

GRAPHICAL METHODS FOR DETERMINING MODULI
OF PAVEMENT AND SUBLAYERS FROM DEFLECTION DATA

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by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

In this investigation a relationship between the ratio of the moduli of two layers in a two-layer pavement system and the ratio of deflections in a load deflected basin was developed. Charts correlating the relationship between these ratios are given in the report. By means of these charts, the moduli of the asphaltic concrete layers and the sublayer can be determined from dynaflect or Benkelman beam deflection data. A method of determining the moduli is outlined. This method can be used as an aid in correcting pavement deflections for changes in subgrade modulus values due to changes in subgrade moisture. The method is explained by means of examples.

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INTRODUCTION

For pavement evaluation and rehabilitation there is a growing need for knowing the modulus of the asphaltic concrete pavement layer and the modulus of the support provided by its underlying layers. The nondestructive method for obtaining these values usually uses pavement surface deflection data. Although methods are available for predicting pavement deflections from the moduli of the top layer and the underlying layers, no suitable method is available to reverse the process, that is determining the moduli of the layers from the deflection data. This investigation was aimed at providing a graphical method whereby this can be done.

OBJECTIVE AND SCOPE

The objective of this investigation was to develop charts, based on elastic theory, which would help in determining the moduli of the asphaltic concrete pavement layer and its supporting layers from data obtained by means of dynamic loading devices such as the dynaflect or nondynamic devices such as the Benkelman beam. To achieve this objective the method for analyzing two-layer elastic systems as developed by Burmister⁽¹⁾ and Chevron⁽²⁾ was used.

THE TWO-LAYERED SYSTEM

The two-layered system considered in this investigation is shown in Figure 1. The top layer is the pavement thickness, h_p , which consists of one or more asphaltic concrete layers. The average moduli, E_p , and average Poisson's ratio, U_p , of this top layer are assumed to represent the average elastic properties of the materials in the top asphaltic concrete layers. The bottom layer is the non-asphaltic subbase and soil subgrade of semi-infinite depth having a modulus, E_s , and Poisson's ratio, U_s .

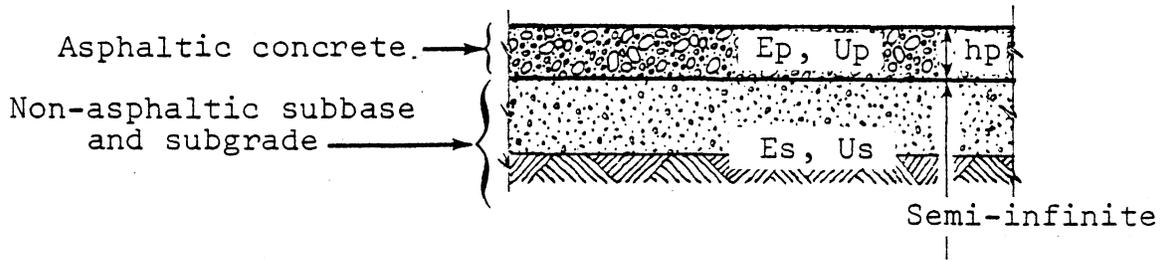


Figure 1. Two-layered pavement system.

DYNAFLECT DEFLECTIONS

The dynaflect is a machine which provides a dynamic load of 0 to 2,600 lb. (1,170 kg) at a frequency of 8 cycles per second (8 Hz) on a pavement through two force wheels and measures deflections at the center of the two wheels and at one-foot (30 cm) intervals from the center of the wheels and parallel to them. Thus five deflections as shown in Figure 2 are recorded.

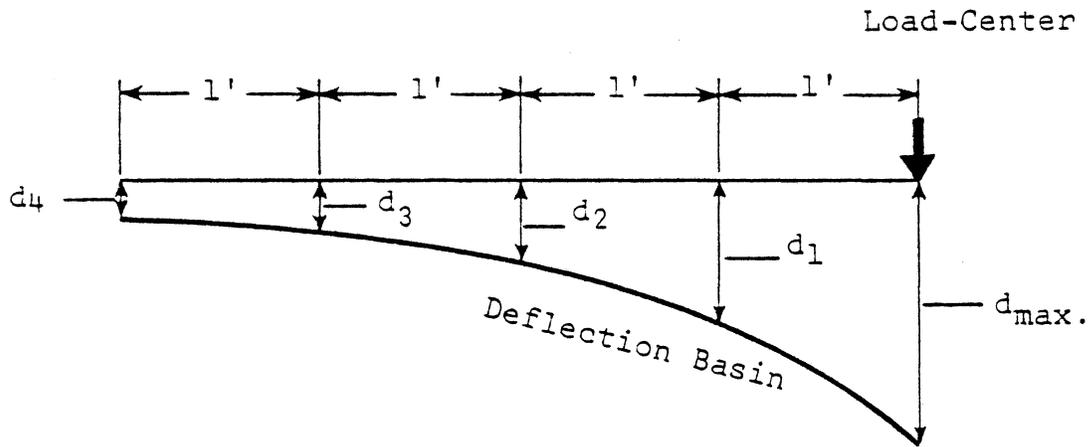


Figure 2. Deflection measured with dynaflect equipment.

USE OF DEFLECTION DATA
TO DETERMINE MODULI OF LAYERS

Variables

Theories and computer programs are available whereby if the elastic properties of pavement layers, i.e., the modulus and Poisson's ratio of materials and their thickness in each layer, are known, the surface deflections at any point on the pavement can be determined. However, no method or program is available for determining the elastic properties of the materials in the layered system from the thicknesses of the layers and the surface deflection data. The author believed that the only feasible approach to developing such a method was to develop charts whereby the elastic properties of the materials, the thickness of the layers, and the surface deflections could be correlated. Such charts then could be used to determine the unknown variable when the other variables were known.

In applying the technique, the variables to be correlated were as follows: (1) Wheel load, (2) tire pressure, (3) number of layers, (4) Poisson's ratio of each layer, (5) modulus of elasticity of each layer, (6) thickness of each layer, and (7) surface deflections. Because a chart system for correlating all these variables over varied ranges of values would be very cumbersome and difficult to use, the number of variables had to be reduced to the minimum necessary for practical usage. This was done as explained below.

1. Wheel load and tire pressure — Various agencies, including Virginia, have correlated dynaflect deflections with Benkelman beam deflections for a wheel load of 9-kips (40 kN) and a tire pressure of 70 psi (48 N/cm²), or a radius of contact of 6.4 inches (16.3 cm). Hence, in this investigation the wheel load and tire pressure and radius of contact are considered as constants of the values cited.
2. Number of layers — To simplify the evaluative technique, the pavement was divided into (a) the asphaltic concrete layer or layers, and (b) the non-asphaltic concrete layer or layers. This was necessary because the structural modulus of the asphaltic concrete is dependent on daily temperature variations while the structural modulus of its underlying layer or layers is dependent on daily moisture variations. The modulus of the asphaltic concrete layers, when determined separately from the non-asphaltic concrete layers, can be converted to the modulus at the standard temperature, which is needed

for pavement rehabilitation. Similarly, weak underlying layers indicate a need for subgrade strengthening. Hence in this investigation a solution for a two-layer system was considered.

3. Poisson's ratio of each layer — Data obtained from the computer study using the Chevron program was utilized to correlate the ratio of the moduli of the two-layered system and the ratio of the deflections in a deflection basin. This correlation showed that for a given value of the ratio of the elastic moduli of the two layers, the ratio of two deflections in a deflected basin does not change very much with changes in the Poisson's ratio of each of the two materials. A few examples of these are shown in Table 1. From these it can be seen that when $E_p/E_s = 1$, for any change in the Poisson's ratio (i.e., U_p or U_s) there is no change in the value of d_1/d_{max} or spreadability*, or d_2/d_{max} . When $E_p/E_s = 6, 30, \text{ or } 120$ for extreme changes in U_s or U_p , the change in d_1/d_{max} , spreadability and d_2/d_{max} is 4.1%. However, when calculating E_p and E_s from the ratio of deflections or spreadability, it has been found that the effect of change in the values of Poisson's ratio is negligible.
4. Modulus of elasticity of each layer — A study was made over all practical ranges of combinations of E_p and E_s to determine the method by which the moduli of the layers in a pavement could be correlated with the deflection data. It was found that the ratio of a deflection in a deflected basin to the maximum deflection like d_1/d_{max} , d_2/d_{max} , or spreadability correlates very well with E_p/E_s . A few examples of $E_p/E_s = 10, 50, \text{ and } 100$ are given in Table 2. These examples show that irrespective of the values of E_p and E_s (and also irrespective of their Poisson's ratios or maximum deflections) the value of d_1/d_{max} , or d_2/d_{max} , or spreadability is constant for a given value of E_p/E_s and h_p . Similarly, for a given value of d_1/d_{max} , or d_2/d_{max} , or spreadability and h_p , the value of E_p/E_s is constant.

Therefore, for a given value of h_p , d_1/d_{max} or d_2/d_{max} have a fixed relationship with E_p/E_s , irrespective of the values of the Poisson's ratio of the materials in the layered system.

*Spreadability is the percent ratio of the mean of the five deflections to d_{max} recorded in a deflected basin by means of a dynaflect and is

$$\frac{d_{max} + d_1 + d_2 + d_3 + d_4}{5 d_{max}} \times 100.$$

Table 1
Change in Ratio of Deflections with Change in Poisson's Ratio

Ep Es	Up	Us	d ₁ d _{max} x 100	d ₂ d _{max} x 100	Spread.	Basic Data		
						Ep (psi)	Es (psi)	hp (in.)
1	0.47	0.47	0.277	0.134	31.35	100,000	100,000	0
1	0.15	0.15	0.277	0.134	31.35	100,000	100,000	0
% Change	68	68	0	0	0			
6	0.47	0.47	59.03	40.42	49.91	30,000	5,000	15
6	0.47	0.15	58.51	40.85	50.47	300,000	50,000	15
% Change	0	68	-0.8	-1.0	-1.1			
30	0.47	0.47	79.32	59.19	62.97	300,000	10,000	10
30	0.47	0.15	79.42	59.89	63.73	300,000	10,000	10
% Change	0	68	-0.1	-1.2	-1.6			
120	0.47	0.47	80.26	55.57	60.24	300,000	2,500	5
120	0.47	0.15	80.64	56.54	61.08	300,000	2,500	5
% Change	0	68	-0.5	-1.7	-1.4			
30	0.40	0.40	77.66	55.85	60.60	300,000	10,000	9
30	0.13	0.40	76.03	53.56	59.02	300,000	10,000	9
% Change	68	0	2.1	4.1	2.6			

Units: 1 psi = 0.69 kN/m²; 1 in. = 2.54 cm.

Table 2
 Relationship Between $\frac{E_p}{E_s}$ and Ratio of Deflections

$\frac{E_p}{E_s}$	E_p (psi)	E_s (psi)	$\frac{d_1}{d_{max}} \times 100$	$\frac{d_2}{d_{max}} \times 100$	Spread.	Basic Data	
						hp. (in.)	Up Us
10	100,000	10,000	59.04	32.50	45.7	6	.47
10	300,000	30,000	59.04	32.50	45.7	6	.15
10	500,000	50,000	59.05	32.49	45.7	6	.47
Max. Change	400,000	40,000	0	0	0		
50	200,000	4,000	85.08	73.83	75.1	15	.47
50	400,000	8,000	85.12	73.83	75.1	15	.47
50	500,000	10,000	85.06	73.77	75.1	15	.47
Max. Change	300,000	6,000	0	0	0		
100	400,000	4,000	87.49	70.04	71.1	8	.47
100	500,000	5,000	87.64	70.01	71.1	8	.47
Max. Change	100,000	1,000	0	0	0		

Units: 1 psi = 0.69 kN/m²; 1 in. = 2.54 cm.

Development of Design Charts

The above discussion shows that for given deflection data the ratio of the elastic moduli of materials in a two-layer system can be obtained, irrespective of the Poisson's ratio of the materials in the layered system.

By means of the Chevron program deflections at 0, 1, 2, 3 and 4 ft. (0, 30, 60, 90, and 120 cm) for 9,000 lb. (8,160 kg.) wheel load were determined for different values of E_p and E_s with $U_p = 0.47$ and $U_s = 0.47$. Based on this information, the following charts were drawn.

1. Figure 3 — Chart relating d_1/d_{max} vs. E_p/E_s vs. h_p
2. Figure 4 — Chart relating d_2/d_{max} vs. E_p/E_s vs. h_p
3. Figure 5 — Chart relating spreadability vs. E_p/E_s vs. h_p .

Similar charts can be drawn to suit the deflection measuring device used by an agency. For example, agencies using the Benkelman beam need a chart relating d_2/d_{max} vs. E_p/E_s vs. h_p , which is given in Figure 4.

CAUTION: a. Do not use for $\frac{d_1}{d_{max}}$ greater than 80.
 b. Do not extrapolate.

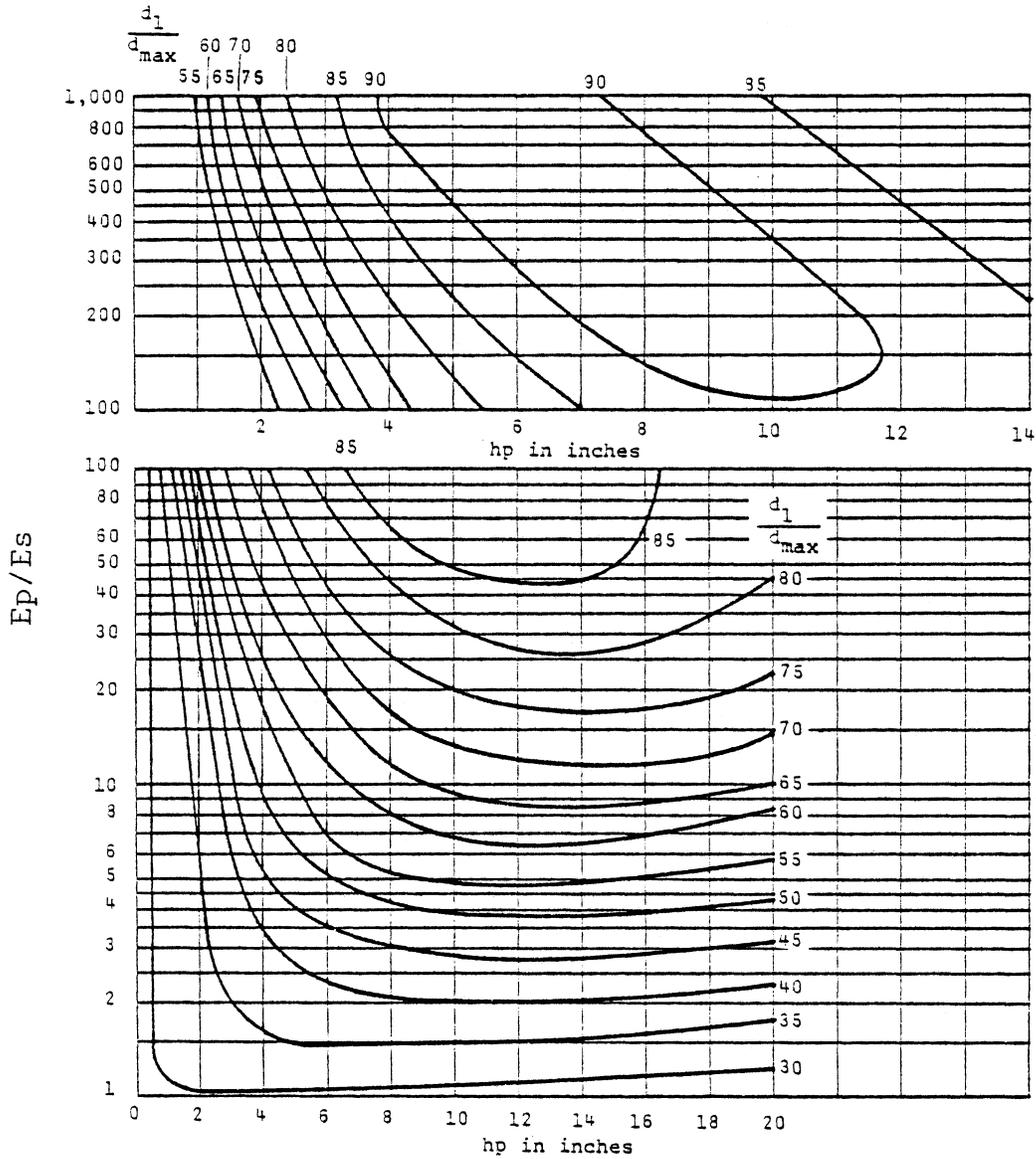


Figure 3. $\frac{d_1}{d_{max}}$ versus $\frac{E_p}{E_s}$ versus hp.

(Wheel load = 9,000 lbs; tire pressure = 70 psi; tire contact radius = 6.4 inches)

Conversion factors: 1 inch = 2.54 cm
 1 pound = 0.45 kg
 1 psi = 0.69 kN/m²

CAUTION: a. Do not use for $\frac{d_2}{d_{max}}$ greater than 80.
 b. Do not extrapolate.

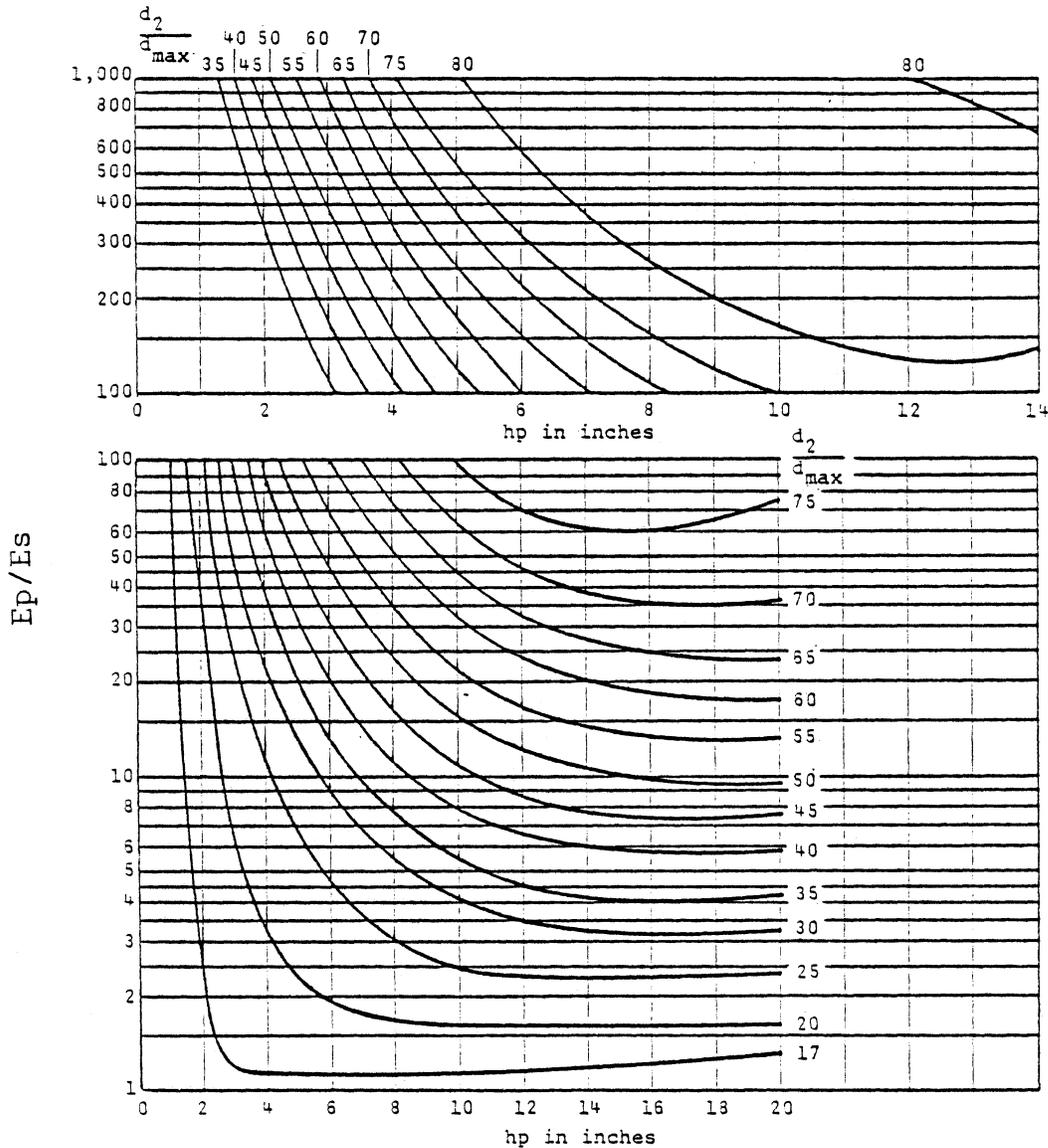


Figure 4. $\frac{d_2}{d_{max}}$ versus $\frac{E_p}{E_s}$ versus hp .

(Wheel load = 9,000 lbs; tire pressure = 70 psi; tire contact radius = 6.4 inches)

Conversion factors: 1 inch = 2.54 cm
 1 pound = 0.45 kg
 1 psi = 0.69 kN/m²

CAUTION: a. Do not use for values greater than 80.
 b. Do not extrapolate.

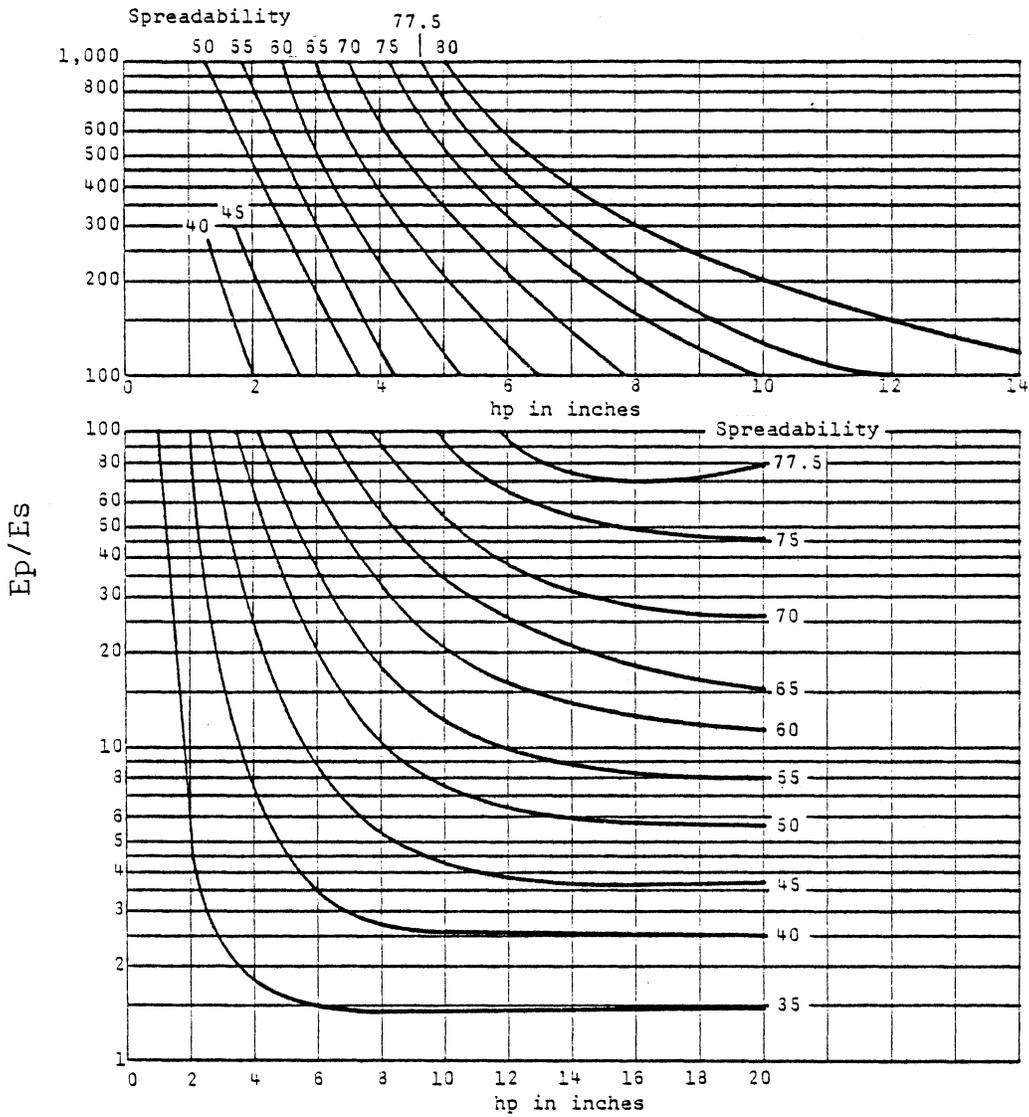


Figure 5. Spreadability versus $\frac{E_p}{E_s}$ versus hp.

(Wheel load = 9,000 lbs; tire pressure = 70 psi; tire contact radius = 6.4 inches)

Conversion factors: 1 inch = 2.54 cm
 1 pound = 0.45 kg
 1 psi = 0.69 kN/m²

Choice of Design Chart

The choice of design chart would depend on the data obtained. For example, in the case of the dynaflect machine for which d_{\max} , d_1 , d_2 , d_3 , and d_4 are measured, the charts in Figures 3 through 5 could be used.

The elastic theory assumes that the materials are homogeneous. In practice this is not so; therefore, the shape of the deflected basin and the deflections obtained in the deflected basin would not be the same as obtained by the theoretical approach used in the Chevron program. The following recommendations are, therefore, given.

1. When deflections d_{\max} and d_1 are given, Figure 3 could be used.
2. When deflections d_{\max} and d_2 are given (as in the case of the Benkelman beam), Figure 4 could be used.
3. When deflections d_{\max} , d_1 , d_2 , d_3 , and d_4 are given, the mean value of E_p/E_s can be obtained by use of the chart in Figure 5, in which spreadability fully accounts for the nonhomogeneity of the materials in the layered system. It is, however, recommended that the average value of E_p/E_s as obtained from figures 3, 4, and 5 be used for pavement evaluation.

TECHNIQUE FOR DETERMINING THE MODULI OF EACH LAYER

The method of determining E_p/E_s has been described in the previous paragraph. Burmister's design chart, shown in Figure 6, could be used to determine the values of E_p and E_s . In this chart the thickness of the top layer, h_p , is correlated with E_p/E_s and a factor F_w . The h_p is expressed in terms of the radius of the contact area, which is taken as 6.4 inches (16.3 cm.) in this investigation. Thus, given h_p and E_p/E_s , the value of F_w could be determined from this chart.

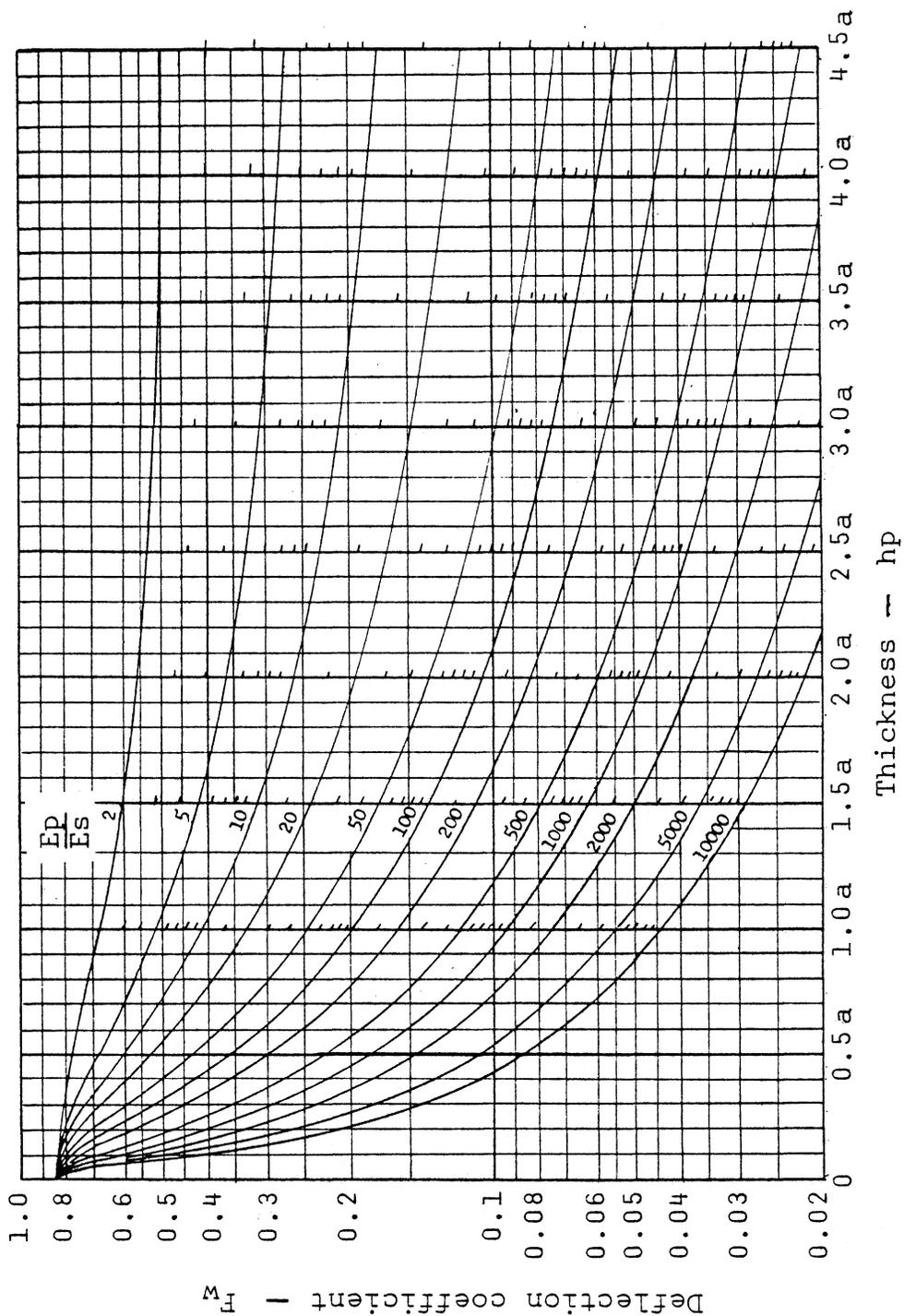


Figure 6. Burmister's influence curves of the deflection coefficient - F_w for the two-layer system.

$$F_w = \frac{E_s \cdot d_{\max}}{1.5 \cdot p \cdot a}$$

Then using Burmister's equation for flexible plates,

$$E_s = \frac{1.5 p \cdot a}{d_{\max}} \cdot F_w, \quad (1)$$

where

p = tire pressure 70 psi (48 N/cm²), and

a = radius of contact area, 6.4 inches (16.3 cm.).

With E_s having been determined, the value of E_p could be obtained from the ratio of E_p/E_s .

Appendix 1 gives three examples of deflection data from which E_p and E_s have been estimated by use of Figures 3, 4, 5 and 6. These three examples have $E_p/E_s = 6, 30, \text{ and } 120$; and $E_p = 30,000$ psi and 300,000 psi (20,700 or 207,000 kN/m²); $E_s = 2,500, 5,000, \text{ and } 10,000$ psi (1,725, 3,450 or 6,900 kN/m²); and $h_p = 4, 15, \text{ or } 16$ inches (10.0, 38.0 and 40.6 cm). Thus these three examples cover a wide range of values. As shown, the maximum deviation of the average estimated value of E_p and E_s from the actual value is 4.3%. This deviation could be due to either (1) a lack of accuracy in reading the charts, or (2) the fact that the pavement is not elastic and homogenous as assumed in the Chevron program. Examples in this appendix therefore show that by use of the ratios of deflection or spreadability, the modulus of each layer could be estimated.

Appendix 2 gives an evaluation of a 5-mile (8-km) project by the dynaflect measurement technique. The pavement is 8 years old and consists of a 9.5-inch (24-cm) asphaltic concrete over an 8-inch (20.3-cm) untreated aggregate with 6 inches (15.2 cm) of soil cement underneath.

The asphaltic concrete modulus, E_p , of this pavement is 253,000 psi (1,745 MN/m²). Maupin determined the modulus of a new asphaltic concrete in the laboratory at 70°F (48 N/cm²) as 233,000 psi (1,607 MN/m²).⁽⁴⁾ The author determined that the modulus of asphaltic concrete in a 1-year old pavement corrected for 70°F (17.8°C) was 300,000 psi (2,068 MN/m²).⁽⁵⁾ This 8-year old pavement should show a much higher modulus because the pavement becomes brittle with age. The low value of the E_p of this pavement indicates a failure of the asphaltic concrete layer. The pavement shows extreme longitudinal cracking and some alligator cracking. The asphaltic concrete samples taken from the pavement show that it had stripped adjacent to the cracks and also adjacent to its underlying aggregate layer, which was moist.

The combined modulus of the underlying layers and the subgrade, E_s , of the pavement is 6,500 psi (45 MN/m²). This value is much lower (less than half) than is obtained for underlayers consisting of an aggregate layer over 6-inches (15.2 cm) of soil cement. It is speculated that the underlying layers failed because of the following two causes: (a) the aggregate contained a lot of fines and mica (mica makes the material highly resilient); and (b) a thick, weak and resilient aggregate layer sandwiched between two strong layers of soil cement and asphaltic concrete results in a pavement receiving very little benefit of support from the soil cement. The author has determined the optimum thickness of nonresilient, untreated aggregate layer to be 4 inches (10 cm) to prevent reflection cracks from soil cement and provide a reasonable transfer of the load to the soil cement.⁽⁶⁾

ADVANTAGES OF USING THIS METHOD

This method of evaluating pavements is highly useful as follows:

1. It determines the modulus of the asphaltic concrete layer and its underlying layers by a nondestructive surface deflection technique.
2. It helps in maintaining case histories of pavements. By this method, changes in the modulus of the asphaltic concrete layer or changes in the modulus of each underlying layer can be determined. It can also help in determining the thickness of an overlay and the strength contributed by an overlay.

An example of an evaluation of an overlay is shown in Appendix 3. This example has been particularly chosen to show that the temperature corrected maximum deflection⁽³⁾ after the overlay (0.017 in. = 0.043 cm) was higher than before the overlay (0.014 in. = 0.036 cm). This was so because, due to moisture and other changes in the subgrade, the modulus of the underlying layer decreased from 14,600 psi (10,100 kN/m²) before the overlay to 8,400 psi (5,800 kN/m²) after the overlay. As shown in Appendix 3, the maximum deflection after correcting the subgrade modulus was 0.012 inch (0.031 cm) as compared to 0.014 inch (0.036 cm) before the overlay.

CONCLUSION

The charts developed in this investigation could be used to determine the moduli of the pavement and the subgrade when two or more deflections in a deflected basin are known. The report explains the method to be used. The method will help in providing corrections needed because of changes in the moisture content of the subgrade and base materials.

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APPENDIX 1

EXAMPLES FOR EVALUATION OF MODULI OF LAYERS

Example No.	Fig. Used	Ep/Es		Fw (Fig. 6)	Es (psi)		Ep (psi)		% Change
		Est. from Fig.	Actual		Estimated	Actual	Estimated	Actual	
1	Given $d_{max} = 0.0486$ in., $d_1 = 0.0287$ in.; $d_2 = 0.0197$, spread. = 49.9; hp = 15 in.								
	3	6.2	6.0	.35	4,836	5,000	29,983	30,000	0
	4	6.0	6.0	.36	4,977	5,000	29,862	30,000	0
	5	5.8	6.0	.37	5,133	5,000	29,771	30,000	-1
Average									0
2	Given $d_{max} = 0.0112$ in., $d_1 = 0.0091$ in., $d_2 = 0.0076$ in.; spread. = 70.5; hp = 16 in.								
	3	30	30	.16	9,600	10,000	288,000	300,000	-4
	4	30	30	.16	9,600	10,000	288,000	300,000	-4
	5	28	30	.17	10,200	10,000	285,600	300,000	-4.8
Average									4.3
3	Given $d_{max} = 0.093$; $d_1 = 0.0701$; $d_2 = 0.0440$; spread. = 54.8; hp = 4.0 in.								
	3	120	120	.35	2,523	2,500	302,750	300,000	+0.9
	4	130	120	.35	2,451	2,500	318,630	300,000	+6.2
	5	120	120	.35	2,523	2,500	302,750	300,000	+0.9
Average									2.7

Units: 1 psi = 0.69 kN/m²; 1 in. = 2.54 cm.

APPENDIX 2

EVALUATION OF A PAVEMENT FROM DYNAFLECT MEASUREMENTS

Milepost	Es (psi)	Ep (psi)
150 - 151	6,200	252,000
151 - 152	5,900	230,000
152 - 153	6,100	279,000
153 - 154	7,100	270,000
154 - 155	7,000	236,000
Average	6,500	253,000

Units: 1 psi = 0.69 kN/m².

APPENDIX 3

EXAMPLE OF CORRECTING DEFLECTION DATA FOR VARIATIONS IN MOISTURE OF A SUBLAYER

1. Field Data

Condition	Date	$d_{\max}^{(3)}$ at 70°F (inches)	d_1/d_{\max}	d_2/d_{\max}	Spread.	hp (inches)
Before Overlay	5-18-77	.014	73.8%	54.8%	54	9.7
After Overlay	11-2-77	.017	82.7%	61.3%	67	10.4

2. Determining values of E_s and E_p by use of Figures 3, 4, and 5 as explained in Appendix 1.

Condition	E_s (psi)	E_p at 70°F (psi)
Before Overlay	14,600	253,000
After Overlay	8,400	320,000

3. Correcting d_{\max} due to change in E_s after the overlay

$$\text{Corrected } \frac{E_p}{E_s} \text{ after the overlay} = \frac{E_p \text{ after the overlay}}{E_s \text{ before the overlay}} = \frac{320,000}{14,600} = 21.9$$

F_w for the corrected $\frac{E_p}{E_s}$ from Burmister's chart (Figure 6) = 0.25

$$\text{Corrected } d_{\max} \text{ of the overlaid pavement} = \frac{F_w(1.5 \text{ pa})}{E_s} = \frac{0.25 \times 1.5 \times 70 \times 6.4}{14,600}$$

$$= .012 \text{ inch}$$

Units: 1 psi = 0.69 kN/m²; 1 inch = 2.54 cm.

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