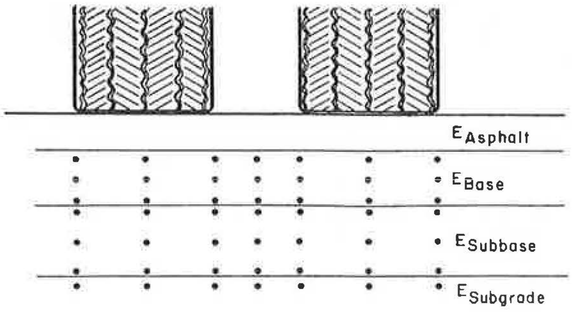
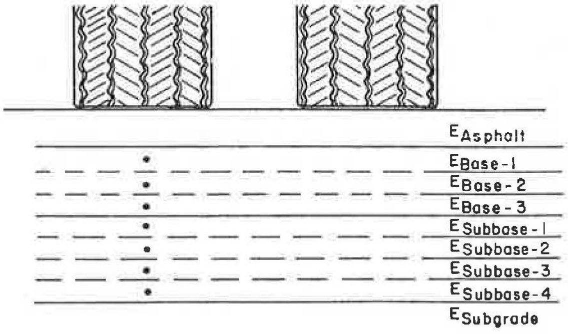


Figure 2. Locations for stress-dependent modulus calculations in thin layer BISAR analysis.



ulus to vary with depth, since it can change from sublayer to sublayer. Because the layers are thin, the problem of calculating tensile stresses in the bottom of the layers is reduced.

The structural evaluation of the pavement structure in Figure 2 was accomplished with the elastic-layer program BISAR, which was developed by Shell Research (4). The BISAR program was used because it has the capability to analyze more than five layers, and the level of friction at layer interfaces in the pavement structure can be varied. With the small thickness of the base sublayers, it was necessary to assume no friction at the asphalt-base interface. If full friction has been used at the asphalt-base interface, the thin sublayer at the top of the base would be calculated to be in tension because of the influence of the tension at the bottom of the asphalt layer. In reality, the friction at the asphalt-base interface lies somewhere between full friction and no friction. However, the assumption of no friction for analytical purposes is reasonable. Full friction was assumed for all other interfaces.

By using a fixed modulus for the asphalt and the relations in Equations 1 and 2 for the base, subbase, and subgrade, the assumed moduli for the seven locations in Figure 2 were iterated until each converged with the calculated stress-dependent modulus. If tensile stresses in any layer were greater than an arbitrary limit of 35 kPa (5 psi), the results were considered unacceptable and new moduli were assumed. Figure 3 contains the plot of moduli versus depth for the pavement structure in Figure 2 and assumes material properties for the fall season (seasonal material characterization is discussed later) and a 100-kN (22.4-kip) single-axle load. The moduli computed from the PSAD2A program are compared in Figure 3 with those from the thin layer BISAR analysis. The significantly smaller moduli calculated from PSAD2A for the base and subbase layers are mainly due to the effect of averaging in the zero modulus values from the lower positions in each layer.

It was concluded that the thin layer BISAR analysis was an appropriate method of using elastic-layer theory to model the stress sensitivity of materials in a pavement structure. Because the moduli were calculated only along the axis of load symmetry and restrictions were placed on tensile stresses, the difficulties associated with the PSAD2A program had been alleviated. However, practical limitations of computer execution time would make a thin layer BISAR analysis for all the AASHO Road Test pavement sections unfeasible. In addition, it would not be practical to incorporate this detailed a structural analysis in a pavement management system.

Development of an Equivalent Procedure

To develop a simpler structural analysis that still contained the advantages of the thin layer BISAR procedure, an approach that used an equivalent layer modulus was examined. This approach uses a single stress-dependent modulus for each layer instead of dividing the base and subbase into sublayers. This single modulus is equivalent to the sublayer moduli, in that the calculated stress-strain response in the asphalt and subgrade layers is the same as the response calculated with the thin sublayer analysis. For the equivalent layer analysis, it was found that if the single stress-dependent modulus for each layer is converged by using the stress condition at middepth in the layer, the calculated stress-strain response in the asphalt and subgrade will be nearly the same as for the thin layer analysis. This concept is shown in Figure 4, where the same pavement structure as in Figure 3 is examined. The moduli calculated from the small layer BISAR analysis and the equivalent layer analysis are shown, as are results from the structural analysis that include (a) surface vertical deflection, (b) asphalt tensile strain, (c) subgrade compressive strain, and (d) subgrade shear stress.

The four parameters above were selected because combined they represent most of the structural response variables used in current pavement design procedures and they cover a wide range of pavement response. If the equivalent layer analysis could produce similar results for all of these parameters, it could replace the thin layer analysis. This comparison between the thin layer analysis and the equivalent layer analysis was made for a variety of pavement structures and axle loads. The results are given in Table 1 and indicate very good agreement in nearly all cases. Based on this detailed examination, it was concluded that the equivalent layer procedure should be used to analyze the AASHO Road Test pavement sections and that it would also be appropriate for a pavement management system. A modified version of the BISAR program was developed that converges the single stress-dependent modulus for each layer in an iterative procedure by using the stress condition at middepth in the layer.

Figure 3. Moduli versus depth below asphalt for example pavement structure with 100-kN (22.4-kip) single-axle load.

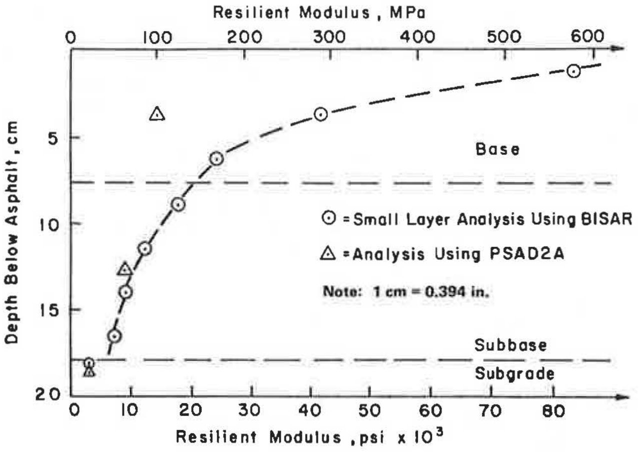


Figure 4. Example of equivalent layer analysis for pavement structure and load in Figure 3.

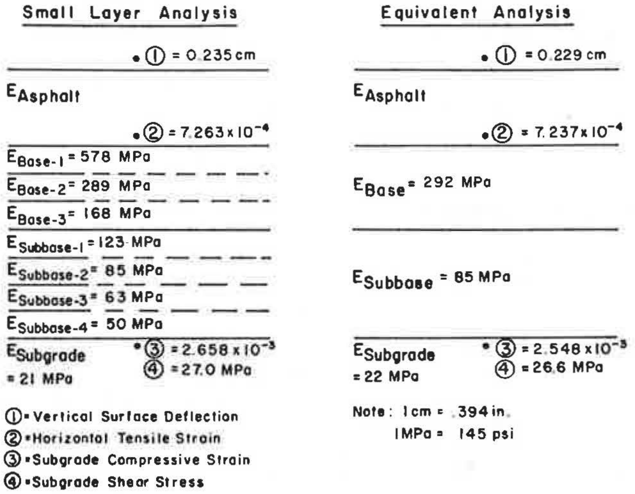


Table 1. Comparison of thin layer and equivalent layer analysis.

Pavement Thickness (cm)				Ratio[a] for			
Asphalt Concrete	Base	Subbase	Single-Axle Load (kN)	Surface Deflection	Asphalt Strain	Subgrade Strain	Subgrade Shear Stress
5	8	0	9	0.92	0.97	1.02	0.91
5	8	0	53	0.97	0.97	0.91	0.91
8	8	10	9	0.99	1.00	1.00	0.95
8	8	10	53	0.99	1.00	0.98	0.98
8	8	10	80	0.97	0.99	0.99	0.95
8	8	10	100	0.98	1.00	0.99	0.96
13	15	20	80	0.99	1.01	1.00	0.97
13	15	20	100	0.98	1.01	1.00	0.97
13	15	20	133	0.97	1.00	1.00	0.96

Note: 1 cm = 0.394 in, 1 kN = 0.225 kip.
[a] Ratio = value of equivalent analysis ÷ value of thin layer analysis.

Table 2. Elastic moduli of AASHO Road Test materials.

	Material							
	Asphalt Concrete		Base		Subbase		Subgrade	
Seasonal Moduli	kPa	psi	kPa	psi	kPa	psi	kPa	psi
March-April (spring)	4.9×10^6	0.71×10^6	$6\,900\,\theta^{0.6}$	$3\,200\,\theta^{0.6}$	$10\,000\,\theta^{0.6}$	$4\,600\,\theta^{0.6}$	$427\,000\,\sigma_d^{-1.06}$	$8\,000\,\sigma_d^{-1.06}$
May-August (summer)	1.6×10^6	0.23×10^6	$7\,800\,\theta^{0.6}$	$3\,600\,\theta^{0.6}$	$10\,800\,\theta^{0.6}$	$5\,000\,\theta^{0.6}$	$960\,000\,\sigma_d^{-1.06}$	$18\,000\,\sigma_d^{-1.06}$
September-November (fall)	3.1×10^6	0.45×10^6	$8\,700\,\theta^{0.6}$	$4\,000\,\theta^{0.6}$	$11\,700\,\theta^{0.6}$	$5\,400\,\theta^{0.6}$	$1\,440\,000\,\sigma_d^{-1.06}$	$27\,000\,\sigma_d^{-1.06}$
December-February (winter)	11.7×10^6	1.7×10^6	345 000[a]	50 000[a]	345 000[a]	50 000[a]	345 000[a]	50 000[a]

[a] Assigned values assuming frozen conditions.

ANALYSIS OF AASHO ROAD TEST SECTIONS

Seasonal Material Characterization

Because pavement performance varies according to climatic and seasonal conditions, it was appropriate to structurally analyze the AASHO Road Test pavement sections on a seasonal basis. With these results, an attempt could be made to evaluate seasonal pavement performance. To accomplish this, the material properties for the asphalt surfacing, base, subbase, and subgrade were characterized for four different seasonal periods of the year. This consisted of modulus values for the asphalt, values of A and B for the fine-grained subgrade (Equation 1), and values of k_1 and k_2 for the granular base and subbase (Equation 2). The seasonal values used in this study were developed for AASHO Road Test materials by Finn and others (5) and are listed in Table 2 (5). These seasonal material values were primarily developed from laboratory testing and are related to triaxial-type loading conditions.

Poisson's ratio was assumed constant for each material and was assigned the following values: asphalt, 0.30; granular base, 0.40; granular subbase, 0.40; and fine-grained subgrade, 0.45.

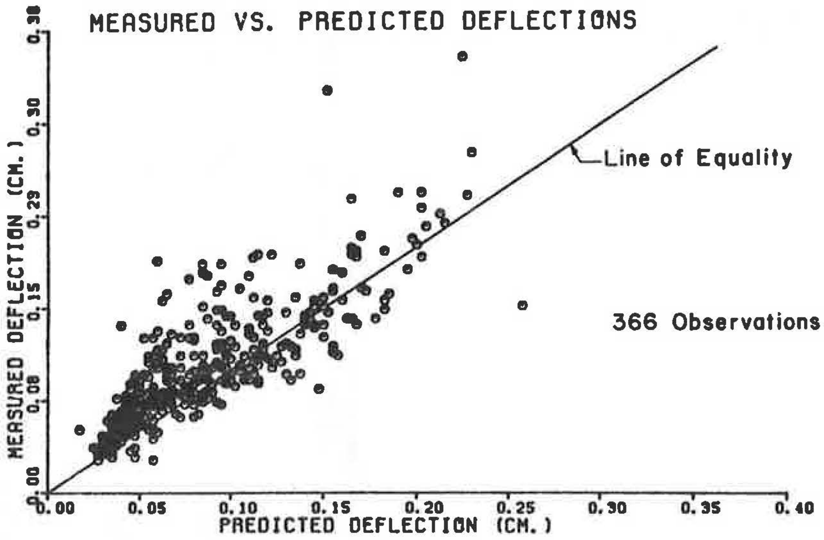
Structural Analysis

The structural analysis of the flexible pavement sections was completed by analyzing for four seasons all of the 284 combinations of flexible pavement structures and axle loads in the main AASHO Road Test experiment (6). The modified BISAR program was used to conduct the analysis by using the material properties listed in Table 2. Four stress-strain parameters were calculated for each analysis. These included tensile strain at the bottom of the asphalt layer, subgrade shear strain, subgrade compressive strain, and subgrade strain energy. An earlier evaluation of AASHO Road Test pavement sections indicated that a simple linear elastic computation of subgrade compressive strain correlated fairly well with pavement performance (7). For this reason, three of the four parameters calculated are related to subgrade response. The asphalt strain was included because it is frequently used as a predictor of asphalt cracking. Pavement deflection was specifically not included because of difficulties in predicting pavement deflection when the depth to rigid foundation (depth of roadbed) is not known (8).

All of the four parameters were calculated for positions directly beneath the wheel load in their respective layers. It is realized that sometimes maximum stresses or strains do not occur at these locations but, rather, at points between the two loads of a dual tire configuration. There were three primary reasons for calculating stresses and strains for only the locations directly beneath the load:

1. The stress-dependent modulus calculation for each layer is for the stress condition under the load. In reality, the layer moduli are different for locations between the loads, and any calculations of stresses or strains between the loads may not be accurate.
2. The purpose of the structural analysis was not the precise evaluation of stresses and strains within the pavement structure but, rather, the comparison of mechanistic parameters with pavement performance. Because conditions between the loads are probably highly correlated with conditions at the same depth under the load, the additional consideration of parameters between the loads may not make any improvement in the performance prediction.
3. The calculation of stresses and strains at other locations in the pavement structure would have greatly increased the computer time necessary for the structural analysis.

Figure 5. Measured versus predicted deflections for fall and spring seasons.



RESULTS OF ANALYSIS

The mechanistic parameters calculated from the structural analysis of AASHO Road Test pavement sections, along with other data related to axle loads and pavement performance, were used to develop a performance prediction model that was implemented in a pavement management system. The development of this performance model and associated improvements to the pavement management system is described in a separate paper (1). The results of the structural analysis with regard to deflection measurements and ratios of layer moduli are discussed in this section.

Comparison of Results with Deflection Measurements

To determine with what accuracy the material characterizations in Table 2 and the modified BISAR program represent actual pavement response, surface deflections were calculated for a large number of pavement structures and axle loads that were part of the AASHO Road Test main experiment. These predicted deflections were then compared with Benkelman beam deflection measurements taken during the AASHO Road Test. Because the depth of the roadbed for the AASHO Road Test was known (6), the problem described earlier of predicting deflection measurements without accurate knowledge of the depth of roadbed was removed. A total of 183 pavement sections from loops 2 through 6 were analyzed; they included single-axle loads from 9 to 133 kN (2-30 kips) (6). Deflection measurements were made during fall and spring seasons for each section, thereby representing the times of the year when the pavement was in its best and worst condition, respectively.

The predicted deflections are compared with the deflection measurements in Figure 5. This figure shows the accuracy of the predictions for 366 points for one spring and one fall deflection for each pavement section. Figure 5 indicates that the measured deflections are generally slightly higher than the predicted deflections. However, this trend is not serious, and the figure indicates very good correlation, considering the wide range of pavement structures, loads, and seasonal conditions being examined. The root mean square error of the predicted deflection measurements is 0.028 cm (0.011 in), which is quite reasonable when compared with the root mean square error of 0.015 cm (0.006 in) for 30 replicate deflection measurements. These replicate data give an indication of the repeatability of the deflection measurements made at the AASHO Road Test.

Evaluation of Modulus Ratios

The ratio of elastic moduli for two adjacent layers in the pavement structure has long been considered an important factor in pavement response. Therefore, it was important to examine the layer modulus ratios that were calculated by using the modified BISAR program. The current Shell pavement design procedure determines the moduli for granular base materials by using a ratio of base to subgrade modulus between 2 and 4 (9). This procedure was developed from estimates of the dynamic moduli of pavement materials by using wave velocity measurements generated from the road vibration machine. Calculated moduli from wave velocity measurements of approximately 50 pavement structures were found to have a modulus ratio that ranged from 1 to 5 for adjacent unbound pavement layers (10). Recommendations were made to use a modulus ratio of roughly 2 for structural evaluation of unbound granular layers.

The modulus ratio is generally limited by the development of tensile strains in the bottom of unbound layers. If the ratio becomes too large, the tensile strains will have the effect of decompacting the upper layer, thereby reducing the modulus of the upper layer and the modulus ratio. In this study, calculations of modulus ratios for unbound layers were made from the results of the AASHO Road Test structural analysis. The results for the three-layer pavement structures showed general agreement with the range of modulus ratios, from 1 to 5, contained in the Shell data mentioned above. The modulus ratios of base to subbase were generally lower than that of subbase to subgrade, as is shown in Figures 6 and 7. However, some very high modulus ratios were found for the two-layer pavement structures, as illustrated in Figure 8. Further examination showed that the high ratios occurred when high stresses in the pavement structure caused the base modulus to be high and the subgrade modulus to be low. This condition, therefore, occurred with the heavier loads and thinner pavement structures.

An example of this condition is shown in Figure 9, where the moduli from the thin layer BISAR analysis are plotted for a 5-cm (2-in) asphalt and 7.6-cm (3-in) base pavement structure for single-axle loads of 9 and 53 kN (2 and 12 kips). Because of the higher stresses caused by the heavier load, the

Figure 6. Modulus ratios for base and subbase layers in three-layer pavement structure.

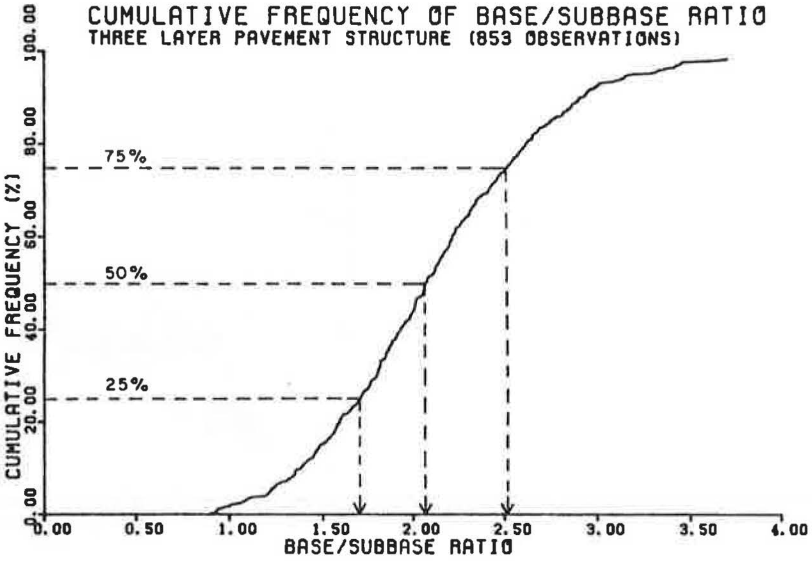


Figure 7. Modulus ratios for subbase and subgrade layers in three-layer pavement structure.

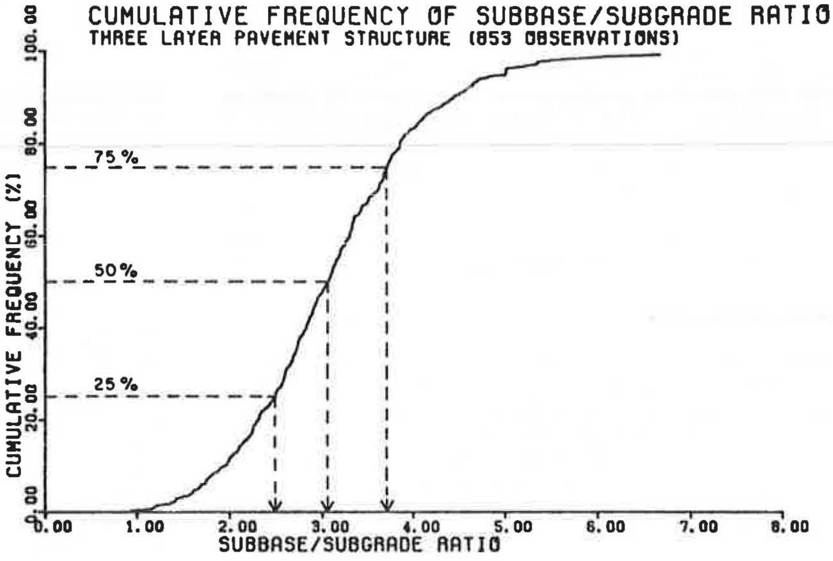


Figure 8. Modulus ratios for base and subgrade layers in two-layer pavement structure.

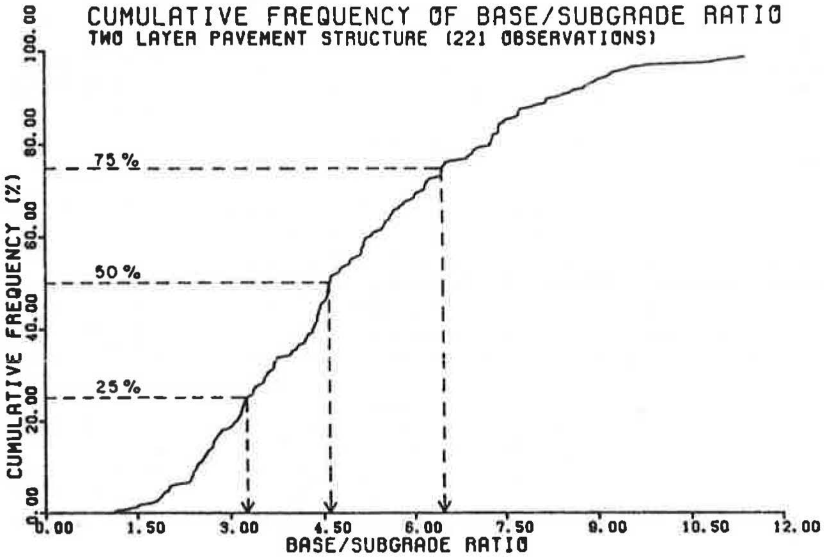
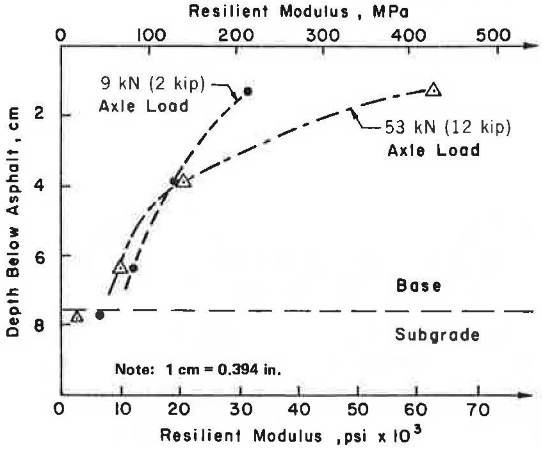


Figure 9. Moduli versus depth for 9- and 53-kN single-axle loads.



modulus of the base was higher and the modulus of the subgrade was lower than for the lighter load. This caused a higher modulus ratio for the heavy load.

It was concluded that the modulus ratios are not fixed within a certain range of values but can vary significantly, depending on the state of stress in the pavement layers. This conclusion was reinforced by the fact that the structural analysis, which was used to calculate the modulus ratios, had close agreement with actual deflection measurements.

CONCLUSIONS

This paper has presented the findings from a nonlinear elastic analysis of AASHO Road Test flexible pavement sections. The results of this analysis were not intended as a precise evaluation of pavement structures and were used in the development of a performance prediction model. Based on the findings from this study, the following conclusions are made:

1. The problems encountered when using the PSAD2A program to analyze pavement structures were solved by using a thin layer BISAR analysis;
2. An equivalent layer procedure that uses a modified BISAR program produced results very similar to the thin layer BISAR analysis;
3. The modified BISAR program and the seasonal material characterizations produced predicted surface deflections that were in good agreement with deflection measurements taken at the AASHO Road Test; and
4. Modulus ratios between adjacent unbound pavement layers are not fixed within a certain range of values but can vary significantly, depending on the state of stress in the pavement layers.

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