Some Notes on Pavement Structural Design—Part 2

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This continuation of the paper of the same title presented at the 1963 Annual Meeting of the Highway Research Board is concerned with the elastic layered system method of pavement design proposed by Burmister in 1943. It is shown that for subgrades with CBR ratings from about 4 to 20, the Burmister equation can provide thickness requirements that are practically identical with those of the Corps of Engineers. Over the same range of subgrade support, the design curve provided by the Burmister equation practically coincides with the thickness requirements given by the Canadian Department of Transport's design equation, T = K log P/S, when using empirically determined values for K. The reason for the good agreement in the latter case is investigated. It is shown that the approximate method of analysis for a multilayered pavement system referred to in last year's paper can lead to underdesign for a small number of pavement layers and to overdesign for a larger number of layers. Reference is made to the development of the method of pavement design in which all materials above the subgrade are treated with an asphalt binder. The urgent need for a simple laboratory method for accurately measuring the modulus of elasticity or some other rational strength value of subgrades and different pavement materials is emphasized.

•THIS paper, like last year's (1), is concerned primarily with the elastic layered system approach to pavement design (Fig. 1) that was originally published by Burmister (2) in 1943.

It is reasonable to ask how closely the thicknesses of flexible pavements provided by the elastic layered system approximate the thickness requirements of some of the empirical methods in current use. The Corps of Engineers' design curves, based on CBR ratings of subgrade strength, are well known and are supported by results from extensive full-scale field tests.

In Figure 2, the solid line represents the Corps of Engineers' design curve for an airplane single wheel load of 60,000 lb at 100-psi tire inflation pressure. The broken line curve represents the Burmister equation, assuming that the granular base material has an elastic modulus E_1 of 15,000 psi. The use of the Burmister equation to obtain the thicknesses indicated by the broken line curve of Figure 2 is illustrated by Table 1. The relationship between Burmister's deflection factor F_W, pavement thickness expressed as T/r, and the ratio of pavement elastic modulus to subgrade elastic modulus E_1/E_2 was shown previously (1, Fig. 1). The relationship between CBR and plate bearing values (1, Fig. 15) provides a common basis of comparison for the two designs.

From Figure 2, it is apparent that for subgrade CBR values ranging from about 4 to 20, the range of subgrade strengths most frequently encountered in practice, the pavement thickness requirements given by the Burmister equation are practically identical with those of the Corps of Engineers. For subgrade CBR values lower than 4 and greater

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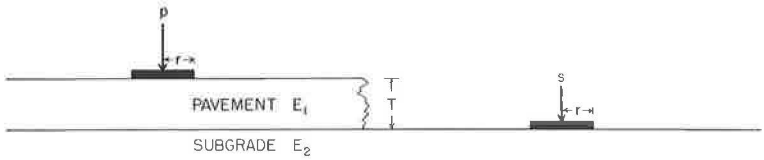

$T = K \log \frac{p}{s}$ CANADIAN D.O.T. (1)

$W_p = \frac{1{\cdot}18\,pr}{E_2} \times F_w$ PAVEMENT *(BURMISTER)*

$W_s = \frac{1{\cdot}18\,sr}{E_2}$ SUBGRADE *(BOUSSINESQ)*

WHERE T = THICKNESS OF PAVEMENT
p = WHEEL LOAD
s = SUBGRADE SUPPORT
K = PAVEMENT FACTOR

WHERE W_p = PAVEMENT DEFLECTION
W_s = SUBGRADE DEFLECTION
r = RADIUS OF LOADED AREA
E_2 = ELASTIC MODULUS OF SUBGRADE
F_w = DEFLECTION FACTOR

WHEN $W_p = W_s$

$F_w = \frac{s}{p}$

SUBSTITUTING IN EQUATION (1)

$K = \frac{T}{-\log F_w}$ (2)

Figure 1. Relationship between Canadian Department of Transport and Burmister equations for pavement design.

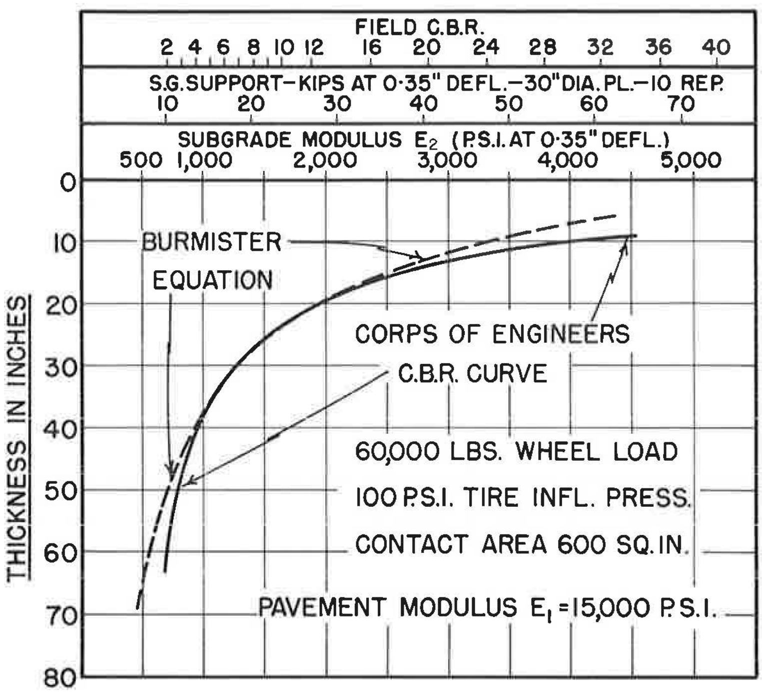

Figure 2. Comparison of Corps of Engineers and Burmister design curves for 60,000-lb wheel load.

TABLE 1

DATA FOR CONSTRUCTION DESIGN CURVE FOR AN AIRPLANE SINGLE WHEEL LOAD BURMISTER EQUATION[a]

$\frac{E_1}{E_2}$	Subgrade Elastic Modulus, E_2 (psi)	Subgrade Support, S^b (lb)	$F_w = \frac{S}{P}$	$\frac{T}{r}$	Pavement Thickness, T (in.)
4	3,750	48,240	0.804	0.60	8.3
5	3,000	38,590	0.643	0.88	12.1
6	2,500	32,160	0.536	1.16	16.0
8	1,875	24,120	0.402	1.56	20.1
10	1,500	19,290	0.322	1.87	25.8
15	1,000	12,860	0.214	2.70	37.2
20	750	9,650	0.161	3.46	47.8
30	500	6,430	0.107	4.70	65.0

[a]Single wheel load, P = 60,000 lb,
Tire inflation pressure = 100 psi,
Pavement deflection = 0.35 in.,
Tire contact area = equiv. to 27.64-in. diam. bearing plate,
Radius of contact area, r = 13.82 in., and
Elastic modulus of pavement material, E_1 = 15,000 psi.

$^bS = \frac{E_2\, w\, r}{0.376} = \frac{E_2\,(0.35)(13.82)}{0.376} = 12.86\, E_2$

than 20, the Burmister curve calls for slightly less thickness than the Corps of Engineers' curve. However, Foster (3) has pointed out that for the higher subgrade CBR values, the Corps of Engineers' design curves are probably conservative. In addition, the compaction of granular base over very soft subgrades to a specified density is very difficult, and the normal value of the elastic modulus E_1 of the granular material may not be achieved throughout the full depth. This lower E_1 value would have to be compensated for by a somewhat greater thickness to attain the same load-carrying capacity, which in this case is a single wheel load of 60,000 lb.

CANADIAN DEPARTMENT OF TRANSPORT VS BURMISTER DESIGN CURVES

The design equation

$$T = K \log \frac{P}{S} \tag{1}$$

(Fig. 1) was developed from the analysis of hundreds of plate bearing tests on flexible pavements on airport runways in Canada (4), and has been used successfully by the Canadian Department of Transport for the design of flexible pavements at more than 100 airports during the past fifteen years. The pavement factor K in Eq. 1 was evaluated empirically by substituting measured values for P, S, and T and solving for K. This resulted in an empirical relationship between K and the diameter of the loaded area (circular steel plates) (1, Fig. 5).

By employing Eq. 1, and the value of K = 35 indicated (1, Fig. 5) for a 12-in. diameter bearing plate, the solid line thickness design curve of Figure 3 is obtained for a wheel load of 9,000 lb at a tire inflation pressure of 80 psi for very heavy traffic. The

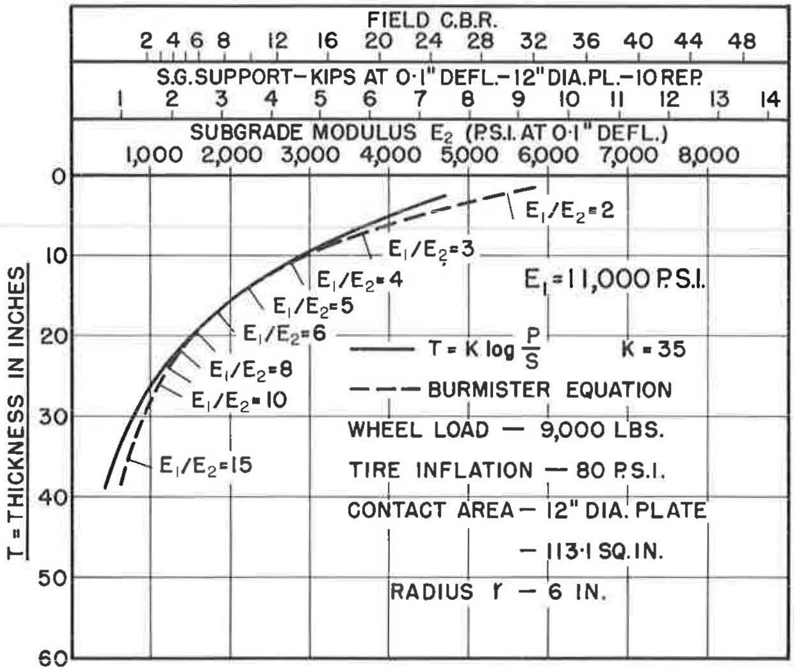

Figure 3. Comparison of Canadian Department of Transport and Burmister design curves for 9,000-lb wheel load.

TABLE 2

EVALUATION OF PAVEMENT CONSTANT K BY BURMISTER EQUATION[a]

$\frac{E_1}{E_2}$	Subgrade Elastic Modulus, E_2 (psi)	Subgrade Support, S^b (lb)	$F_W = \frac{P}{S}$	$\frac{T}{r}$	Pavement Thickness, T (in.)	$\frac{P}{S}$	$\text{Log}\,\frac{P}{S}$	$K = \frac{T}{\log \frac{P}{S}}$
3	3,667	5,865	0.652	1.30	7.8	1.535	0.1860	41.9
4	2,750	4,400	0.490	1.85	11.1	2.046	0.3108	35.7
5	2,200	3,520	0.391	2.35	14.1	2.557	0.4077	34.5
6	1,833	2,930	0.326	2.82	16.9	3.070	0.4871	34.7
7	1,571	2,510	0.279	3.22	19.3	3.586	0.5546	34.8
8	1,375	2,200	0.244	3.65	21.9	4.091	0.6118	35.8
10	1,100	1,760	0.196	4.30	25.8	5.114	0.7087	36.4
15	733	1,170	0.130	5.95	35.7	7.679	0.8853	40.0

[a]Single wheel load, P = 9,000 lb;
Tire inflation pressure = 80 psi;
Pavement deflection = 0.1 in.;
Tire contact area = equiv. to 12-in. diam. bearing plate;
Radius of contact area, r = 6 in.;
Elastic modulus of pavement material, E_1 = 11,000 psi.

$^bS = \frac{E_2\,w\,r}{0.376} = \frac{E_2(0.1)(6)}{0.376} = 1.6\,E_2$

tire contact area is assumed to be equal to that of a 12-in. diameter circular steel plate. The broken line curve in Figure 3 is given by the Burmister equation for the same wheel load and tire inflation pressure (Table 2) if it is assumed that the elastic modulus E_1 of the pavement material has a value of 11,000 psi. It is clear from Figure 3 that for the range of CBR subgrade strength ratings from about 3 to 20, the flexible pavement thickness requirements indicated by Eq. 1 and by the Burmister equation are practically identical. For subgrade CBR strength values less than 3 and more than 20, the use of Eq. 1 in conjunction with a value of 35 for the pavement factor K indicates slightly less pavement thickness than the Burmister equation calls for.

Consequently, for the most commonly occurring range of subgrade CBR strength ratings (3 to 20), the Burmister equation derived from a purely theoretical study of the elastic properties of a layered pavement system is capable of providing flexible pavement thickness requirements practically identical with those indicated by the entirely empirical Corps of Engineers and Canadian Department of Transport methods of design.

DISCUSSION OF THE PAVEMENT FACTOR K

It was shown (1) that Eq. 1, derived empirically from the analysis of data from plate bearing tests, is closely related mathematically to the design equation developed by Burmister from a theoretical study of the elastic properties of a two-layer pavement system. As illustrated by Figure 1, the mathematical bridge between these two design equations is provided by

$$K = \frac{T}{-\log F_W} \tag{2}$$

Previously provided values (1, Fig. 10) for Burmister's deflection factor F_W are seen to depend on pavement thickness T and the ratio E_1/E_2, in which E_1 and E_2 are elastic moduli of the pavement and subgrade, respectively. Therefore, it follows from this and Eq. 2 that the value of the pavement factor K in Eq. 1 also depends on the pavement thickness T and the ratio of E_1/E_2. This is illustrated in Figure 4. Consequently, since Eq. 1 and the Burmister equation appear to be mathematically identical, it is clear that if the values of K provided by Figure 4 were employed for Eq. 1, the design curve provided by Eq. 1 would coincide at all points with the broken line curve in Figure 3 given by the Burmister equation. The difference between the solid and broken line curves in Figure 3, therefore, is due to the use of the empirical value of 35 for the pavement factor K in Eq. 1.

From Figure 3 it can be seen that the value of the ratio of E_1/E_2 ranges from 2 to 15 for different points on the broken line Burmister design curve. It would be expected from an examination of Figure 4 that a range of values from 2 to 15 for E_1/E_2 would result in a corresponding substantial range of values for the pavement factor K. Nevertheless, Figure 3 demonstrates that when K has the constant empirical value of 35, the solid line design curve provided by Eq. 1 practically coincides with the broken line design curve given by the theoretical Burmister equation for a wide range of subgrade strength ratings. It is worthwhile investigating the reason for this apparent inconsistency.

Figure 5 illustrates a typical plot of load test data obtained by a 30-in. diameter bearing plate at 0.5-in. deflection on the subgrade and on the surface of 12 in. of granular base at a number of Canadian airports. Figure 6 provides similar information for a granular base thickness of 21 in. Similar graphs of plate bearing test data have been published elsewhere (4, 5). The plots of data in Figures 5 and 6, and in other similar graphs, led to the development of Eq. 1 and to the empirical values for the pavement factor K (1, Fig. 5).

In Figure 7, Line (1), K = 35, represents the straight line relationship between the load-supporting values at the surface of 15 in. of normal granular base and the corresponding load-supporting values of underlying subgrades of different strengths, both measured with a 12-in. diameter bearing plate at 0.1-in. deflection, that would be expected on the basis of Eq. 1 if the pavement factor K had a constant empirical value of

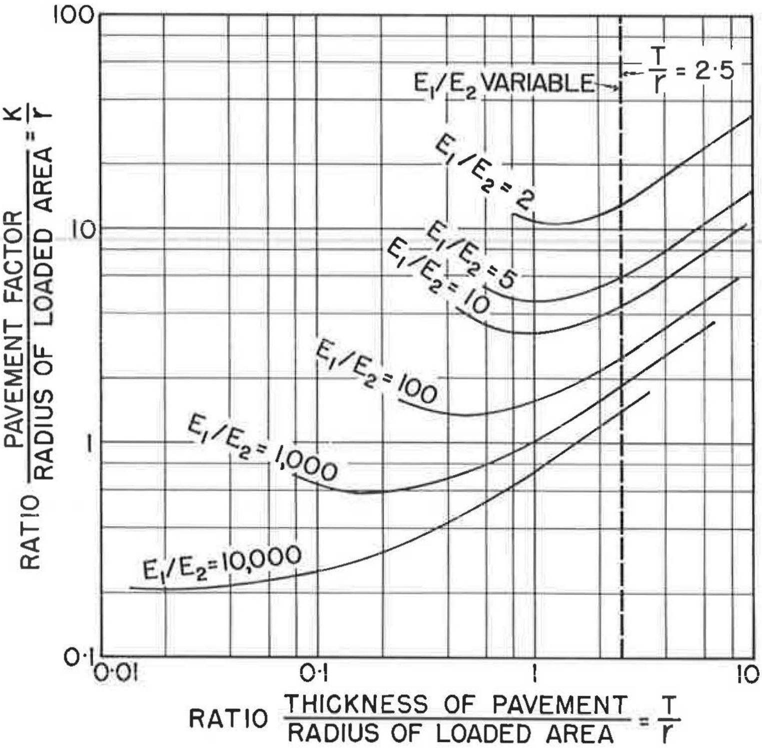

Figure 4. Theoretical relationships between pavement factor K, E_1/E_2, and pavement thickness T.

35, regardless of the strength of the subgrade. On the other hand, Lines (2), (3), and (4) indicate, for a 12-in. diameter bearing plate at 0.1-in. deflection, the curved line relationships between loads on subgrades of different strengths vs the corresponding loads on 15-in. thicknesses of granular bases having elastic moduli of 10,000, 15,000, and 20,000 psi, respectively, given by the Burmister equation. Consequently, the problem arises as to whether the relationship between load on the subgrade and the corresponding load on 15 in. of granular base is provided more accurately by the straight line relationship of Line (1) or by the curved line relationship of Lines (2), (3), and (4). The straight line relationship of Line (1) appears to be supported empirically by actual plate bearing test data such as those of Figures 5 and 6. On the other hand, the curved line relationship of Lines (2), (3), and (4) is indicated by the theoretically derived Burmister equation for an elastic two-layer pavement system.

It was realized at the time Eq. 1 was originally developed that a constant value of K for any given granular material, on which the straight line relationship of Figures 5 and 6 and Line (1) of Figure 7 depends, could apply to only a limited range of subgrade support and of thickness of granular base. Quite obviously, if a layer of granular material were placed on a subgrade as strong as itself, it would provide no increase in load-carrying capacity. In this case, because the value of P/S in Eq. 1 would be unity, the value of the pavement factor K would become infinite. Figure 8 demonstrates that according to the Burmister strength curve, when 15 in. of granular base having an elastic modulus E_1 of 10,000 psi is placed on subgrades of increasing strength, as the values of the ratio of P/S in Eq. 1 approach unity, the corresponding values of K increase from 35 to 50, 75, 100, and 200, and finally become infinite when the strength of the subgrade becomes equal to that of the base course material, that is, when the value of P/S becomes unity.

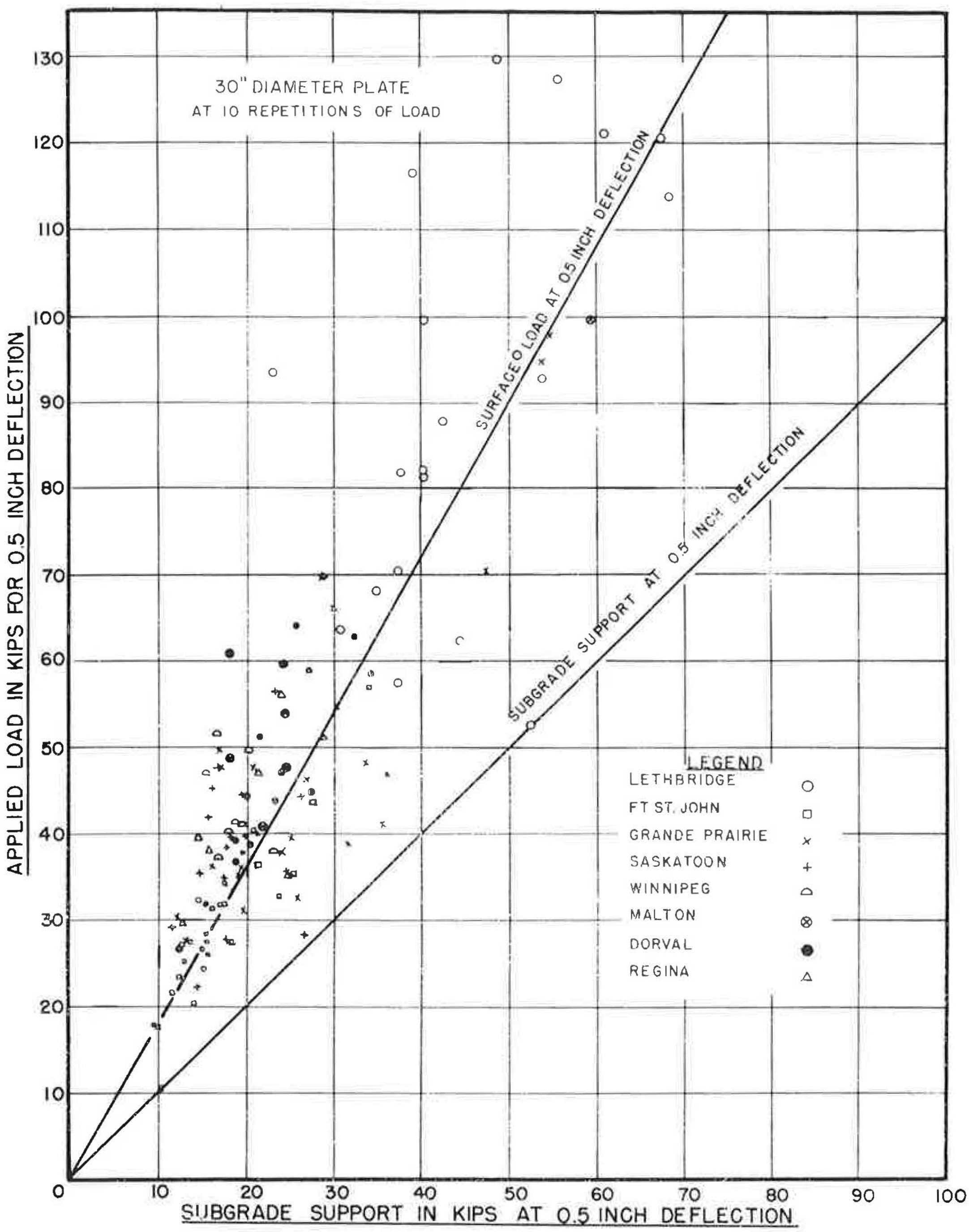

Figure 5. Applied load on 12-in. pavement vs subgrade support.

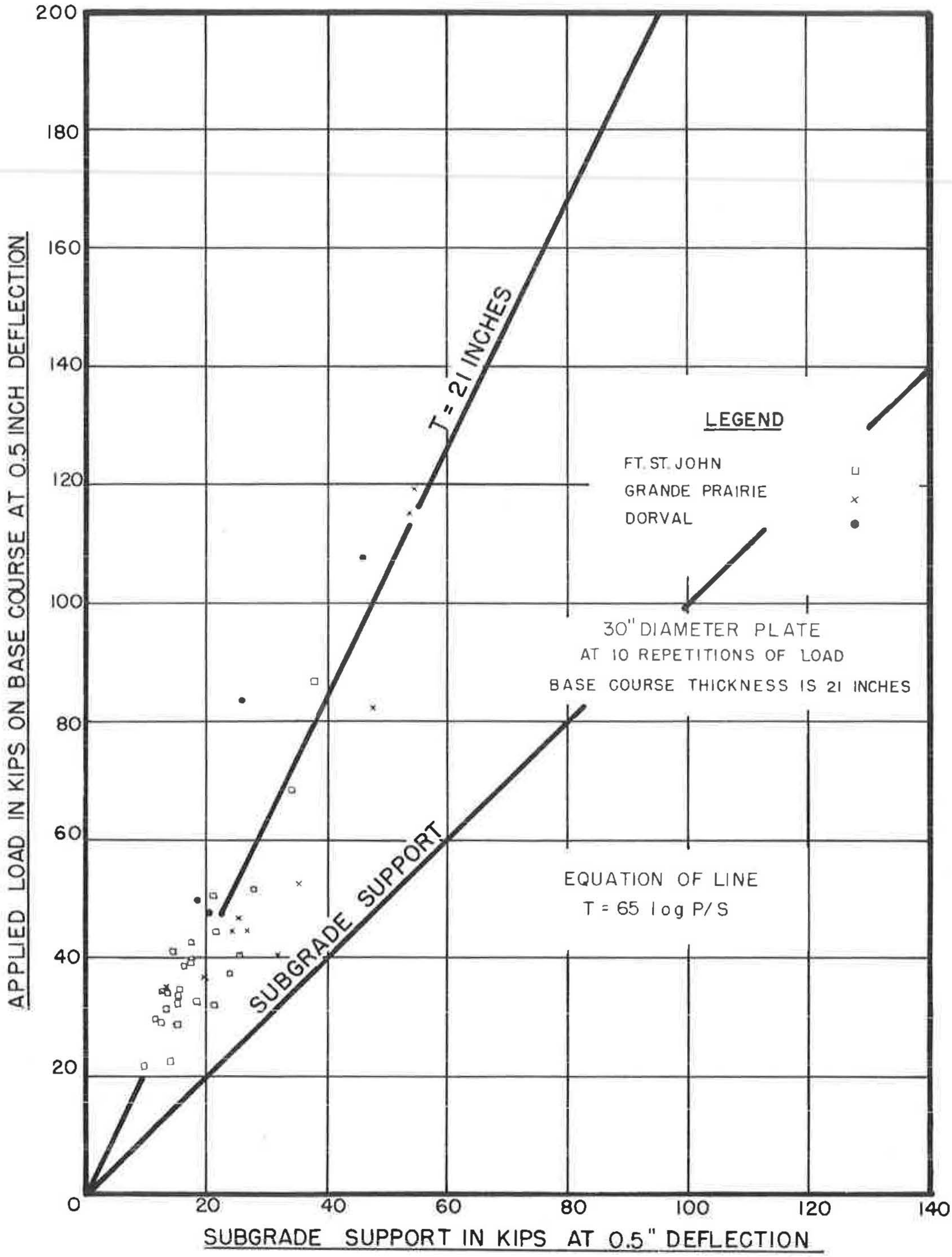

Figure 6. Applied load on 21-in. pavement vs subgrade support.

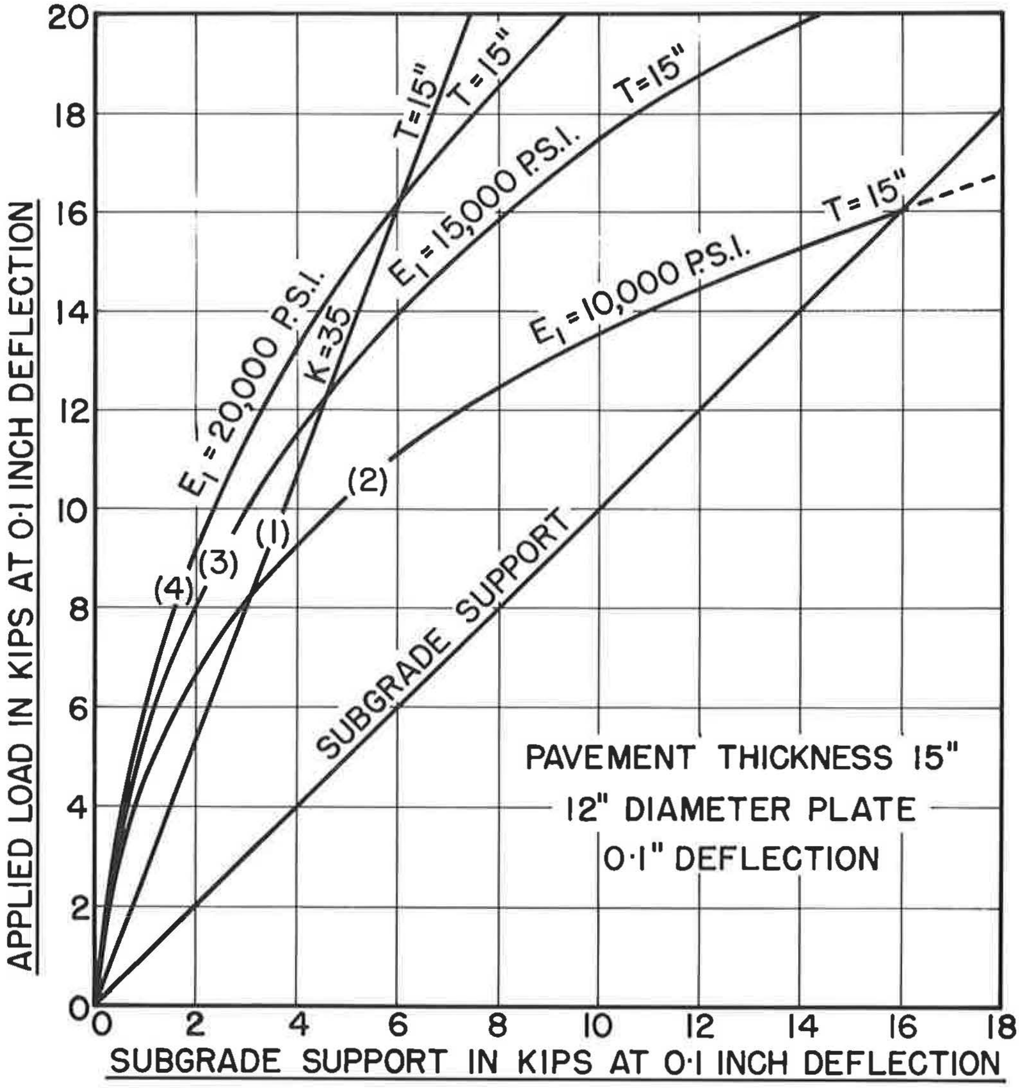

Figure 7. Comparison of applied loads on 15-in. pavement indicated by Canadian Department of Transport empirical design and Burmister theoretical design.

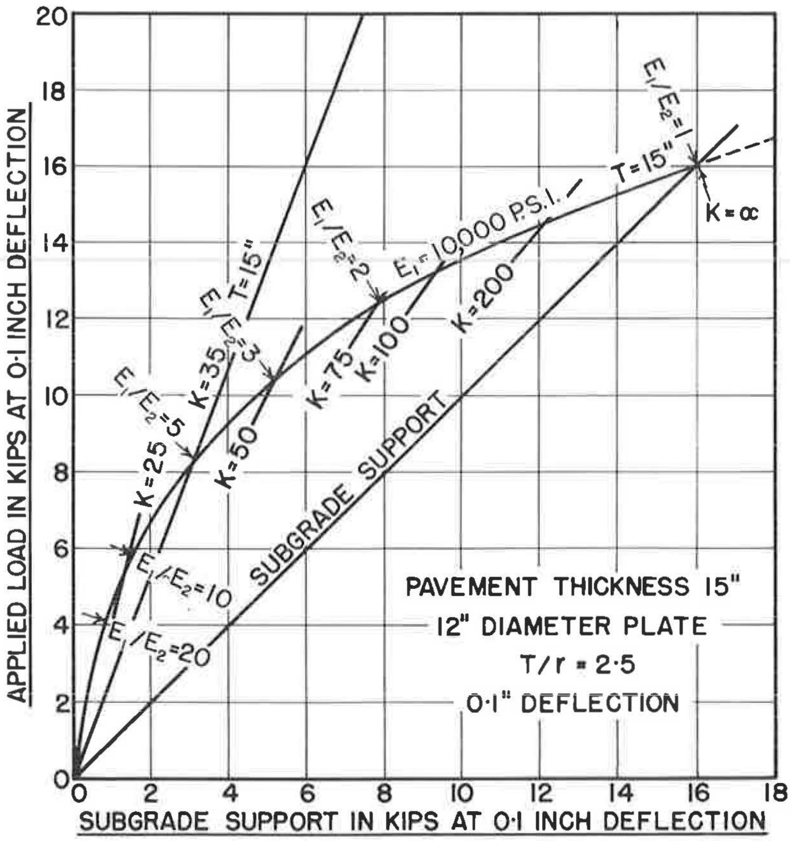

Figure 8. Relationship between empirical and theoretical values of pavement factor K for a given 15-in. pavement.

The Burmister strength curve of Figure 8 also shows that for stronger and stronger subgrades the value of the ratio E_1/E_2 decreases (the elastic modulus of the granular base E_1 = 10,000 psi and is constant, whereas the elastic modulus of the subgrade E_2 increases as the strength of the subgrade is increased) and becomes unity when the elastic modulus of the subgrade E_2 becomes equal to the elastic modulus of the base course material E_1. Therefore, the curved line of Figure 8 represents the case in which the values of E_1 and T/r are constant, but the ratio E_1/E_2 changes with a change in subgrade strength (subgrade elastic modulus E_2), and the applied load P increases as the value of the ratio E_1/E_2 decreases. This set of conditions is also illustrated by the heavy vertical line in Figure 4, which represents a constant value for T/r of 2.5 but a wide range of values for the ratio of E_1/E_2.

If the relationship between load on the subgrade and load on a superimposed specified thickness of any given granular base material should be represented by curved lines such as Lines (2), (3), and (4) in Figure 7, how is the straight line relationship in Figures 5 and 6, that appears to be indicated by plotting actual load test data, to be explained? There would appear to be several possible explanations. One, of course, is the certain scatter of data inevitably associated with plate bearing tests on pavements, which makes it difficult to plot relationship trends with complete confidence.

Another reason is that the load test data were obtained at eight different airports for Figure 5 and at three different airports for Figure 6. The E_1 or elastic modulus values of the granular materials at the different airports are not likely to have been identical. Figure 7 indicates that for the same range of subgrade strengths, a given thickness of granular materials with different E_1 values could provide load test values that would seem to cluster along Line (1), when instead they could actually belong to a series of curved lines representing different E_1 values, such as Lines (2), (3) and (4).

A third possible reason is that it is difficult to compact granular materials to high density on weak subgrades, but this can be achieved readily on strong subgrades. It is known that the elastic modulus E_1 of any given granular material will be low if it is poorly compacted and higher if it is thoroughly compacted. Consequently, even if under certain standard conditions, all base course materials at the airports represented by the data of Figures 5 and 6 had approximately the same E_1 value, the E_1 value actually developed in the field could be lower than this on weak subgrades due to poor compaction and could be higher on stronger subgrades because of compaction to higher density. This gradual increase in the E_1 values of any given granular base when placed on stronger and stronger subgrades would also make the load test data seem to cluster along Line (1) of Figure 7, rather than along curved lines like Lines (2), (3), and (4) where they might actually belong because of the different E_1 values developed in the field.

It would seem on the basis of this discussion, therefore, that the load test data for subgrades and for given thicknesses of superimposed granular base, which appear to support a straight line relationship in Figures 5 and 6, would in each case probably be more accurately represented by either a single curved line or by a series of curved lines similar to Lines (2), (3) and (4) in Figure 7 where each curved line corresponds to a different value of elastic modulus E_1 for the granular base material.

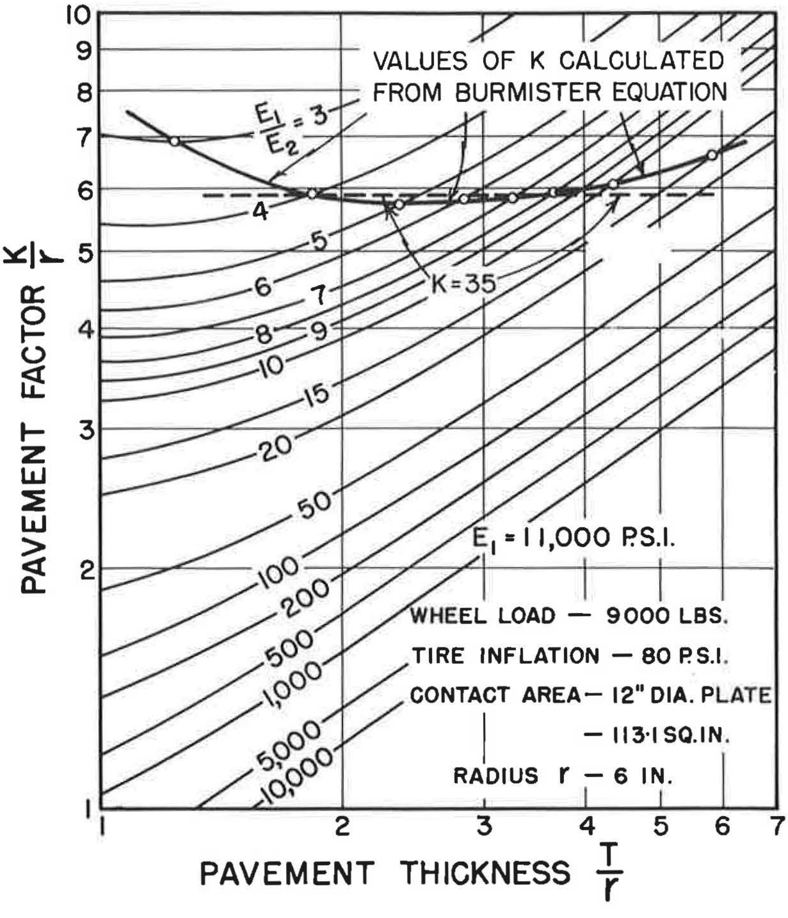

Figure 9. Relationship between theoretical and empirical values of pavement factor K.

This discussion has shown that for any given base course material, it seems quite unlikely that the pavement factor K in Eq. 1 can have a constant value that depends only on the diameter of the loaded area (1, Fig. 5) and that it cannot, therefore, be represented by a straight line relationship like that of Line (1) in Figure 7. Instead, it appears that the value of K also depends on the thickness of granular base and on the strength of the subgrade on which it is placed. It is of interest, therefore, to determine why in Figure 3 the use of a constant value of 35 for the pavement factor K in Eq. 1 provides a design curve (solid line) for a wheel load of 9,000 pounds that for the range of CBR subgrade strength ratings between about 3 and 20 practically coincides with the design curve (broken line) given by the Burmister equation for the same wheel load.

For the Burmister design curve in Figure 3, the elastic modulus of the granular base E_1 has the constant value of 11,000 psi and the applied load of 9,000 pounds is also constant, but both the thickness of base T and the value of the ratio E_1/E_2 increase as the subgrade strength decreases, and vice versa. Table 2 provides corresponding values of subgrade elastic modulus E_2 and pavement thickness T obtained by the Burmister equation, from which the Burmister design curve (broken line curve) of Figure 3 is plotted. Table 2 also gives data obtained by the Burmister equation that enable values for the pavement factor K of Eq. 1 to be calculated for various points along the Burmister design curve.

Values of the pavement factor K associated with the Burmister design curve of Figure 3, expressed in terms of K/r and corresponding values of E_1/E_2 (Table 2), are plotted as the curved solid line in Figure 9. The straight horizontal broken line in Figure 9 represents the value of 35 for the pavement factor K that was employed with Eq. 1 to obtain the solid line design curve of Figure 3.

It is clear from Figure 9 that the corresponding values for T/r and E_1/E_2 change in such a way over a wide range that the values of the pavement factor K obtained from the Burmister equation are practically equal to the empirically derived value of 35. Stated more completely, Figure 9 demonstrates that for the design conditions of Figure 3, the values of the pavement factor K that can be calculated from the Burmister equation are almost identical to the empirically determined value of 35 for the pavement factor K for the range of subgrade strength ratings ordinarily encountered in pavement design (CBR 3 to 20). It is for this reason also that Eq. 1, together with the simple empirical values for the pavement factor K (1, Fig. 5), provides thickness requirements for conventional flexible pavements that are in good agreement with other empirical methods of structural design.

ACCURACY OF APPROXIMATE METHOD OF DESIGN FOR MULTILAYERED PAVEMENTS

During the past decade or so, studies based on the elastic properties of a three-layer pavement have been made to evaluate the stresses and strains at all points in a loaded three-layer pavement system, and rational methods of pavement design employing the values obtained have been proposed (6, 7, 8, 9). It should be noted, however, that the accuracy of these rational methods of design depends on how nearly the pavement materials actually employed on each project are represented by such assumptions as those of elasticity, isotropy, and values of Poisson's ratio employed when applying the rational method, and on the ability of currently available test methods to make the necessary strength measurements on the various pavement materials and on the subgrade soil with the degree of precision required.

Until the influence of these uncertainties on the pavement design requirements provided by these rational methods has been established, there would appear to be room for simpler methods of design that might also be considered to be rational, or at least quasi-rational if they can be devised. It was for this reason that an approximate rational method for the design and evaluation of multilayered pavements was suggested in the final section of last year's paper. For this approximate method it was assumed that a multilayer pavement could be converted step by step to an equivalent two-layer pavement by employing Burmister's analysis for an elastic two-layer pavement system.

It is worthwhile to examine the degree of accuracy that this approximate method provides. Figure 10 illustrates the method of analysis to be employed for this purpose.

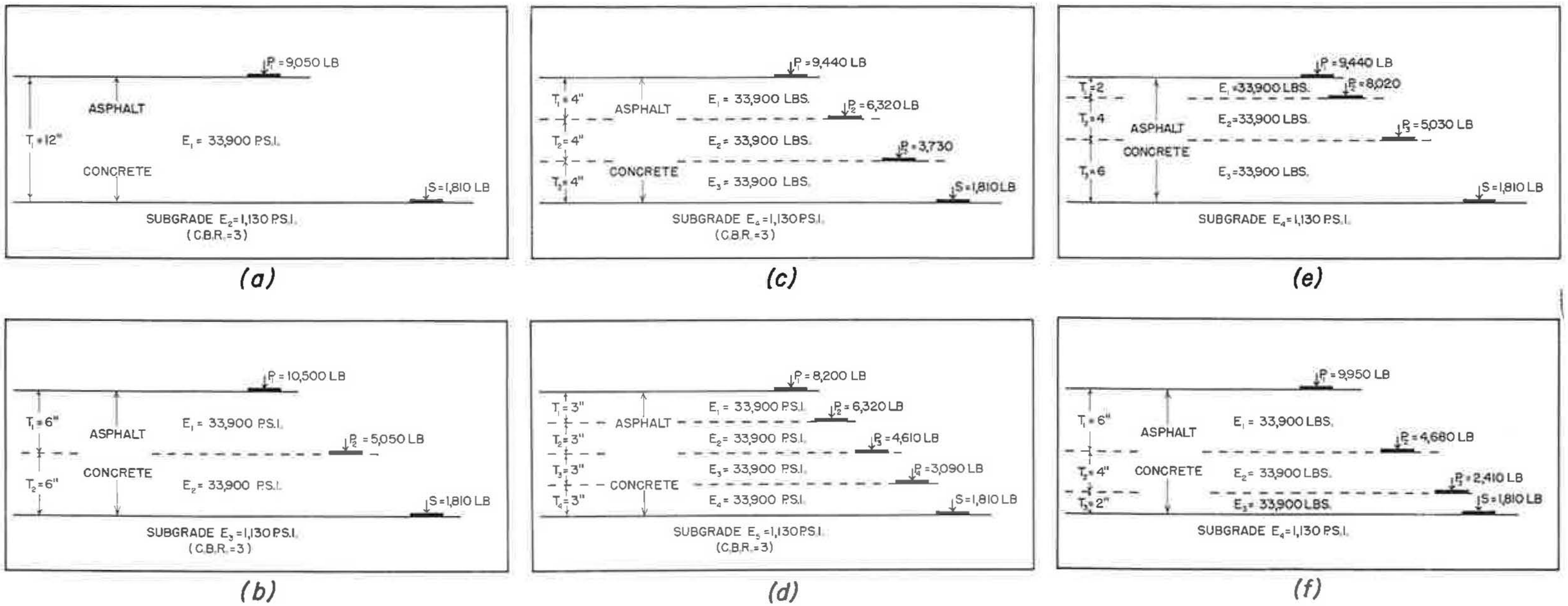

Figure 10. Limitations of approximate method of analysis for multilayer pavement system.

First, Figure 10a, a two-layer pavement system consisting of 12-in. of given pavement material on a specified subgrade, is analyzed by Burmister's method to determine the load it will support on a 12-in. diameter bearing plate at 0.1-in. deflection. It is then assumed (Figs. 10b to 10f) that this 12-in. layer of given pavement material consists of two 6-in. layers, or three 4-in. layers, or four 3-in. layers, etc., and the approximate method of analysis referred to in the last section of the 1963 paper is employed to calculate the load-carrying capacity of each of these multilayer pavement systems. In all cases, the strength of the subgrade (elastic modulus = 1,130 psi), the thickness (12 in.), and strength (elastic modulus = 33,900 psi) of the pavement material remain the same. The calculations for the cases represented by Figures 10a and 10b are illustrated below:

Case 1. Two-Layer Pavement (Fig. 10a)

Given: E_1 = 33,900 psi, E_2 = 1,130 psi, T_1 = 12 in., r = radius of loaded area = 6 in., and pavement deflection = 0.1 in.

Problem: What load will this two-layer pavement support?

Solution:

$$\frac{E_1}{E_2} = \frac{33,900}{1,130} = 30,$$

$$\frac{T_1}{r} = \frac{12}{6} = 2,$$

$$F_W = 0.2\ (\underline{1},\ \text{Fig. } 10),$$

$$S = \frac{E_2 wr}{0.376} = \frac{(1130)(0.1)(6)}{0.376} = 1,810 \text{ lb, and}$$

$$P_1 = \frac{S}{F_W} = \frac{1,810}{0.2} = 9,050 \text{ lb.}$$

Therefore, the two-layer pavement structure illustrated in Figure 10a will support heavy traffic by a wheel load of 9,050 pounds or equivalent.

Case 2. Three-Layer Pavement (Fig. 10b)

Given: E_1 and E_2 = 33,900 psi, E_3 = 1,130 psi, T_1 and T_2 = 6 in., r = radius of loaded area = 6 in., and pavement deflection = 0.1 in.

Problem: What load will this three-layer pavement support?

Solution:

$$\frac{E_2}{E_3} = \frac{33,900}{1,130} = 30,$$

$$\frac{T_2}{r} = \frac{6}{6} = 1,$$

$$F_W = 0.36\ (\underline{1},\ \text{Fig. } 10),$$

$$S = 1,810 \text{ lb (from Case 1), and}$$

$$P_2 = \frac{S}{F_W} = \frac{1,810}{0.36} = 5,050 \text{ lb.}$$

The assumption is now made that an equivalent homogeneous soil of elastic modulus E_{23} will also support a load P_2 = 5,050 lb at 0.1-in. deflection, from which

$$E_{23} = \frac{0.376\ P_2}{wr} = \frac{(0.376)(5,050)}{(0.1)(6)} = 3,170 \text{ psi},$$

$$\frac{E_1}{E_{23}} = \frac{33,900}{3,170} = 107.7,$$

$$\frac{T_1}{r} = \frac{6}{6} = 1,$$

$$F_W = 0.48 \ (\underline{1}, \text{ Fig. } 10), \text{ and}$$

$$P_1 = \frac{P_2}{F_W} = \frac{5,050}{0.48} = 10,500 \text{ lb.}$$

Therefore, according to this approximate method of analysis, the three-layer pavement of Figure 10b will support heavy traffic by a wheel load of 10,500 lb or equivalent.

However, the pavement system of Figure 10b is identical with that of Figure 10a. In both cases it consists of 12 in. of pavement material with an elastic modulus of 33,900 psi on a subgrade with an elastic modulus of 1,130 psi. Therefore, the difference in wheel load supporting values, 10,500 pounds for Case 2 vs 9,050 pounds for Case 1, represents in this instance the degree of accuracy provided by the approximate method for analyzing the three-layer pavement system. In this particular example, the use of the approximate method would lead to 16 percent underdesign because it indicates a supporting capacity of 10,500 lb for a pavement that will actually support only 9,050 lb.

Figure 10c shows that a similar analysis on the basis of three 4-in. pavement layers on the same subgrade results in a load-carrying capacity of 9,440 lb, which represents 4.3 percent underdesign. On the other hand, as demonstrated by Figure 10d, the load-supporting value of 8,200 lb indicated by an analysis based on four 3-in. pavement layers represents 9.4 percent overdesign. Figures 10e and 10f show that the same analysis applied to three pavement layers of unequal thickness (6, 4, and 2 in.), placed in two different sequences results in overestimating the load-carrying capacity of the pavement structure, and, therefore, in underdesign.

The results of a similar set of calculations, summarized in Table 3 for 24 in. of pavement material having an elastic modulus of 12,430 psi on a subgrade with an elastic modulus of 1,130 psi (CBR 3), also indicate a load-supporting value of 9,050 lb on a 12-in. diameter bearing plate at 0.1-in. deflection when analyzed as a two-layer pavement system. However, when the pavement layer itself is divided into two, three, and four layers and analyzed on this basis by the approximate method, the load-carrying capacity of the pavement structure is overestimated by nearly 30 percent.

Figure 10 and the results summarized in Table 3 indicate, therefore, that for the number of layers of pavement ordinarily employed, which seldom exceeds three pavement layers on top of the subgrade, the use of the approximate method referred to in the final section of the 1963 paper for analyzing a multilayer pavement system would lead to overestimating the load-supporting value of a pavement structure by up to 30 percent. In some cases it might be more than this. It should be noted again that the results for all cases covered by Figure 10 are for a homogeneous pavement material, 12 in. thick, with an elastic modulus of 33,900 psi throughout. It is possible that for a typical flexible pavement, which normally consists of three layers of different pavement materials over the subgrade, the tendency of the approximate method to lead to underdesign might be even greater.

TABLE 3

LOAD SUPPORTING VALUES CALULATED BY APPROXIMATE METHOD OF ANALYSIS[a]

No. of Pavement Layers	Load (lb)
1	9,050
2	11,500
3	11,800
4	11,200

[a]Diameter of bearing plate = 12 in.;
Radius of loaded area = 6 in.;
Pavement of deflection = 0.1 in.;
Pavement thickness = 24 in.;
Elastic modulus of pavement material, E_1 = 12,430 psi; and
Elastic modulus of subgrade, E_2 = 1,130 psi (CBR = 3)

EVOLUTION OF FLEXIBLE PAVEMENT STRUCTURAL DESIGN

One of the most important contributions of the AASHO Road Test to highway engineering is an authoritative new approach it has brought to the structural design of asphalt pavements. This new approach involves the incorporation of an asphalt binder into all material above the subgrade. This in turn introduces the need for recognizing the concept of slab action (Fig. 11a), when designing flexible pavements that are to contain these asphalt treated aggregates. Although this type of construction has been employed on a minor scale in the past, previous to the AASHO Road Test there had been no general agreement, and only very limited evidence, that its ability to support load is superior to that of untreated granular materials.

The conventional method of flexible pavement design, which has been employed since the time of MacAdam, is illustrated in Figure 11b. Whereas on most modern highways it has an asphalt surface of some type, a conventional flexible pavement structure consists primarily of sufficient thickness of granular material to carry the anticipated wheel loads and traffic volumes without overstressing or overstraining the subgrade at any point. Because the granular materials employed consist of discrete particles, they have limited load-distributing capacity (Fig. 11b), and substantial thicknesses of granular bases must, therefore, be provided, particularly over poor subgrades.

The principal advantage of conventional flexible pavements in the past has been their relatively low cost due to the wide distribution of abundant deposits of good natural gravels. However, their use also has several serious disadvantages. Their principal fault is the huge volume of granular material required per mile of heavy duty highway, especially on weaker subgrades. This is due to the usual practice of carrying the full depth of granular base and subbase from shoulder to shoulder to provide natural drainage for the granular material. In addition, depths of granular base approaching and exceeding 30 in. are required over poorer subgrade soils on major highways carrying high traffic volumes which include many heavy trucks.

Figure 43 from the 1963 paper (1) demonstrates that the load-carrying capacity of granular materials per inch of thickness decreases quite rapidly after reaching a maximum at a thickness approximately equal to the diameter of the loaded area, which is about 12 in. for heavy highway vehicles. For the conditions illustrated, it can be determined from this figure that the 5-in. increment in pavement thickness from 30 to 35 in. adds load-supporting value at an average rate of about only 120 lb/in. of thickness, vs an average increase in load support of about 340 lb/in. of thickness for the first 10.5 in. of pavement, which is the optimum thickness in this particular case. Consequently, the use of great thicknesses of granular bases is a very inefficient way to employ granular materials to obtain increased wheel load supporting capacity.

Another rapidly developing major disadvantage of conventional flexible pavement design was stressed in a recent report by (10). This report emphasizes that the natural

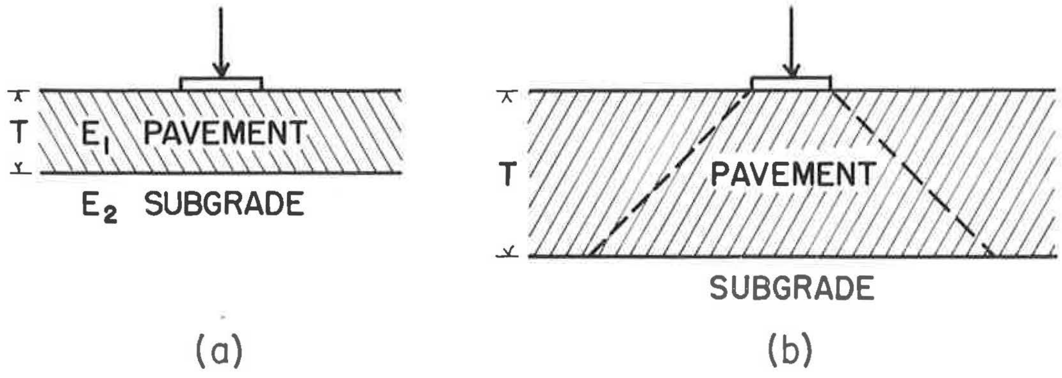

Figure 11. Evolution of flexible pavement structural design: (a) layered system slab action, and (b) conventional flexible pavement.

deposits of readily available good aggregates are becoming exhausted in many regions, and that one of the most serious problems facing highway engineers in North America is the conservation of the remaining good natural aggregates by learning how to upgrade the quality of the relatively undeveloped large deposits of inferior granular materials.

In view of the developing scarcity of good natural aggregates, which has already been eliminating consideration of conventional flexible pavements for major roads in some areas, the published result (11) concerning the special base sections at the AASHO Road Test have become available at a most opportune moment in the development of highway technology. These results have opened the door to a whole new field of opportunity in flexible pavement design.

Analysis of data from the special base sections at the AASHO Road Test (11) showed that a layer of pavement material made by incorporating about five percent of 85/100 penetration asphalt cement into a relatively unstable sandy gravel in a hot mix plant had the same load-carrying capacity as a layer of untreated sandy gravel four times as thick, and as a layer of good quality crushed stone three times as thick. Because the asphalt-treated aggregate is waterproof when well designed, the width of base required is only slightly more than the width of the main pavement. Consequently, where it can be economically justified, the use of asphalt-treated aggregates for the full depth above the subgrade decreases the thickness and width of base courses and results in large reductions in the quantities of aggregates required by conventional flexible pavement design. In addition, by improving their quality and increasing their load-supporting capacity, this treatment enables the huge volumes of inferior aggregates in natural deposits to be utilized for flexible pavement construction. Therefore, full depth asphalt-treated base provides a practical answer to the two major disadvantages of conventional flexible pavement design, namely, the very large volume of granular base materials it requires and the developing scarcity of good natural aggregates.

A recent survey has shown that 38 states have now started to employ either "deep strength" (use of an asphalt binder in at least the top 6 in. of the pavement structure or the treatment of all material above the subgrade with asphalt when designing flexible pavements for their highway construction programs.

Because of the economy of granular materials and other advantages it provides, the evolution of flexible pavement design in the immediate future can be expected to be away from the conventional approach shown in Figure 11b and in the direction of full depth treatment with asphalt binders. Most of these benefits result directly from the slab action provided by these binders (Fig. 11a).

NEEDED RESEARCH ON FLEXIBLE PAVEMENT DESIGN

The previous section referred to the important advantages of the recently developed flexible pavement design procedure requiring treatment of all materials above the subgrade with asphalt. One of the principal benefits of this design procedure is the slab action it achieves (Fig. 11a).

Two major questions that still remain to be answered, however, are how this slab action is to be measured, and how it is to be utilized in the structural design of asphalt pavements. Initial theoretical solutions to these questions have been available since the publication of Burmister's analysis of an elastic two-layer pavement system in 1943 (2) (Fig. 1), and they have been supplemented substantially by further studies since that time (6, 7, 8, 9). These answers are illustrated in Figure 30 from the 1963 paper (1). This figure demonstrates the relationship between the elastic modulus E_1 of the pavement material and the pavement thickness T required to support heavy traffic by a 9,000-lb wheel load or equivalent over a CBR 3 subgrade. The elastic modulus E_1 provides a measure of the slab action of the pavement.

This figure also illustrates the very important influence that the value of the elastic modulus E_1 of the pavement material (the magnitude of the slab action of the pavement) can have on the pavement thickness requirement. It indicates that 36 in. of granular material with an elastic modulus E_1 of 9,000 psi would be needed. If sufficient asphalt binder were incorporated into this granular material to increase its elastic modulus E_1 to 12,500 psi, the thickness requirement would be reduced to 24 in. If by some other treatment of the granular material with an asphalt binder, its elastic modulus E_1 were increased to 32,500 psi, the thickness requirement would be only 12 in. For the example illustrated by Figure 30 of Ref. (1), therefore, by increasing the slab action of the pavement in terms of its elastic modulus E_1 from 9,000 to 32,500 psi through the incorporation of the required amount and type of asphalt binder, the pavement thickness T can be reduced from 36 to 12 in., that is, to one-third. In this case, the layer equivalency value achieved by treating the granular material with an asphalt binder would be three.

At the AASHO Road Test, the layer equivalency values obtained by treating the sandy gravel subbase material with asphalt cement were three in terms of the good quality crushed stone base employed at the Road Test, and four in terms of the untreated sandy gravel. These layer equivalency values, however, were obtained empirically by the relative performance of the special base sections under the test traffic. No systematic large-scale attempt was made to determine the relative strengths of these three materials in terms of elastic modulus E_1 values or other fundamental strength units because this was outside of the scheduled scope of the Road Test.

Among the most serious mistakes that could be made would be failure to keep the layer equivalency values of the AASHO Road Test in their proper perspective, and to expect a great deal more from them than they are actually able to provide. It needs to be clearly realized that the layer equivalency values established by AASHO Road Test data apply essentially to the particular materials employed for the Road Test. They are not necessarily applicable to similarly treated and untreated aggregates available for ordinary paving projects elsewhere nor for treatments different from those selected for the special base sections at the AASHO Road Test. Consequently, the question that highway engineers everywhere ask themselves are: "What layer equivalencies can I obtain if I treat the aggregates available for this particular paving project with a given asphalt binder?" and "What asphalt treatment do I have to apply to the aggregates available for this particular paving project, to obtain the required layer equivalency of two, three, etc., that is needed to make such treatment economically attractive?" Furthermore, highway engineers want to be able to obtain this information during the design stage for each paving project, not after it has been built.

Because, apart from the findings of the AASHO Road Test, equally authoritative information on layer equivalencies does not exist, the development of a method that can be employed to obtain specific answers to these questions is the most pressing research problem in flexible pavement structural design at the present time. To have to build small full-scale test sections incorporating various treatments of the granular or soil materials available for each paving project and to evaluate them by traffic or other field tests to establish layer equivalencies before the paving project could be designed is too costly and time consuming. Therefore, a research program is urgently needed to develop a suitable laboratory test for this purpose. This program of research might be conducted as follows:

1. The ultimate objective of the research program would be the development of a simple, reliable, rapid laboratory test that would enable layer equivalencies to be established when different types and quantities of asphalt binders are incorporated into the particular aggregates (and in some cases soils) that are available for each proposed paving project.

2. It seems unlikely that this objective can be achieved by working solely with laboratory tests. It appears to require a closely coordinated program of field and laboratory tests. As it exists in a pavement, the material in each layer, subbase, base course, and asphalt surface (and the subgrade also) is subjected to definite restraints. Each layer is restrained because it is either sandwiched between, or in firm contact with, other layers. Because of these restraints, the strength value developed by the material in each layer in a pavement in service may be quite different from the strength value measured for an isolated sample of the same material by a simple test in the laboratory, where there may be no restraints on the sample or where the restraints applied to the sample are not representative of those exerted in the field. A good example of this would be a simple laboratory compression test in which no restraints were applied to the sample.

3. It would be the principal function of the field testing crew to develop or perfect suitable simple field tests for measuring the strengths of the materials in the subgrade, subbase, base course, and asphalt surface, as each of these materials exists within its respective layer in a pavement in the field. The equipment developed and employed for field testing should enable both static and dynamic strength tests to be made. The field testing crew would also obtain a representative sample of the material from the subgrade and from each pavement layer at each test site in the field, together with other pertinent field data, and would forward the samples and a copy of the complete field information to the laboratory.

4. It would be the principal function of the laboratory staff to develop the simplest, most reliable, and rapid laboratory procedure that would duplicate for these samples of materials in the laboratory, the strength values measured for them in-place in the field.

5. It is assumed that the procedures employed for all strength tests conducted in the field and in the laboratory would enable basic characteristics such as elastic modulus, and stress and strain to be determined in fundamental units of measurement.

6. This research program could utilize existing paved highways to develop and perfect the required field and laboratory testing procedures. At the same time, however, specially constructed test sections in which granular materials are treated with various types and quantities of asphalt binders should be incorporated into new highway paving projects and investigated over a period of time under in-service conditions to establish the potential range of layer equivalencies made possible by these treatments and the conditions under which they are most effective.

Representative values of stress and strain, elastic modulus, shear strength, and other fundamental characteristics measured for the subgrade and each of the pavement materials available for a paving project are useful for design purposes only if a rational method of design exists that is capable of utilizing this fundamental information. Theoretical rational methods of pavement design have been developed on the basis of the elastic properties of two- and three-layer pavement systems. However, the degree of accuracy of these methods still remains to be established. Assuming that the laboratory procedure developed is able to duplicate the elastic moduli, stress and strain, and other fundamental characteristics of the subgrade and pavement materials as they exist in a pavement in the field, an adequate rational method of design must be capable of achieving the following:

1. It must be able to utilize these fundamental laboratory determined values to calculate the thickness requirements for the proposed component layers to provide a pavement having the overall structural strength needed for the design wheel load.

2. It must provide calculated values for load vs deflection for this overall pavement design that will agree with measured values for load vs deflection obtained for the overall pavement structure after it has been built in accordance with the design requirements.

Consequently, the research program outlined previously should provide data that will indicate whether any of the existing rational methods of design are sufficiently accurate for practical use, or whether some new more precise rational method of design still remains to be developed.

SUMMARY

Results presented indicate that for subgrades with CBR ratings from 4 to 20, the thickness requirements for a 60,000-lb airplane wheel load given by Burmister's design equation for an elastic two-layer pavement system are practically identical with those of the Corps of Engineers. For subgrade CBR values from 3 to 20, the thickness requirements for a 9,000-lb highway wheel load provided by Burmister's design equation for an elastic two-layer pavement system are practically identical with those given by the Canadian Department of Transport's design equation, $T = K \log P/S$, when using an empirically determined value for the pavement factor K. A discussion of values of the pavement factor K in the design equation, $T = K \log P/S$, calculated theoretically from the Burmister equation, vs experimentally determined values of K is included.

Because of the slab action and other advantages it possesses, it is pointed out that the evolution of flexible pavement design in the immediate future is likely to be toward the adoption of the treatment of all materials above the subgrade with asphalt. A research program is outlined for the purpose of providing urgently needed information on the range of layer equivalency values to be obtained by treating granular materials with different types and quantities of asphalt binders.

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