PAVEMENT DESIGN & PERFORMANCE STUDY
PHASE B: DEFLECTION STUDY

Interim Report No. 3

A Method for Evaluating the Structural Performance of Subgrades and/or the Overlying Flexible Pavements

by

N. K. Vaswani
Highway Research Engineer

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

SUMMARY

The structural evaluation of flexible pavement is now carried out mostly by deflection measuring devices such as the dynaflect or Benkelman beam. The object of this investigation was to determine whether the properties of the deflected basin measured by these devices on the pavement surfaces could enable evaluation of the subgrade and/or its overlying pavement separately.

The properties of the deflected basin are defined by the maximum deflection and the spreadability, which is the average deflection expressed as a percentage of the maximum deflection. A theoretical analysis showed that these properties are a function of the modulus of elasticity of the subgrade, the average modulus of elasticity of the pavement over the subgrade, and the thickness index of the overlying pavement.

A general chart was developed which correlates maximum deflection and spreadability with (i) the subgrade strength, (ii) the average pavement strength, and (iii) the thickness index of the pavement. This chart was tested for structural evaluations of the subgrade and/or its overlying pavement for satellite projects in Virginia. Ten typical examples of the satellite projects are given in the report and the change in their structural behavior with time is discussed.

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INTRODUCTION

Following publication of the WASHO Road Test Results, much sophisticated equipment was developed for evaluating the structural performance or strength of pavements. In spite of the availability of all this equipment many states, including Virginia, have been unable to determine whether failures or changes in the structural behavior of flexible pavements are attributable to (i) the subgrade only, (ii) the pavement over the subgrade, or (iii) both the subgrade and the pavement.

The surface deflections of a pavement have proved to be a very valuable indicator of the structural performance of the pavement as a whole, including its subgrade; and most states, including Virginia, have equipment for measuring these deflections. The commonly adopted apparatus is the Benkelman beam. The dynaflect is being used in Virginia. Both measure the maximum and other vertical displacements within the deflected basin.

SCOPE

In this investigation a theoretical evaluation was conducted in which the maximum deflection data and other available displacements in the deflected basin were used to evaluate the strength of the subgrade separately from the strength of the overlying pavement, and thus determine the amount of change in the strength of the subgrade separately from the change in the strength of the overlying pavement. The study was divided into three parts as stated below:

(i) A theoretical determination of the thickness equivalency
     values of materials having different moduli of elasticity
     and Poisson's ratios.

(ii) A correlation of the maximum deflection with the properties
      of the deflected basin for varying layered systems.

(iii) The development of a pavement evaluation chart which evaluates
      the subgrade strength separately from the pavement strength.

PURPOSE

The purpose of this study was as follows:

(i) By theoretical analysis, to develop a general chart with which the vertical displacements obtained from the deflected basin could be used to separately evaluate the subgrade and the overlying pavement.

(ii) To determine whether the theoretical evaluation in (i) above could be applied to the pavement in practice.

VARIABLES, CONSTANTS AND ASSUMPTIONS

The dependent variables in this investigation were: (i) the maximum deflection of the deflected basin, (ii) the spreadability of the deflected basin, and (iii) the curvature of the deflected basin.

The maximum deflection "d_{max}" is the deflection under the center of the applied load.

The spreadability is the average deflection expressed as a percentage of the maximum deflection and in this investigation was taken as follows

$$\text{Spreadability} = \frac{d_{max} + d_1 + d_2 + d_3 + d_4}{5\, d_{max}} \times 100 \text{ percent} \qquad (1)$$

where d_1, d_2, d_3 and d_4 are the deflections at 1, 2, 3 and 4 ft. from the center of the applied load. Thus the spreadability shows the degree to which the load spreads over the pavement surface. The higher the spreadability, the more will be the spread of the load, and vice versa.

A theoretical correlation was developed between spreadability and the curvature at 4 ft., 2 ft., and 1 ft. A curvature is considered as the percent ratio of a vertical displacement in a deflected basin to the maximum displacement as shown in Figure 1. This correlation was developed for two and three layer systems with moduli of elasticity E_1 of the top layer varying from 30,000 to 3,000,000 psi, E_2 for the second layer as 30,000 and 300,000 psi, and E_s varying, for the subgrade, from 250 to 30,000 psi. The combinations of the layered systems adopted and the correlation at 4 ft., 2 ft., and 1 ft. are given in Figure 1. As is evident from this figure an excellent correlation exists between these two variables. The relationship between spreadability and curvature
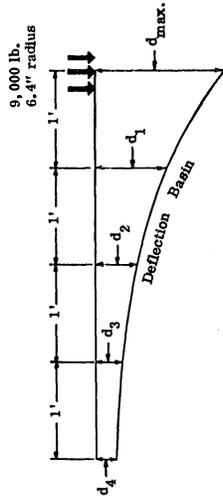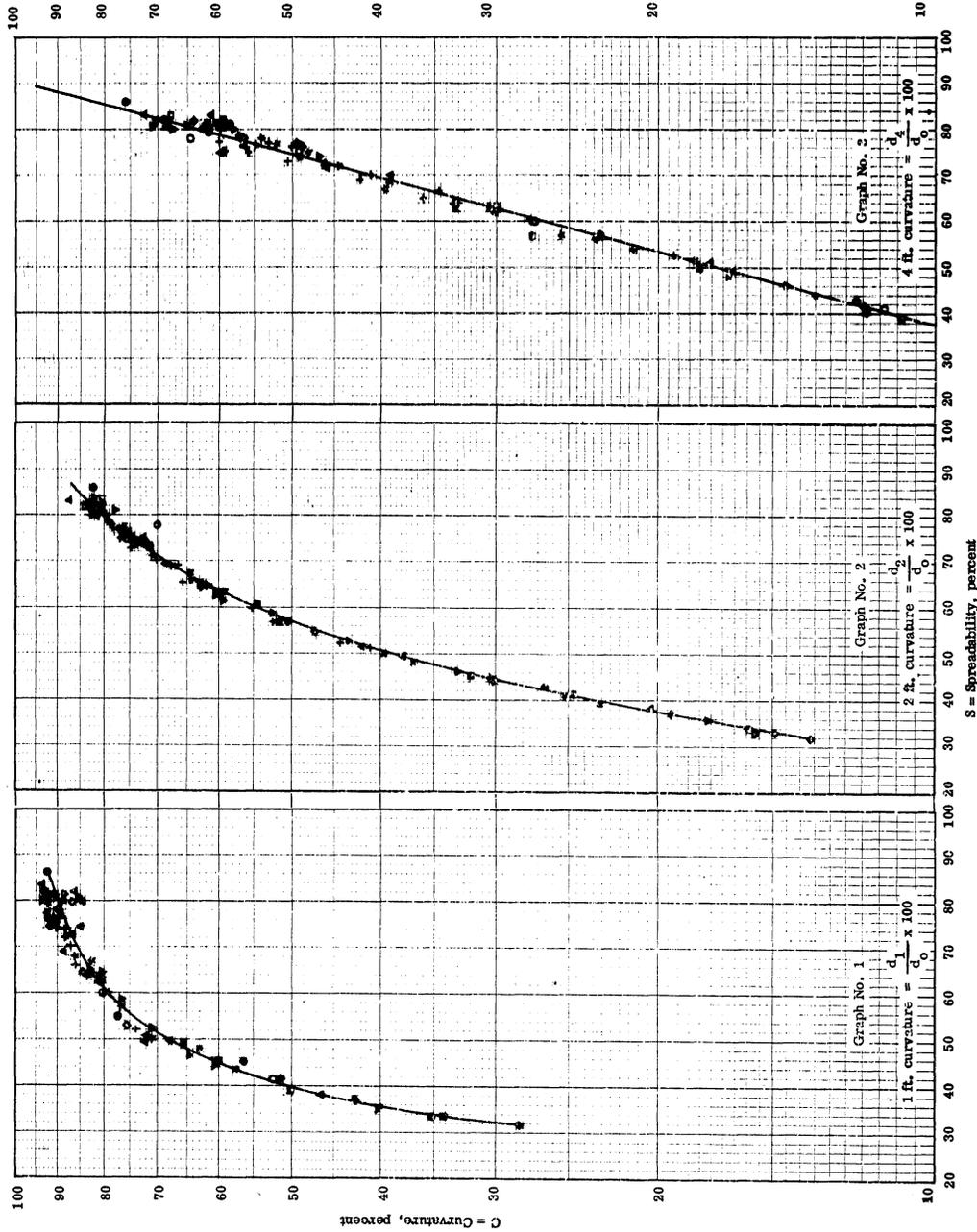
$$\text{Spreadability} = \frac{d_0 + d_1 + d_2 + d_3 + d_4}{5\,d_0} \times 100 \quad (\text{See Graph No. 1})$$

$$1 \text{ ft. curvature} = \frac{d_1}{d_0} \times 100 \quad (\text{See Graph No. 1})$$

$$2 \text{ ft. curvature} = \frac{d_2}{d_0} \times 100 \quad (\text{See Graph No. 2})$$

$$4 \text{ ft. curvature} = \frac{d_4}{d_0} \times 100 \quad (\text{See Graph No. 3})$$

9,000 lb.
6.4" radius

$d_{max.}$

Deflection Basin

INDEX:

o	$E_1 = 30,000$ psi and $E_s =$	250 psi
•	$E_1 = 300,000$ psi and $E_s =$	250 psi
▲	$E_1 = 30,000$ psi and $E_s =$	500 psi
▲	$E_1 = 300,000$ psi and $E_s =$	500 psi
▼	$E_1 = 30,000$ psi and $E_s =$	1,000 psi
▼	$E_1 = 300,000$ psi and $E_s =$	1,000 psi
□	$E_1 = 3,000,000$ psi and $E_c =$	2,500 psi
◇	$E_1 = 30,000$ psi and $E_s =$	2,500 psi
♦	$E_1 = 30,000$ psi and $E_s =$	5,000 psi
×	$E_1 = 300,000$ psi and $E_s =$	30,000 psi
★	$E_1 = 300,000$ psi, $E_2 = 30,000$ psi and $E_s = 1,000$ psi	
+	$E_1 = 30,000$ psi, $E_2 = 300,000$ psi and $E_s = 1,000$ psi	

Graph No. 3 — $4 \text{ ft. curvature} = \frac{d_4}{d_0} \times 100$

Graph No. 2 — $2 \text{ ft. curvature} = \frac{d_2}{d_0} \times 100$

Graph No. 1 — $1 \text{ ft. curvature} = \frac{d_1}{d_0} \times 100$

S = Spreadability, percent

C = Curvature, percent

Figure 1. Relation between spreadability and curvature.

at 4 ft. is linear on a semi-log scale. It was therefore thought unnecessary to consider both spreadability and curvature in the rest of the investigation. It was felt that any suitable correlation obtained with spreadablity could also be obtained with curvature. Then for the rest of the investigation the maximum deflection and spreadability were treated as the dependent variables.

In Virginia, the dynaflect equipment is used for measuring surface deflection. This equipment is used to measure the deflections at the center of the applied load, i. e. , d_0 , and those at 1 ft. , 2 ft. , 3 ft. , and 4 ft. from the center of the applied load along the longitudinal axis of the vehicle. The dynaflect deflections have been correlated with the Benkelman beam deflections and a modifying factor of 28.6 has been established, i. ,e. , the dynaflect deflection x 28.6 = Benkelman beam deflection. [1]

In the investigation, to permit use of the data from the dynaflect equipment, the spreadability was calculated from the deflection data at 0, 1, 2, 3 and 4 ft. from the applied load. Because of the good relationship between curvature and spread-ability, it is felt that the procedure described herein could easily be developed for the Benkelman beam or any other similar device which measures maximum deflection and at least one additional deflection in the deflection basin.

The maximum deflection and spreadability are a function of the wheel load and the tire pressure. A maximum wheel load of 9,000 lb. as allowed in Virginia [2] was chosen for use in the investigation. The tire pressure was taken as 70 psi over a circular contact area.

In the theoretical evaluation, the materials in the layered system were assumed to be elastic, isotropic and homogeneous, and it was assumed that there was a perfect bond between the adjacent layers. A Chevron Computer Program[3] was used for this evaluation.

Pavement systems with layers of decreasing strength from the top of the pavement towards the subgrade were taken into consideration. The sandwich layer system nor the case of weaker layers over stronger layers are included in the results because of their different behavior. This difference in behavior is indicated by a few examples in the following pages and also in the report on model studies[4]conducted prior to this investigation.

Figure 2 shows the deflection basins for a single layer system with varying moduli of elasticity and Poisson's ratios. The shape of the deflection basin is similar for all the cases shown. The maximum deflection varies depending on the modulus of elasticity, the Poisson's ratio, or both. Thus, if the Poisson's ratio is kept constant, any amount of maximum deflection and a similar basin can be obtained by varying the modulus of elasticity only, instead of varying both.
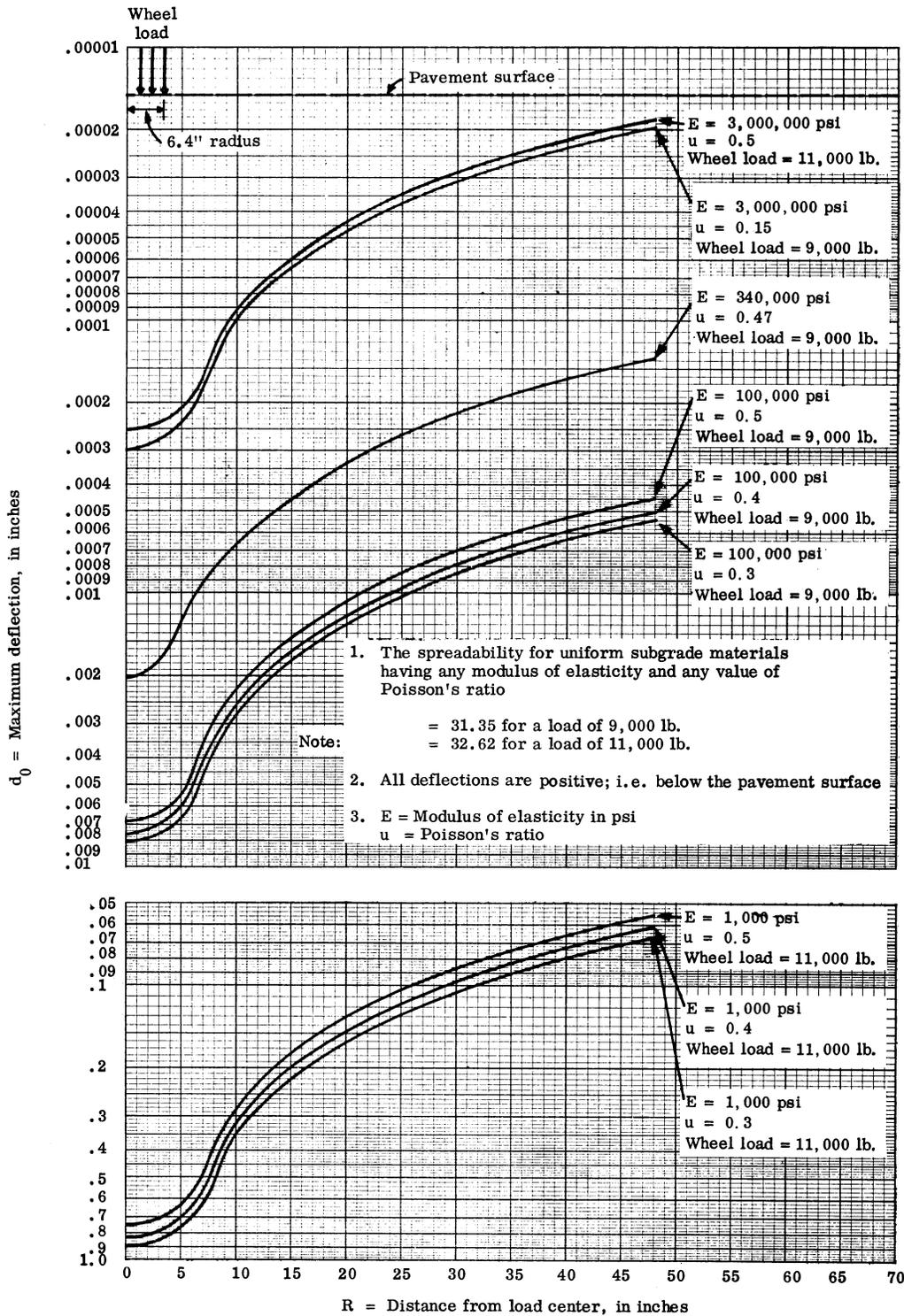
Figure 2. Deflection basin for a single layer with variable load, modulus of elasticity and Poisson's ratio.

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The Poisson's ratio of all materials used in the theoretical evaluation of flexible pavements was assumed to be 0.47. However cases of subgrades with values other than 0.47 were also tried but ultimately were not adopted for design. The 0.47 value was assumed to facilitate the correlation between the theoretical and field investigations.

SUBGRADE

A subgrade could be considered as a single layer system of semi-infinite depth. The maximum deflection and the deflected basins for loads of 9,000 and 11,000 lb., with moduli of elasticity varying from 1,000 psi to 3,000,000 psi and Poisson's ratios of 0.3, 0.4, 0.47 and 0.5, were determined by the elastic modulus theory. A few examples of the shapes of the deflected basins so obtained are given in Figure 2. This figure shows that though the maximum deflection varies inversely to the modulus of elasticity and Poisson's ratio, the shape of the deflected basins remains the same.

The spreadability as defined above was calculated for the theoretical deflection basins of a semi-infinite layer and varying moduli of elasticity. The spreadability value was found to be constant for a given load irrespective of the modulus of elasticity. The spreadability was not only calculated by means of five ordinates in the deflected basin but by various numbers of ordinates. It was again found to be constant for the given number of ordinates. The spreadability as defined above -- by five ordinates -- was found to be 31.35 for a 9,000 lb. wheel load and 32.62 for a 11,000 lb. wheel load as shown in Table 1. Thus, for a given loading the spreadability is seen to be constant for uniform subgrades regardless of the strength (modulus of elasticity) or Poisson's ratio.

TABLE 1

CALCULATION OF SPREADABILITY ON A SEMI-INFINITE SINGLE LAYER

Wheel Load* (lbs.)	E_s** (psi)	u***	Distance from load center — ft.					Spreadability
			0'	1'	2'	3'	4'	
			Deflections in inches					
11,000	1,000	0.5	0.7426	0.2298	0.1108	0.0735	0.0548	32.62
11,000	1,000	0.4	0.8317	0.2573	0.1241	0.0823	0.0613	32.62
11,000	1,000	0.3	0.9010	0.2788	0.1345	0.0891	0.0665	32.62
11,000	3,000,000	0.5	2.475×10^{-4}	7.659×10^{-5}	3.69×10^{-5}	2.448×10^{-5}	1.826×10^{-5}	32.62
9,000	100,000	0.5	6.717×10^{-3}	1.862×10^{-3}	9.025×10^{-4}	5.980×10^{-4}	4.500×10^{-4}	31.35
9,000	100,000	0.4	7.523×10^{-3}	2.085×10^{-3}	1.011×10^{-3}	6.698×10^{-4}	5.040×10^{-4}	31.35
9,000	100,000	0.3	8.150×10^{-3}	2.259×10^{-3}	1.095×10^{-3}	7.256×10^{-4}	5.460×10^{-4}	31.35
9,000	340,000	0.47	2.052×10^{-4}	5.688×10^{-4}	2.757×10^{-4}	1.827×10^{-4}	1.375×10^{-4}	31.35
9,000	3,000,000	0.15	2.918×10^{-4}	8.088×10^{-5}	3.921×10^{-5}	2.598×10^{-5}	1.955×10^{-5}	31.35

* Tire pressure = 70 psi

** E_s = Modulus of elasticity of the subgrade

*** u = Poisson's Ratio

$$\text{Spreadability} = \frac{\text{Sum of deflection at 0, 1', 2', 3 and 4'}}{5 \times \text{deflection at 0}} \times 100$$

THICKNESS INDEX AND SUBGRADE FACTOR

In the AASHO Road Tests, the resistance to deflection or the structural behavior of a pavement was defined by the following model equation.

$$\log d_{max} = a_0 + a_1 h_1 + a_2 h_2 + a_3 h_3 + \ldots = a_0 + D \qquad (2)$$

where

d_{max} = the deflection under the center of the applied load

a_0 = a constant

a_1, a_2, a_3 = the coefficients of relative strength; they are termed thickness equivalencies in this investigation and could be defined as equivalent strengths per inch depth of the material in a given layer

h_1, h_2, h_3 = the thicknesses of the layers having thickness equivalency values of a_1, a_2, a_3 respectively, and

D = thickness index, is equal to $a_1 h_1 + a_2 h_2 + a_3 h_3$

To theoretically determine the thickness equivalencies of the materials for given moduli of elasticity, maximum deflections were calculated with the top layer of a given modulus of elasticity resting over a subgrade with a modulus of elasticity of 1,000 psi. Figure 3 shows the relationship between the maximum deflection and thicknesses of the top layers with given moduli of elasticity.

To determine the theoretical thickness equivalency of each of these materials the thickness equivalency of one material had to be assumed as unity. An example of evaluating the thickness equivalency of a material is given below.

In Figure 3, for $d_0 = 0.35$, the thickness of the layer with E = 30,000 psi is 4"; while the thickness of the layer with E = 300,000 psi for the same value of d_0 is 0.8". Thus the thickness equivalency of the material with E = 30,000 psi at $d_0 = 0.35$ is equal to $\frac{0.8}{4} = 0.2$. In a similar manner the thickness equivalency of the material having E = 30,000 psi is determined for different values of d_0 from Figure 3. An average of the thickness equivalency values so obtained is considered as the thickness equivalency of the material having E = 30,000 psi. It was found that there was very little difference between the thickness equivalencies obtained for the same material with varying amounts of deflections. The thickness equivalencies of the materials 'a' so determined are given below and also in Figure 3.

For E equal to 5,000 psi, a = 0.2   For E equal to 340,000 psi, a = 1.16

For E equal to 30,000 psi, a = 0.44   For E equal to 3,000,000 psi (u = 0.15), a = 2.00

For E equal to 300,000 psi, a = 1.00   For E equal to 4,000,000 psi (u = 0.15),

a = 2.16 (by extrapolation)
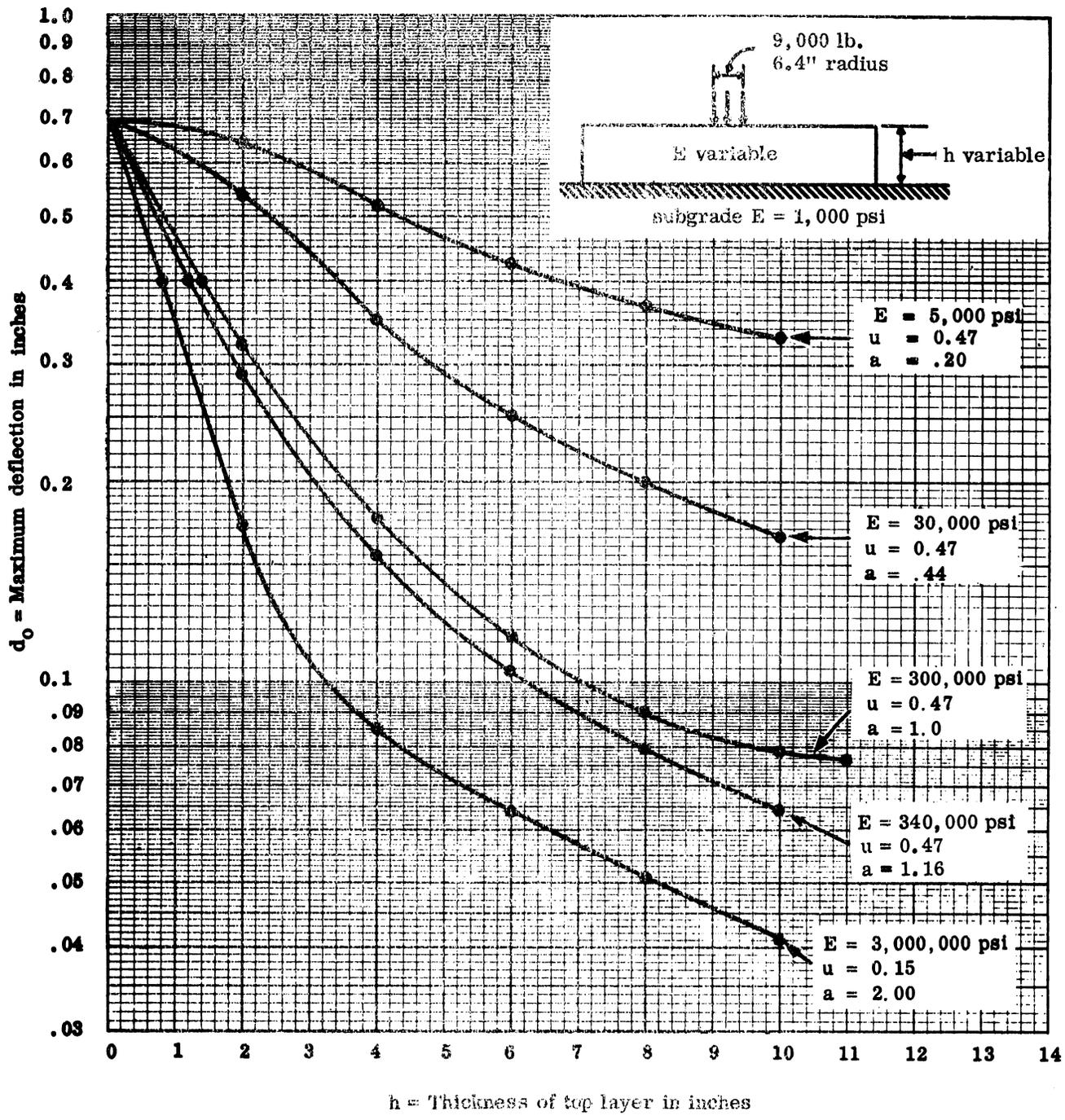
Figure 3. Evaluation of thickness equivalency values.

To determine whether the thickness equivalency values would change with the subgrade, thickness equivalency values for $E = 30,000$, $300,000$ and $3,000,000$ psi were determined in the manner explained above but with a subgrade having $E_s = 5,000$ psi. The values remained almost the same as given above.

An evaluation was carried out to determine whether the thickness equivalency values determined would satisfy the AASHO model equation No. 2 given above. This was done by varying the number, thicknesses and strengths of the different layers. The relationship between the maximum theoretical deflection and the thickness index is shown in Figure 4. This relationship is given by the equation $\log d_0 + 0.92 \log D = -0.173$. It has a correlation coefficient of 0.985 and a standard error of estimate of 0.098.

It may be pointed out that in 1968 a similar type of relationship was developed from satellite projects in Virginia; this relationship was $\log d_0 + 0.068\ D = 2.06$.[5] This relationship could be converted in the general equation to the form $\log d_0 + a \log D = b$ as determined by the theoretical evaluation mentioned above, where a and b are constants of the equation.

The investigations carried out on satellite projects in Virginia also showed that deflection is a function not only of the strength of the pavement structure over the subgrade but also that of the subgrade. A 1969 investigation[6] gave the following equation: $\log d_0 + 0.043\ (D + \text{subgrade factor}) = 0.32$. This equation could also be converted in the general equation to the form $\log d + a \log (D + \text{subgrade factor}) = b$, where a and b are constants. Figure 5 (main curves left to right) shows how the subgrade strength contributes towards the decreased deflections.
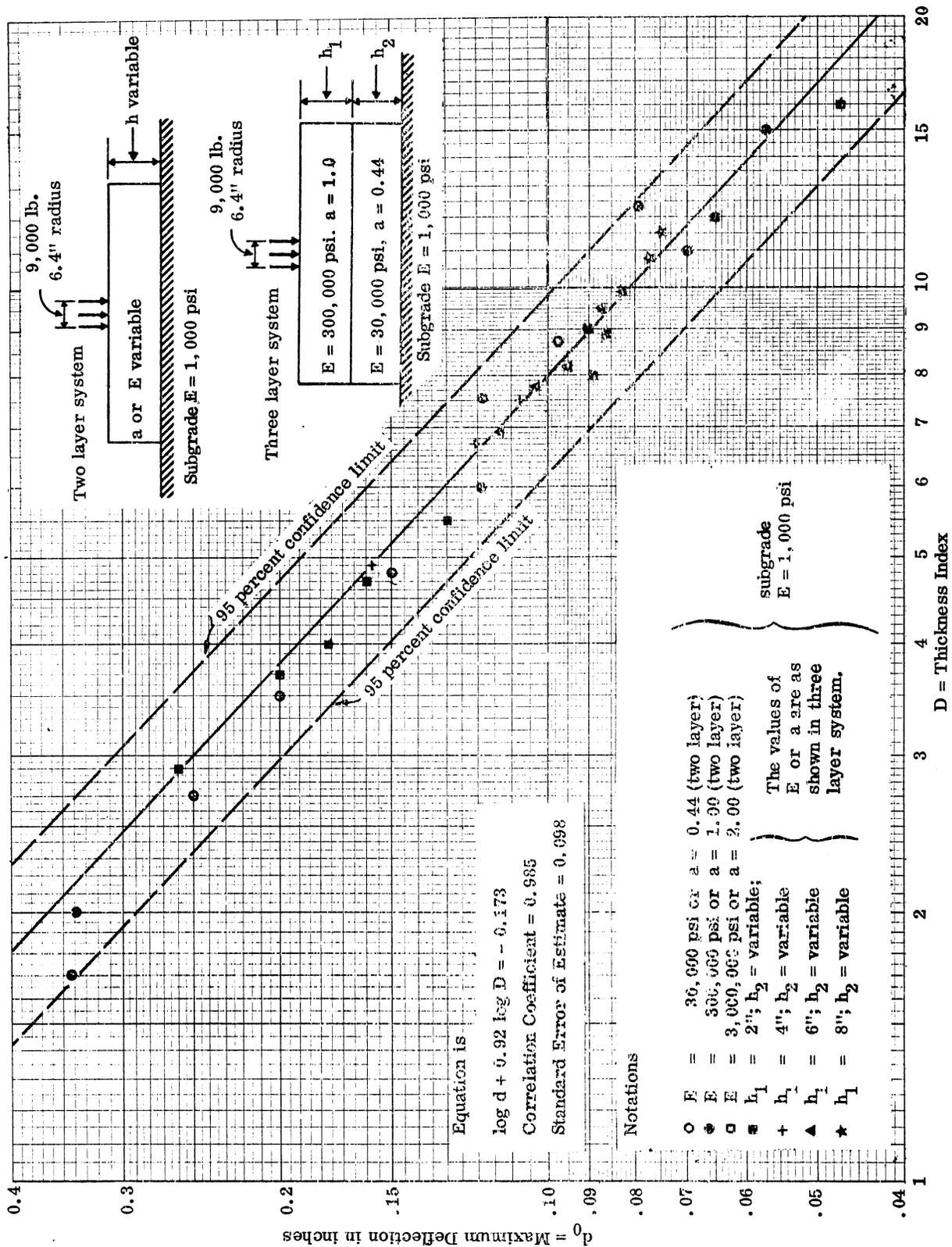
Figure 4. Correlation between deflection and thickness index based on layered theory.

INTERACTION OF SUBGRADE AND/OR PAVEMENT OVER THE
SUBGRADE WITH MAXIMUM DEFLECTION AND SPREADABILITY

The theoretical evaluation discussed above showed that the spreadability of a single layer system remains constant for any value of the modulus of elasticity of the subgrade, while the maximum deflection decreases as the modulus of elasticity of the subgrade increases.

The relation between E_s and d_0 is given by the general equation

$$d_0 = \frac{1}{E_s} \, f \, (\frac{1}{u}, \, p, \, and \, a) \tag{3}$$

where

d	$=$	vertical displacement
E_s	$=$	subgrade modulus
u, p and r	$=$	Poisson's ratio, tire pressure, and radius of contact.

In this investigation the respective values were, $u = 0.47$, $p = 70$ psi, $r = 6.4"$ and $z = 0$; hence $E_s d_0 = $ a constant.

Stronger pavement layers over the subgrade increase the spreadability while reducing the deflection. In some cases it may be possible to determine the amount of decrease in deflection caused by the overlying pavement layers. If this is determined then the deflection of the subgrade could be calculated by adding this decrease in deflection to the total deflection determined on the top of the pavement. The deflection of the subgrade, along with the spreadability value of the pavement over the subgrade, will enable the determination of the modulus of elasticity of the subgrade, the thickness index of the pavment and the average modulus of elasticity of the pavement layers.

In Figure 5 seven main curves have been drawn. Each of these main curves is for a different modulus of elasticity of the subgrade. The subgrade modulus of elasticity for all the main curves is given in Table 2. Each of these main curves is divided into subcurves. The subcurves — A, B and sometimes C — for each of the main curves have pavement layer moduli of elasticity of 30,000; 300,000; and 3,000,000 psi, respectively, as shown in Table 2. Each main and subcurve is marked with a thickness index value, D.
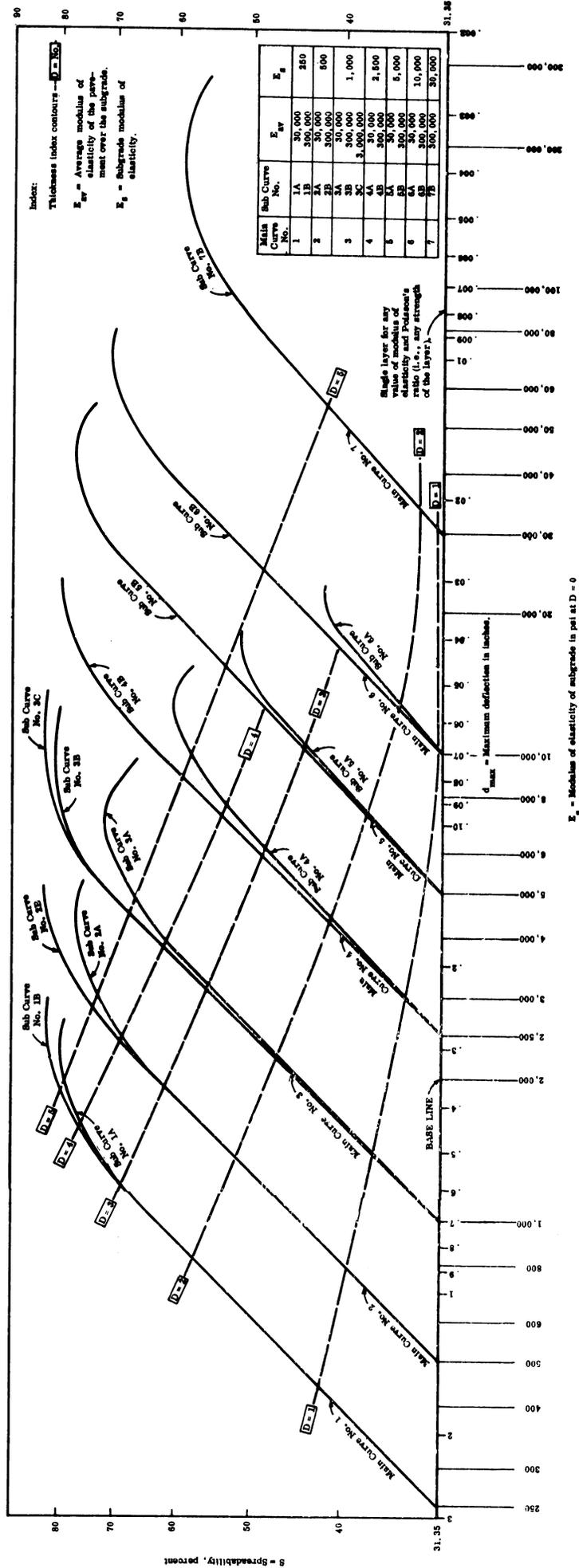
Figure 5. General evaluation chart for determining changes in the subgrade and/or pavement strength of flexible pavements.

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TABLE 2

DETAILS OF MAIN CURVES AND SUBCURVES

Main Curve	E_s, psi	Subcurve	E_1, psi
1	250	1A	30,000
		1B	300,000
2	500	2A	30,000
		2B	300,000
3	1,000	3A	30,000
		3B	300,000
		3C	3,000,000
4	2,500	4A	30,000
		4B	300,000
5	5,000	5A	30,000
		5B	300,000
6	10,000	6A	30,000
		6B	300,000
7	30,000	7B	300,000

Thus if maximum deflection and spreadability values are known, the subgrade modulus of elasticity, the thickness index of the pavement and the average modulus of elasticity, E_{av}, of the pavement could be determined. For example, given $d_0 = 0.078$ in. and S = 60, from Figure 5 it is found that $E_s = 2,500$ psi, D = 5.0 and $E_{av} = 300,000$ psi.

In Figure 5 all the main curves are almost parallel to each other. The spacing between them is based on the maximum subgrade deflection, or the modulus of elasticity of the subgrade. Once the deflection or modulus of elasticity of any subgrade is known, the main curve for deflection vs. spreadability could be extrapolated.

A theoretical evaluation of a single layer system showed that for $E_s = 1,000$ psi the maximum deflection is equal to 0.7. Thus the equation of $E_s \times d_0 = 1,000 \times 0.7 = 700$ lb./in. could be applied for interpolating any main curve for any value of E_s or d_0.

The extrapolation of the subcurves is not based on a simple arithmetic relationship like that shown for the main curves. This is evident from curves 3A, 3B and 3C for the pavements (over the subgrade) having moduli of elasticity of 30,000; 300,000; and 3,000,000 psi respectively. For the same modulus of elasticity of the subgrade, the spacing between the subcurves increases with an increase in the modulus of elasticity of the pavement over the subgrade. This change tends to zero along the tangent lengths of the curves but becomes more prominent when the curves bend. It may, therefore, be necessary to calculate and plot more curves between these bends to facilitate extrapolation.

Each of the subcurves shown in Figure 5 was determined by assuming a uniform modulus of elasticity of the pavement over the subgrade. In practice the pavement consists of materials in layers with different moduli of elasticity. In that case an average modulus of elasticity of the pavement needs to be determined.

As an example, a three layer system is discussed below and its results are shown in Figure 6. In this example, the modulus of elasticity, E_1, of the top layer is taken as 300,000 psi and the modulus of elasticity, E_2, of the second layer from the top is taken as 30,000 psi. The subgrade modulus of elasticity, E_s, is equal to 1,000 psi, which represents curve no. 3 of the general evaluation chart given in Figure 5. The thicknesses of the top and the second layers were varied. Three cases with the top layer thicknesses equal to 2, 4 and 6 inches respectively were taken. In each case the thickness of the second layer was varied from 0 to 2 inches up to 8 inches. These three cases are shown by curves a, b and c in Figure 6. This figure shows the following:

(i) Any point on any of the curves a, b and c for the three layer system follows the contours of the thickness index, D, for subcurves 3A and 3B for the two layer system.

(ii) All three curves, a, b, and c, lie within subcurves 3A and 3B, which are for the pavements having the modulus of elasticity of the pavement over the subgrade equal to 30,000 and 300,000 psi respectively. These three curves show that as the average modulus of elasticity of the pavement layers over the subgrade increases, the curves move from subcurve 3A (E = 30,000 psi) towards subcurve 3B (E = 300,000 psi).

Curve 3B — (E = 300,000 psi;
E_s = 1,000 psi)

Curve 3A — (E = 30,000 psi;
E_s = 1,000 psi)

Curve b — three layer system
(h_1 = 4" and h_2 = 2" to 8")

Curve c — three layer system
(h_1 = 6" and h_2 = 2" to 8")

Curve a — three layer system
(h_1 = 2" and h_2 = 0" to 8")

Index:
(1) Two layer system — — — —
(2) Three layer system ————

h variable

9,000 lb.
6.4 in. radius

Two layer system | E = 30,000 or 300,000 psi
a = 0.44 or 1.0

Subgrade E_s = 1,000 psi

h_1 variable h_2 variable

9,000 lb.
6.4 in. radius

E_1 = 300,000 psi, a = 1.0

E_2 = 30,000 psi, a = 0.44

Three layer system

Subgrade E_s = 1,000 psi

BASE LINE

S = Spreadability

d_{max} = Maximum deflection in inches.

Figure 6. Fitting the 3-layer systems into curve no. 3 of the general evaluation chart.

The average modulus of elasticity of the pavement over the subgrade could be calculated from the equation

$$\frac{h_1 E_1 + h_2 E_2 + \ldots}{h_1 + h_2 \ldots} .$$

Thus for curves a and b at D = 5 the value of E_{av} is 69,000 psi for curve a and 170,000 psi for curve b. Similarly at D = 7 the values of E_{av} are 126,000 psi for curve b and 178,000 psi for curve c.

The above discussion and Figure 6 show (i) that the subcurves with more than two layers could be extrapolated by evaluating the average modulus of elasticity and (ii) for drawing the general curves in Figure 5 evaluation on the basis of a two layer system could be carried out.

BEHAVIOR OF SUBGRADES IN PRACTICE AND THEIR EVALUATION

In the theoretical analysis, as explained previously, the spreadability of a uniform elastic subgrade was found to be constant at 31.35.

Measurements of the subgrade deflections of satellite projects in Virginia have shown that the spreadability value of the subgrade varies and is usually greater than 31.35; but in very poor soils the value is less than 31.35. Since the spreadability values of the subgrade are not constant as defined by a single layer system, it is necessary that the subgrade be considered a combination of two or more layers with their combined strengths being defined not only by the maximum deflection but also by the spreadability value. The need for specifying the spreadability value in addition to the deflection value is evident from the following discussion.

Evaluation of some of the very poor subgrades in Virginia have shown that when spreadability is less than 31.35 the subgrade is of poor quality. When the value is less than 31.35, the subgrade could be considered equivalent to a layered system with a weaker layer lying over a stronger layer. Figure 7 shows three theoretical cases in two and three layer systems wherein a weaker layer lies over a stronger layer; in each case the spreadability value is less than 31.35. The main curves, 1 through 7, in this figure are replicated from Figure 5 and have spreadability values greater than 31.35. The two layer systems shown by curves (b) and (c) are for layers of E = 1,000 psi and E = 250 psi respectively, both over a stronger layer of $E_s = 30,000$ psi. Curve (a) is for a layer similar to that of curve (b) but has in addition a two inch layer of E = 30,000 psi. This curve (a) is shown as a typical example of a silty clay soil with the top two inches having dried to form a thick, rigid crust over the weaker moist subgrade. After the pavement is built this top crust could regain moisture and behave like the two layer system defined by curve (b).
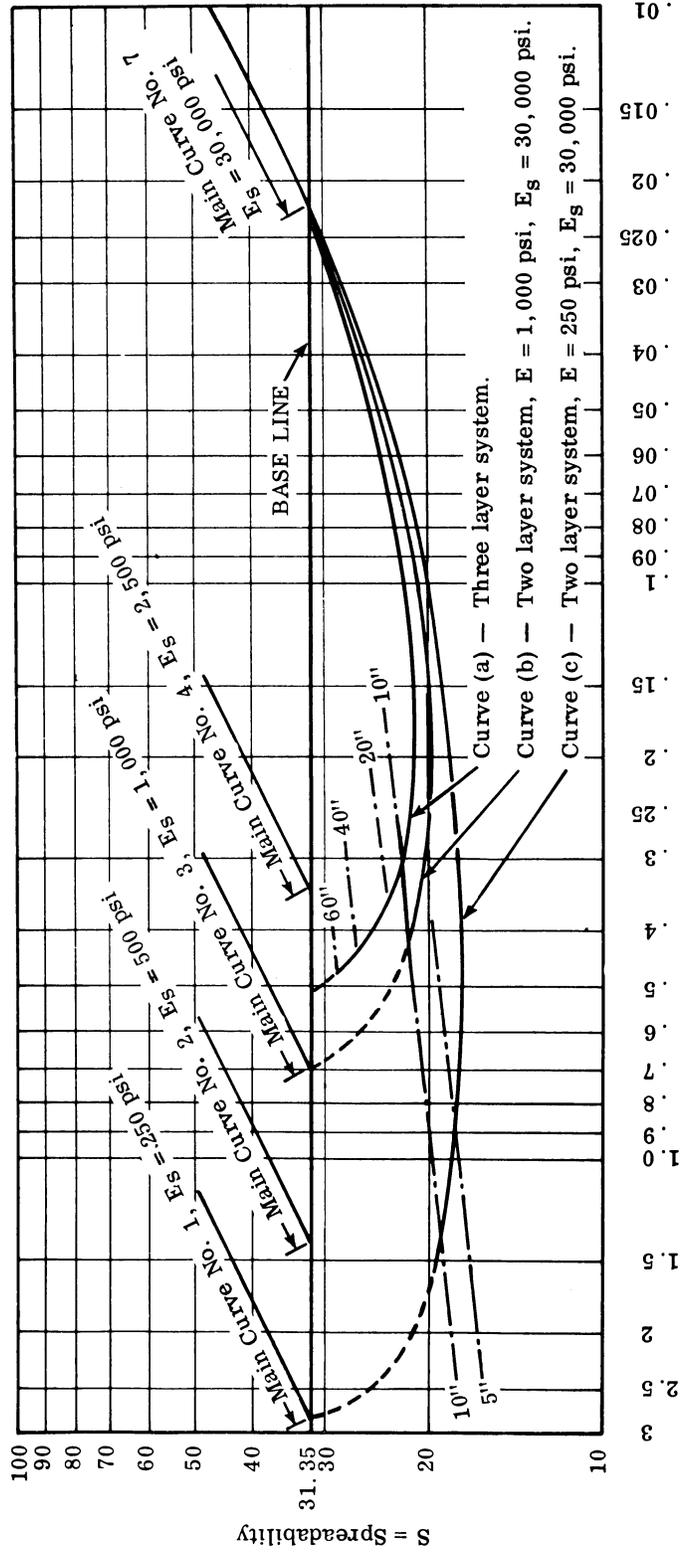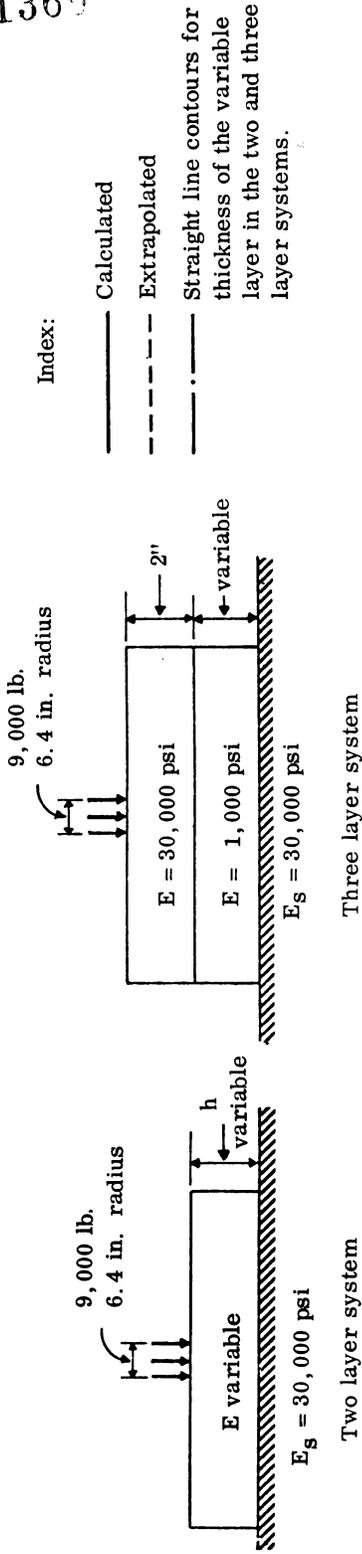
Figure 7. Examples of spreadability values lower than given by one layer system.

Figure 7, in combination with Figure 5, could be used to evaluate the structural strength of the subgrade from the deflection and spreadability data obtained from the field. For the purpose of design the data so obtained could be converted to the base line of spreadability equal to 31.35.

Numerous cases were theoretically evaluated for spreadability values above and below 31.35. For spreadability values above 31.35 there was no negative (upward) deflection in the deflected basin; for spreadability values less than 31.35 a negative deflection as shown in Figure 8 above the horizontal line of the top of the pavement was found to develop. Further, as the spreadability value decreased, the location of the negative deflection in the deflection basin tended to approach towards the load center, which provides a higher slope in the deflected basin. Figure 8 gives four typical examples of such negative deflections. Figure 7 shows that as the spreadability value continues to decrease below 31.35, the subgrade support should be considered poorer and poorer.

To evaluate the behavior of subgrades, dynaflect deflections were measured on a satellite project. Measurements were made (i) on subgrades immediately before the base course was laid, and (ii) on pavements immediately after the base course was laid. The base course consisted of $1\frac{1}{2}$ inch maximum size asphaltic concrete, 9 inches thick. In the 39 recordings of the subgrade deflections only one showed a spreadability of less than 31.35. In most of the cases the spreadability was above 40. Four typical cases of subgrade basin deflections, including one with a spreadability value less than 31.35, are given in Figure 9. Basin deflections of the pavement corresponding to the four typical subgrade basin deflections in Figure 9 are given in Figure 10. An example of an evaluation of the subgrade by converting it to the base line of spreadability = 31.35 and the effect of the pavement over the subgrade are given below.

Example 1

a) Subgrade evaluation before pavement is laid:

In Figure 9, basin B gives the following data: The dynaflect deflection, d_d, is 0.0044 in. and the spreadability, S, is 40.7.

Utilizing the correlation between the maximum deflections for a 9,000 lb. wheel load, $d_0 = 28.6\, d_d$, we have $d_0 = 28.6 \times 0.0044 = 0.1258$ in.

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R = Distance from the center of applied load in ft.
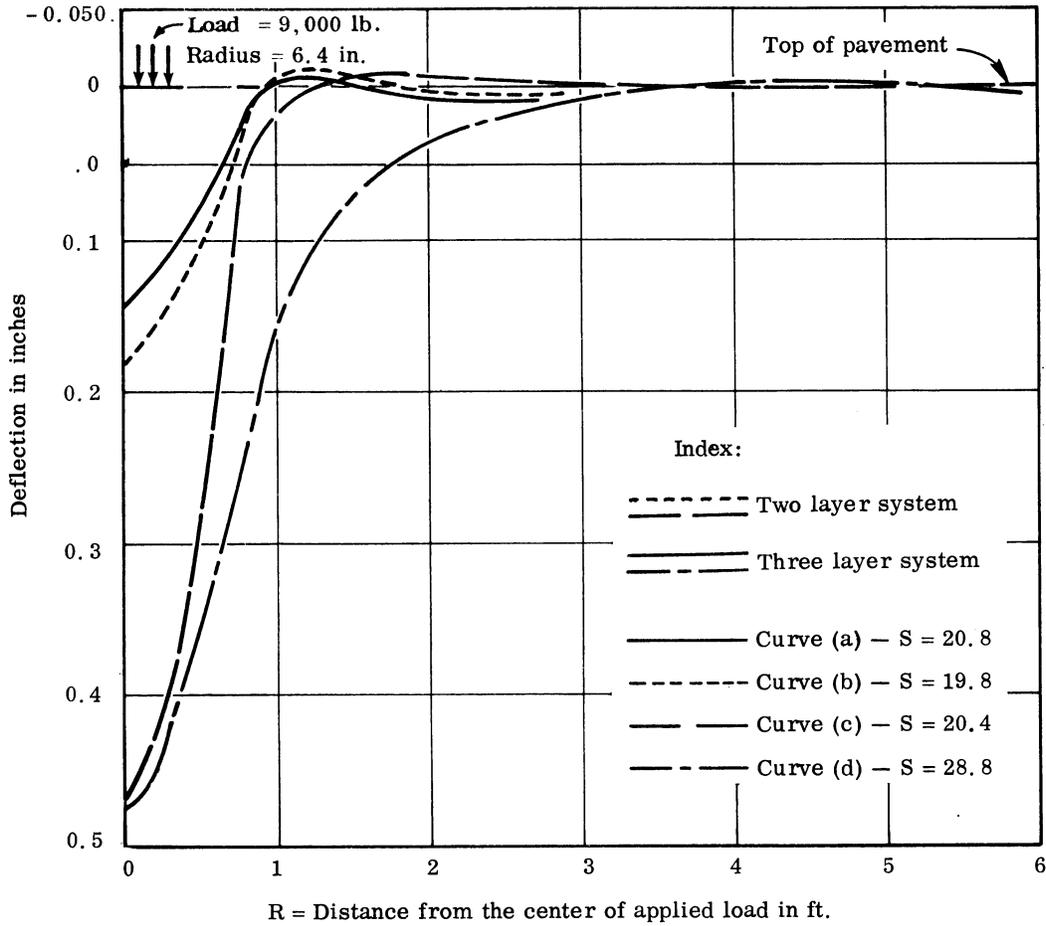
Curve Design	No. of Layers	E_S (psi)	2nd layer from top		Top layer		S	d_0
			E_2 (psi)	h_2 (in.)	E_1 (psi)	h_1 (in.)		
(a)	Three	30,000	1,000	5	30,000	2	20.8	0.147
(b)	Two	30,000	—	—	1,000	5	19.8	0.182
(c)	Two	30,000	—	—	1,000	15	20.4	0.469
(d)	Three	30,000	1,000	60	30,000	2	28.8	0.474
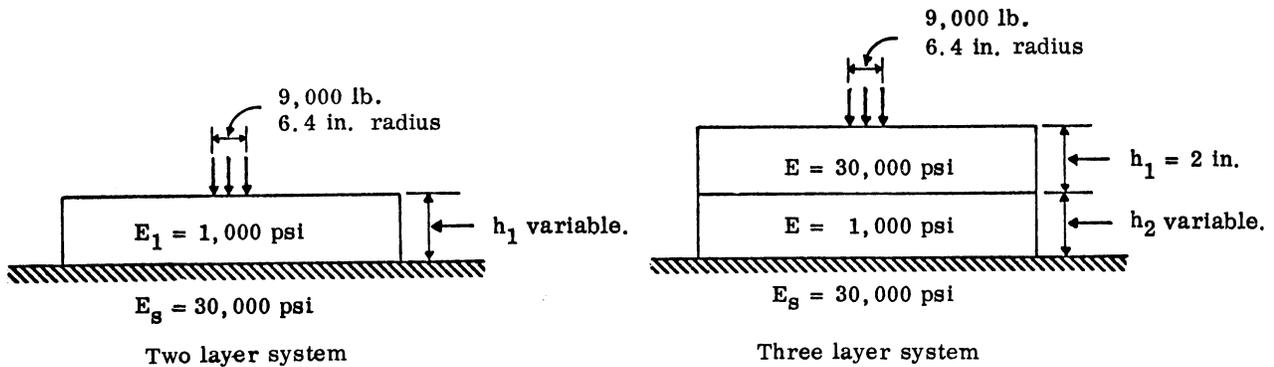
Figure 8. Deflection basin for spreadability values less than 31.35.
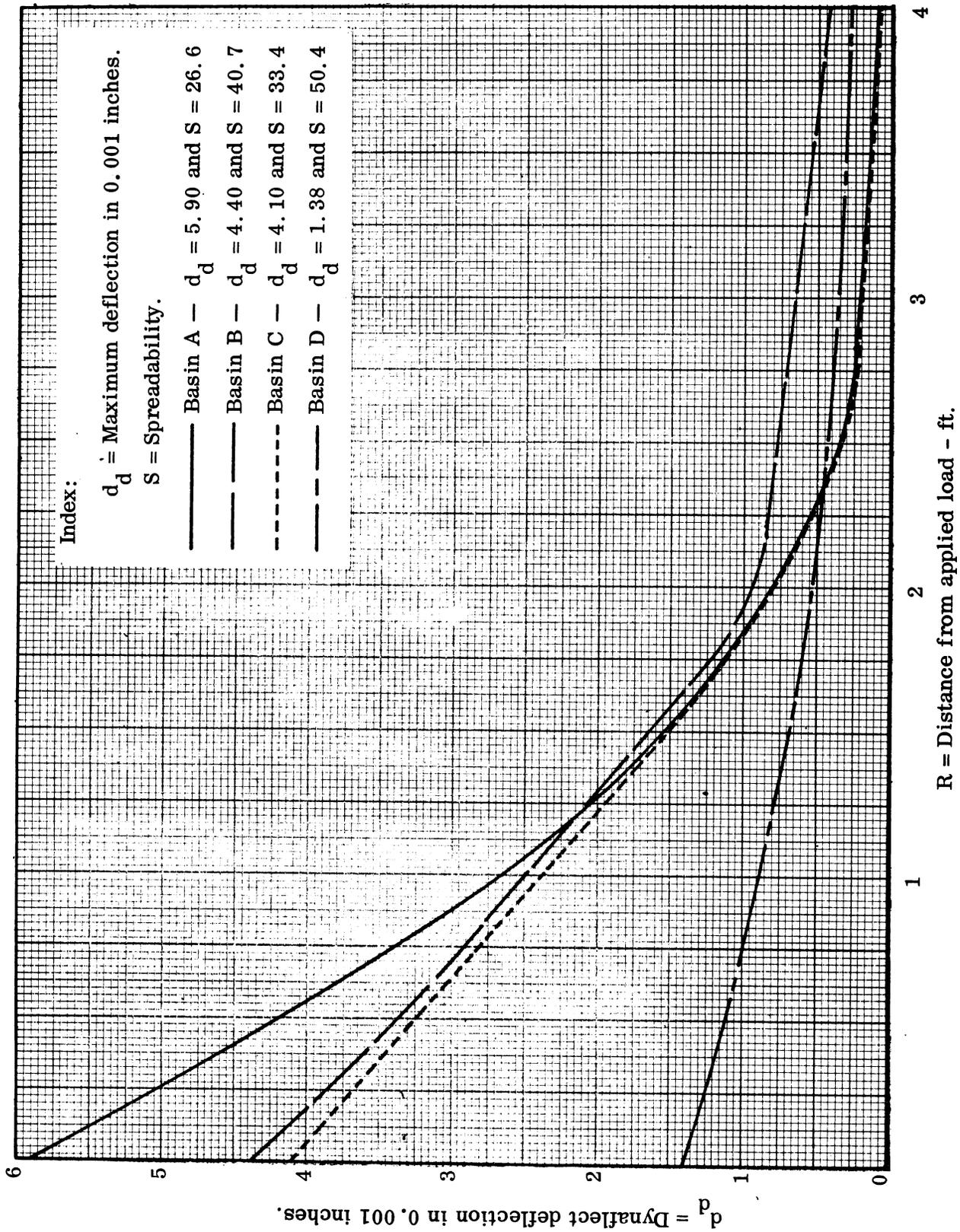
Figure 9. Typical examples of deflection basin of subgrade by dynaflect on satellite project 0031-137-102.

Index:

d_d = Maximum deflection in 0.001 inches.

S = Spreadability.

Basin A — d_d = 5.90 and S = 26.6

Basin B — d_d = 4.40 and S = 40.7

Basin C — d_d = 4.10 and S = 33.4

Basin D — d_d = 1.38 and S = 50.4

R = Distance from applied load - ft.

d_d = Dynaflect deflection in 0.001 inches.
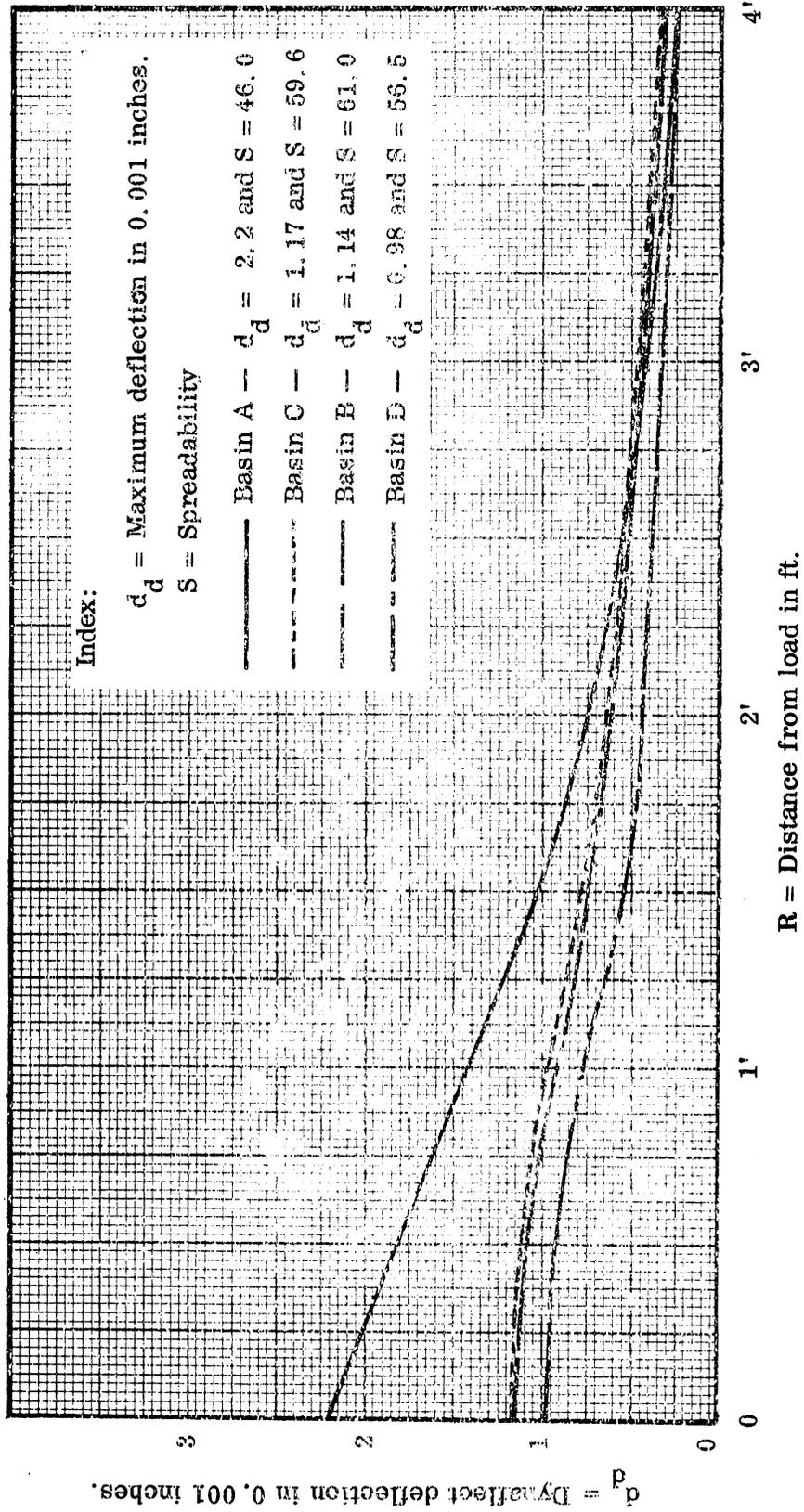
Figure 10. Typical examples of deflection basin of pavements by dynaflect on satellite project 0031-137-102.

Index:

d_d = Maximum deflection in 0.001 inches.

S = Spreadability

———— Basin A — d_d = 2.2 and S = 46.0

—·—·— Basin C — d_d = 1.17 and S = 59.6

— — — Basin B — d_d = 1.14 and S = 61.0

———— Basin D — d_d = 0.98 and S = 55.5

R = Distance from load in ft.

d_d = Dynaflect deflection in 0.001 inches.

Plot this point in the general chart. This is shown by point a in Figure 11. Extrapolate by drawing a line parallel to the main curves. This line cuts the base line (of spreadability = 31.35) at b, where $d_0 = 0.215$ in. Since $E_s d_0 = 700$ lb. per in. we have $E_s = \frac{700}{0.215} = 3,250$ psi. Thus the subgrade strength is equal to a single layer of semi-infinite depth having an $E_s = 3,250$ psi plus a pavement layer of thickness index, D, = 2.1.

b) Subgrade evaluation after the pavement is laid:

The data for the pavement deflection of basin B are shown by point c in Figure 11. The extrapolated line parallel to the main curves and passing through c cuts the base line at e where $d_0 = 0.143$ in. This gives the value of $E_s = \frac{700}{0.132} = 5,300$ psi. This shows that in this case the subgrade strength improved by a value of 5,300 - 3,250 = 2,050 psi. The increase in subgrade strength could be due either to the confining action of the pavement or to the lower level of stress on the subgrade with the pavement on the subgrade. Seed, Chan, Lee et al, have shown the dependence of the modulus of soil on stress.

c) Pavement evaluation:

Point c shows that the pavement over the subgrade has a thickness index, D, = 7.3 and an average modulus of elasticity, E_{av}, approximately equal to 300,000 psi.

The degree of improvement in the subgrade strength after the pavement is laid depends on the deflection and spreadability values of the subgrade. For example, basin A with a subgrade spreadability value of 26.6 would show hardly any improvement in subgrade support after the pavement is laid. The data for the four typical basins shown in Figures 9 and 10 are given in Table 3. These basins are typical examples of subgrade evaluation.

TABLE 3

TYPICAL EXAMPLES OF DEFLECTIONS

Basin	Subgrade Deflections			Base Deflections (B - 3 = 9 in.)		
	d_d (0.001 in.)	d_0 (in.)	s (percent)	d_d (0.001 in.)	d_0 (inch)	s (percent)
A	5.9	0.1687	26.6	2.2	0.0629	46
B	4.4	0.1258	40.7	1.14	0.0325	61
C	4.10	0.1173	33.4	1.17	0.0335	59.6
D	1.38	0.0395	50.4	0.98	0.0280	56.5

PAVEMENT EVALUATION OF SATELLITE PROJECTS
BASED ON GENERAL EVALUATION CHART

In order to develop better designs, pavement research and design engineers regularly evaluate existing pavements. For this investigation a number of satellite projects were considered to determine how the general evaluation chart given in Figure 5 could be used as an aid to better evaluation. The details of these projects are given in Table 4. All data are the average of the actual data recorded in the field. All of the data were recorded in the springtime. It was found that when plotted on the general evaluation chart most of the projects had a positive downward slope, which indicated an increase in deflection and decrease in spreadability with time. Details of four such projects marked A through D in Table 4, are shown graphically in Figure 11. The coordinates of these performance curves or any other curves would first be taken parallel to the main curves and then parallel to the horizontal axis as indicated by the dotted lines PQ and QR on curve C. Thus PQ gives the decrease in the thickness index, D, of the pavement over the subgrade and QR gives the reduction in the value of the modulus of elasticity of the subgrade, or the subgrade support value.

In some cases a positive upward slope indicating an increase in deflection and an increase in spreadability was noted. Four examples of such projects are given by projects E through H in Table 4 and are shown graphically in Figure 12. The coordinate parallel to the main curves gives the increase in the thickness index of the pavement and the coordinate parallel to the horizontal axis gives the reduction in the subgrade support value.

A few cases of very little variation in the deflection and spreadability have been noted. One example of this is given by project J in Table 4 and is shown graphically in Figure 12. This curve shows a slight increase in the thickness index of the pavement with no change in the subgrade support.

No project with a negative upward or downward slope was found. A negative upward or downward would mean an increase in the subgrade support value.

In Virginia thickness equivalencies of the materials used in pavement construction have been determined,[7] and are given in Table 4. Based on these values, the thickness indices, D_V, of the projects mentioned above were calculated and are also given in Table 4. This table also gives the cracking factor on each project for the year evaluated. The performance of these projects based on the general evaluation chart is shown graphically in Figures 11 and 12 and is discussed below.

TABLE 4

FERFORMANCE DATA ON TYPICAL PROJECTS

Satellite Proj. Designation	Pavement Section	Section	D_v	Date of Construction	Performance Data Collected					
					Date	d_0	s	Date	d_0	s
A	7" A.C. + 3" Agg.	0460-009-017	8.0	July 1955	10-25-66	.022	59	4-24-67	.037	51
B	1.5" A.C. + 6" CTA + 4" Agg.	0063-096-105, C501	10.5	Nov. 1964	4-3-67	.020	65	2-27-68	.032	50
C	5" A.C. + 8" Agg.	0015-014-101, C502	7.8	July 1962	11-3-66	.022	52	4-11-67 and 4-2-68	.024 / .033	49 / 47
D	9.5" A.C. + 6" Agg. + 8" CTS	0066-030-001	15.1	June 1962	10-22-66	.0095	63	5-22-69	.0158	57
E	7" A.C. + 6" Agg. + 6" CTS	7960-019-102, C501	11.7	Jan. 1966	4-11-67	.029	54	4-21-69	.034	57
F	3" A.C. + 3" CTA +8" CTS	7360-019-102, C501	13.6	Jan. 1966	4-11-67	.021	70	4-21-69	.013	74
G	7" A.C. + 4" CTA + 6" CTS	7360-019-102, C501	13.6	Jan. 1966	4-11-67	.014	70	4-21-69	.017	77
H	7" A.C. + 4" ATA + 6" CTS	7360-019-102, C501	12.9	Jan. 1966	4-11-67	.015	69	4-21-69	.018	75
J	7" A.C. + 10" Agg. + 6" LTS (in cut)	6050-034-101, C501	—	Sept. 1962	5-5-67	.0153	44	5-8-69	.0152	45
K	8"CRC + 4" Agg. + 6" CTS	0064-002-102, P407	21.2	Dec. 1969	6-15-70	.0074	56			

Notations:

D_v = Thickness index evaluated on the basis of thickness equivalency values. a_v for materials used in pavements in Virginia. These values are given below.

A.C. = Asphalt concrete   — $a_v = 1.0$

CTA = Cement treated aggregate in base   — $a_v = 1.0$

ATA = Asphalt treated aggregate   — $a_v = 0.8$

Agg. = Untreated aggregate   — $a_v = 0.35$

CTS = Cement treated subgrade   — $a_v = 0.44$

LTS = Lime treated subgrade   — $a_v = 0.44$

CRC = Continuous reinforced concrete   — $a_v = 2.16$ (Theoretically evaluated for E = 4,000,000 psi)

d_0 = Maximum deflection under 9,000 lb. wheel load. In this table it is calculated from dynaflect deflection, d_d, by the equation $d_0 = 28.6 \times d_d$

s = Spreadability
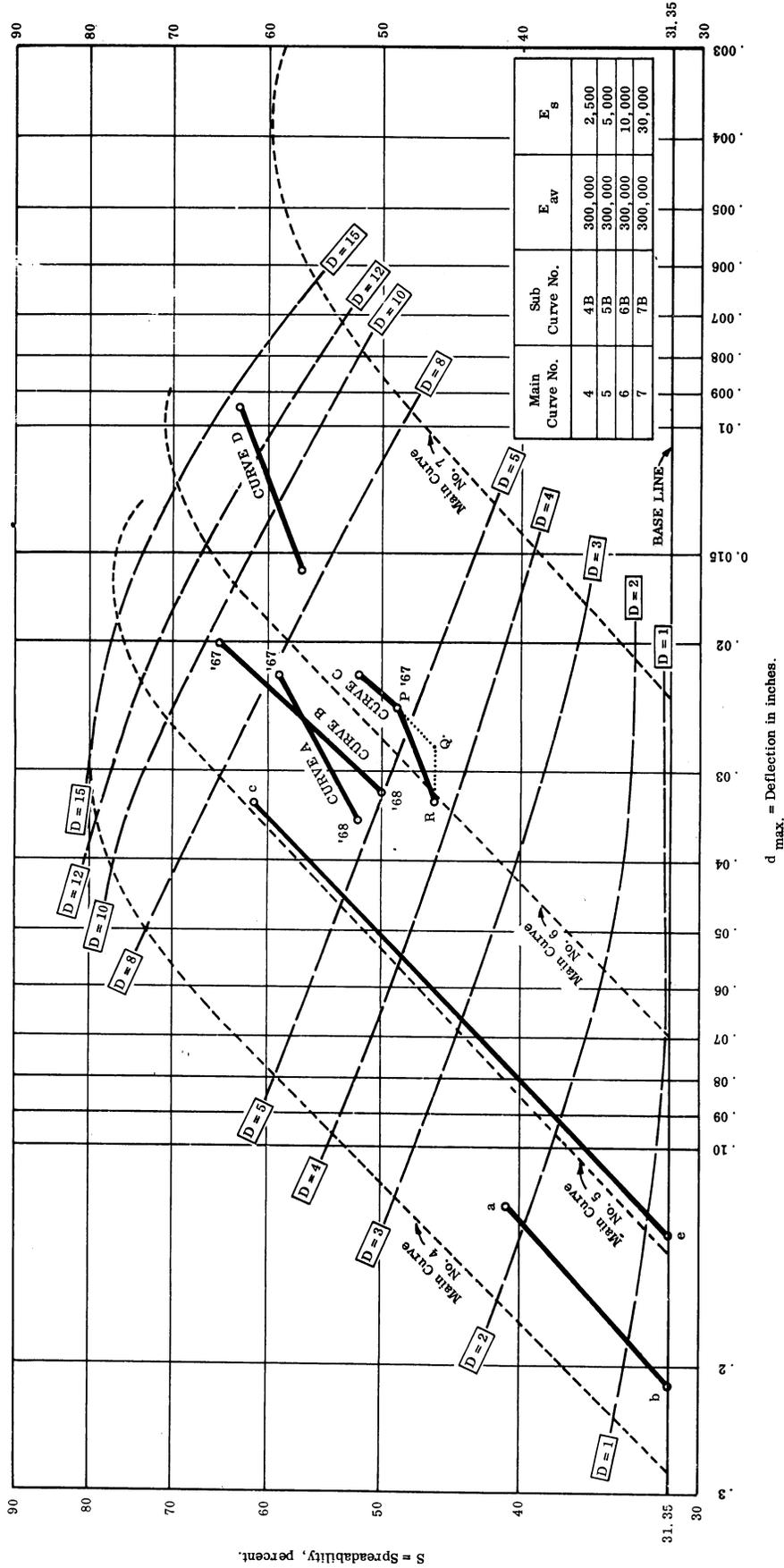
Figure 11. Example of evaluation of satellite projects in Virginia by means of general evaluation chart.

d max. = Deflection in inches.

S = Spreadability, percent.
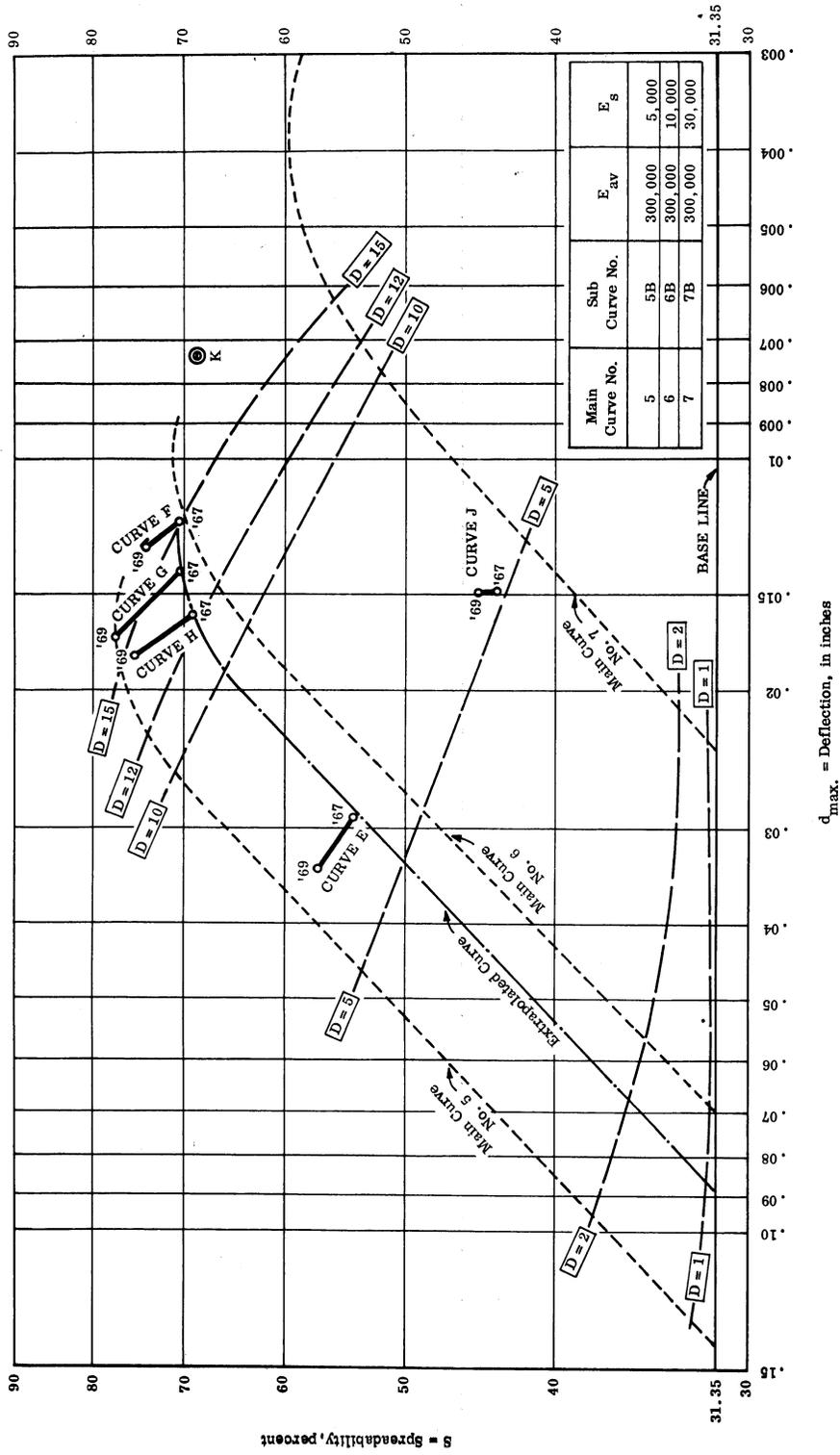
Figure 12. Example of evaluation of satellite projects in Virginia by means of general evaluation chart.

Main Curve No.	Sub Curve No.	E_{av}	E_s
5	5B	300,000	5,000
6	6B	300,000	10,000
7	7B	300,000	30,000

$d_{max.}$ = Deflection, in inches

S = Spreadability, percent

CURVE F

CURVE G

CURVE H

CURVE E

CURVE J

D = 15

D = 12

D = 10

D = 5

D = 2

D = 1

Main Curve No. 7

Main Curve No. 6

Main Curve No. 5

Extrapolated Curve

BASE LINE

K

Project A has a design thickness index, $D_V = 8$ (see Table 4). This value exactly corresponds with the theoretical thickness index during the year 1967 as shown in Figure 11. In one year, from 1967 to 1968, the thickness index of the project decreased from 8 to 5, with a little deterioration in the subgrade support value (see Figure 11). Since the subgrade deterioration is small, resurfacing — if needed — might restore the project to its original strength or the strength required for the present traffic. The Virginia design chart for the thickness index vs. traffic is given in a 1969 report.[7]

Project B has a design thickness index of 10.5. This value also corresponds closely with the theoretical thickness index during the year 1967 as shown in Figure 11. In one year (1967-1968) the thickness index of the project decreased from about 9.8 to about 5. There has been no deterioration in the average modulus of elasticity of the pavement over the subgrade nor in the subgrade support (see Figure 11). The same type of improvement as suggested for project A above would apply to this project, if need be.

Project C has a design thickness index of 7.8. The theoretical thickness index during the year 1966 as shown in Figure 11 is about 6.6. In the year 1966-67 the D value decreased from 6.6 to about 5.4 with no change in the subgrade support. From 1967 to 1968 the D value decreased further to 4.5 and the subgrade support value also decreased. It was found that cracking of the pavement increased considerably in the year 1967-68. The year 1967-68 therefore indicates a periord of high deterioration for this project built in 1962.

Project D has a design thickness index of 15.1, which closely corresponds with the theoretical index of about 14.5 during the year 1966 as shown in Figure 11. In the three years from 1966 to 1969 the value of D decreased from 14.5 to about 8.5, and the subgrade support value decreased considerably. It is therefore probable that the main cause of deterioration is the decrease in subgrade support. In 1966 the pavement had almost no cracks. In 1969 the pavement was mostly cracked.

Projects E through H are experimental projects built next to each other so the subgrade modulus of elasticity of these projects should be the same. The curves for these projects are plotted in Figure 12. The 1967 data for these project lie on the same extrapolated curve for one subgrade support, which indicates the accuracy of this chart. These projects built in January 1966, have a positive upward slope with time as shown in Figure 12, which indicates a slight deterioration in the subgrade support value but an increase in the thickness index. The upward slope indicates that the pavement is performing well, unless the asphaltic concrete is becoming more and more rigid and hence brittle.

Project E has a design thickness index of 11.7 as shown in Table 4, while its theoretical thickness index as shown in Figure 12 was about 6 in 1967. Projects F, G and H have design thickness indices of 13.6, 13.6 and 12.8 respectively as shown in

Table 4. These values are close to their theoretical index values of 15.0, 14.0, and 12.5 respectively in 1967.

Project J has a thickness index value lower than the theoretical thickness index value, but from 1967 to 1969 it showed no change in the subgrade support value and a slight increase in its theoretical index value. This project was built in 1962 and in 1969 it was still without cracks.

Project K (in Table 4) is a recently built continuously reinforced concrete pavement. It is shown by the point marked K in Figure 12. The object of this point is to show the comparative relationship between flexible and rigid pavements.

The evaluation of the nine projects on the basis of the general evaluation chart could be summarized as follows:

(i) The design thickness index, D_V, evaluated on the basis of the thickness equivalency values, a_V, for paving materials used in Virginia usually is close to the theoretical thickness index value.

(ii) The general evaluation chart shown in Figure 5 gives the structural performance of a pavement.

CONCLUSIONS

1. For the proper evaluation of pavements by means of deflection data, the spreadability value of the deflected basin, in addition to the maximum deflection, must be known.

2. The average modulus of elasticity of the pavement over the subgrade is an important factor in pavement evaluation.

3. The general evaluation chart based on a theoretical analysis (shown in Figure 5) could be applied for evaluating the changes in the subgrade and/or the pavement strength of flexible pavements.

4. As the spreadability value of the subgrade continues to decrease below 31.35, the subgrade support should be considered poorer and poorer.

5. The thickness index evaluated on the basis of the thickness equivalency values for paving materials used in Virginia seems to be almost the same as the theoretical thickness index value.

NOTATIONS

a	=	theoretical thickness equivalency of a material
a_v	=	thickness equivalency for materials used for pavements in Virginia
C	=	curvature in percent
D	=	thickness index of the pavement over the subgrade or theoretical thickness index of the pavement over the subgrade
D_v	=	design thickness index calculated from the thickness equivalency values for the materials used for pavements in Virginia
d_{max}	=	maximum deflection of basin in inches or 0.001 inch
d	=	deflection in inches
d_0	=	maximum theoretical deflection in inches under 9,000 lb. wheel load and tire pressure of 70 psi
d_d	=	maximum dynaflect deflection in 0.001 inch
E	=	modulus of elasticity in psi
E_{av}	=	average modulus of elasticity of the pavement over the subgrade in psi
E_s	=	modulus of elasticity of the subgrade in psi
$E_1, E_2, E_3....$	=	modulus of elasticity of the top layer of the pavement, the second layer from the top, the third layer from top.... in psi
p	=	tire pressure
S	=	spreadability value in percent

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