Some Applications of the Elastic Theory Approach to the Structural Design of Flexible Pavements

By DR. NORMAN W. McLEOD*

INTRODUCTION

In current practice, each of the various approaches employed for flexible pavement design is entirely empirical. When the ability of the subgrade, base course, or asphalt surface to support load is referred to, a purely empirical strength number is used. For example, the strength of a subgrade or granular base course material is frequently expressed in terms of a California Bearing Ratio (C.B.R.) value, while for asphalt paving mixtures the Marshall stability value is often employed as a measure of strength. C.B.R. and Marshall stability numbers are meaningless measures of strength unless an engineer has acquired a sufficient background of experience to know how to use them. Flexible pavement design, therefore, is one of the very few remaining fields of civil engineering that is still entirely empirical.

Because of this, numerous attempts have been made to develop rational methods of flexible pavement design. For a rational method, the strengths of all materials, subgrade, base course, and surface would be expressed pounds per square inch. In addition, the pattern of stress distribution throughout the flexible pavement structure due to any given wheel load applied to the pavement surface, together with the corresponding strains being developed at each point, would be known. This would make it possible to provide material of adequate strength at every point in the overall flexible pavement structure.

Attempts to develop rational methods of design for flexible pavements fall into three categories:

(a) elastic theory methods,
(b) visco-elastic theory methods,
(c) ultimate strength or shear strength methods.

Elastic theory methods assume that the pavement has adequate strength for the wheel load to be carried, and that the pavement surface after deflecting as a wheel of a vehicle moves over it, rebounds immediately to its original position.

Visco-elastic approaches assume that the pavement has adequate strength, but after deflecting as a loaded wheel passes over it, the surface does not rebound to its initial position instantaneously, but requires time to return to its original position.

Ultimate strength or shear strength methods assume that the subgrade and each of the pavement layers have measurable shear strength values. If the shear strength of any layer is exceeded, the material in that layer will be displaced or will move by plastic flow away from the loaded area, and rutting or other deformation of the pavement surface will occur.

While much work has been done on each of these three rational methods, no one of them is yet considered reliable enough to be adopted by any large organization for flexible pavement design. The principal current drawback of each of these three approaches is the lack of a simple, rapid, reliable test procedure for obtaining representative strength values in pounds per square inch for subgrade and pavement materials. So far, there

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has been some doubt that any one of these three methods is capable of providing design criteria that can be related with sufficient precision to the actual service performance of flexible pavements.

In spite of these widely recognized criticisms of the three different rational approaches to flexible pavement design, the writer would like to present in this paper some evidence that the layered system elastic theory method of flexible pavement design appears to have some important advantages over the current empirical methods, that are not generally understood and appreciated.

RELATIONSHIP BETWEEN $T = K \log \frac{P}{S}$ AND BURMISTER EQUATIONS FOR AN ELASTIC LAYERED PAVEMENT SYSTEM

Since 1945, the Canadian Department of Transport has made hundreds of plate bearing tests on the subgrade, base course, and surface of flexible pavements on runways and taxiways at a large number of airports in Canada.

Analysis of these plate bearing tests some years ago[1], led to the following equation for flexible pavement design illustrated by Figure 1,

$$T = K \log \frac{P}{S} \qquad (1)$$

where

T = required thickness of pavement in inches

P = wheel load in pounds or kips to be carried (single wheel)

S = subgrade support in pounds or kips measured for the same loaded area and for the same deflection that pertain to P

K = pavement factor, an inverse or reciprocal measure of the increase in strength provided by the **first** unit of thickness of pavement placed on the subgrade.

Because P and S are obtained at the same deflection and for the same loaded area, it follows that Equation (1) can also be written as

$$T = K \log \frac{p}{s} \qquad (1a)$$

where

p = wheel load in pounds per square inch (single wheel)

s = subgrade support in pounds per square inch measured for the same loaded area and for the same deflection that pertain to p,

and the other symbols have the significance previously defined for them.

Analysis of the load test data indicated that the value of the pavement factor K varied with the size of the loaded area, as shown in Figure 2.

By means of Equation (1) and Figure 2, it is possible to construct a chart of curves which indicate flexible pavement thickness requirements for various wheel loads and for different degrees of subgrade support, Figure 3.

While Figure 2 shows that the pavement factor K varies with the diameter of the loaded area, it was realized from the beginning that the value of K must also vary with pavement thickness. Data to establish this were eventually provided by the Hybla Valley Test Project[2]. This was a small test road built in the vicinity of Washington, D.C., near the end of World War II. The subgrade was compacted in layers to a depth of five feet to provide maximum uniformity. Six, 12, 18, and 24 inches of uniform and well compacted granular base were laid on the subgrade, and surfaced with 3, 6, and 9 inches of asphalt concrete. The strengths of the subgrade, of the different thicknesses of granular base, and of the finished pavement were measured by means of plate bearing tests, employing rigid steel plates 12, 18, 24, and 30 inches in diameter.

Equation (1) can be written in rearranged form as

$$K = \frac{T}{\log \frac{P}{S}} \qquad (2)$$

From the Hybla Valley project, measured values are available for S, T, and P, from load tests on the subgrade, and on granular base course thicknesses of 6, 12, 18, and 24 inches, and for bearing plate diameters of 12, 18, 24, and 30 inches. When these measured values are substituted in the right hand side of Equation (2), values for the pavement factor K can be calculated for these various base course thicknesses and bearing plate diameters, Figure 4. It can be seen from Figure 4 that the value of K varies with base course (pavement) thickness as well as with the diameter of the bearing plate. Furthermore, it should be noted that for each bearing plate diameter, the value of K goes through a minimum which occurs at a thickness that appears to lie somewhere between the radius and diameter of the loaded area.

It should be emphasized that Equation (1) and Figures 1, 2, 3, and 4, have resulted from studies of empirical load test data. No preconceived theory was employed for this analysis. Nevertheless, it can be shown very easily that Equation (1) belongs to the elastic theory category of methods of pavement design. Both P and S in Equation (1) are measured with the same loaded area and at the same deflection. Consequently, the ratio P/S in Equation (1) is actually the ratio of a secant modulus of elasticity of the pavement structure as a whole, to a secant modulus of elasticity of the subgrade.

Burmister[3] published in 1943, the results of a purely theoretical approach to pavement design, in which it is assumed that a pavement consists of layers of materials having strictly elastic properties. The 2-layer elastic system investigated by Burmister, for which the elastic modulus of the pavement is E_1, and the subgrade elastic modulus is E_2, is illustrated by Figure 5.

The Boussinesq equation for a rigid bearing plate test on the subgrade, Figure 5, is

$$w_s = \frac{1.18\ sr}{E_2} \qquad (3)$$

while for a similar load test on the surface of the pavement layer, Figure 5, Burmister has developed the equation

$$w_p = \frac{1.18\ pr}{E_2} \cdot F_W \qquad (4)$$

where

w_s = deflection at the surface of the subgrade
w_p = deflection at the surface of the pavement
S = applied load in p.s.i. on a rigid bearing plate on the subgrade
P = applied load in p.s.i. on a rigid bearing plate on the pavement
r = radius of the bearing plate
E_2 = elastic modulus of the subgrade
F_w = deflection factor which varies with pavement thickness T, radius of the loaded area r, and the ratio of the elastic moduli E_1 and E_2, Figure 6.

When the bearing plate diameter and the deflection are the same for load tests on both the subgrade and pavement, Figure 5, Equations (3) and (4) can be equated. In this case $w_s = w_p$, and

$$\frac{1.18\ sr}{E_2} = \frac{1.18\ pr}{E_2} \cdot F_w$$

from which by simplifying

$$F_w = \frac{s}{p} \qquad (5)$$

Equation (1a) can be written as

$$K = \frac{T}{\log \frac{p}{s}} \qquad (6)$$

Rearrangement of Equation (5) gives

$$\frac{p}{s} = \frac{1}{F_w} \qquad (7)$$

from which

$$\log \frac{p}{s} = \log \frac{1}{F_w} = -\log F_w$$

By substitution in Equation (6)

$$K = \frac{T}{-\log F_w} \qquad (8)$$

Equation (8) provides a mathematical bridge between Equation (1) developed empirically from data from plate bearing tests made on airport runways by the Canadian Department of Transport, and Equations (3) and (4) derived by Burmister from purely theoretical considerations based on the elastic properties of a layered system.

Figure 6, developed by Burmister, shows how the value of the deflection factor F_w varies with pavement thickness T, radius r of the loaded area, and with ratios of the elastic moduli E_1 and E_2 of the pavement and subgrade respectively.

On the basis of Equation (8) and the data of Figure 6, the theoretical relationship between the pavement constant K from Equation (1) versus pavement thickness T, shown in Figure 7, can be established. An example of the calculations required for Figure 7 is illustrated in Table 1, using a ratio of 10 for E_1/E_2. In keeping with common practice in soil mechanics, both K and T in Table 1 and Figure 7 are expressed as multiples of the radius r of the loaded area. From the data of Table 1, and from similar tables based on other ratios of the elastic moduli E_1 and E_2, Figure 7 was prepared.

There is a striking resemblance between Figure 7 derived on this purely theoretical basis, and Figure 4 which resulted from the analysis of load test measurements made at the Hybla Valley project. In both Figures 4 and 7, the value of the pavement factor K goes through a minimum when K is plotted versus pavement thickness T. However, Figure 7 indicates that the pavement thickness T at which the minimum value of K occurs, varies with the ratio of the elastic moduli E_1/E_2.

STRUCTURAL DESIGN OF FLEXIBLE PAVEMENTS

Since Equation (1) developed empirically from the analysis of Canadian Department of Transport load test data, and Equations (3) and (4) representing Burmister's purely theoretical approach to pavement design are mathematically related, and both approaches belong to the elastic theory category of methods of pavement design, it is worthwhile to examine their application to a pavement design problem. This is illustrated by Figure 8, which demonstrates flexible pavement design for heavy traffic consisting of single wheel loads of 9,000 pounds or equivalent. The tire inflation pressure is 80 p.s.i., and the tire contract area is therefore assumed to be equal to that of a 12-inch diameter bearing plate. The flexible pavement structure is assumed to be a 2-layer elastic system, Figure 5, consisting of a layer of homogeneous pavement of thickness T and elastic modulus E_1 resting on a subgrade of semi-infinite depth and elastic modulus E_2.

Table 2 contains representative data on which Figure 8 is based.

Three corresponding measurements of subgrade strength are shown across the top of Figure 8: in-place or field California Bearing Ratio (C.B.R.) values, supporting value in kips on a 12-inch diameter rigid bearing plate at 0.1 inch deflection for 10 repetitions of load, and subgrade elastic modulus E_2 in p.s.i. for 0.1 inch deflection and 10 repetitions of load.

It should be noted that Figure 8 is based upon a critical deflection of 0.1 inch for 10 repetitions of load. This is considered to be the critical pavement deflection for heavy traffic consisting of 9,000-lb. single wheel loads or equivalent. Higher critical pavement deflections would be employed for medium and light traffic volumes, respectively.

Values of the pavement elastic modulus E_1 in p.s.i. at 0.1 inch deflection for 10 repetitions of load are shown along the left hand margin of Figure 8.

A single pavement thickness is represented by each curve that crosses Figure 8 from upper left to lower right. For example, curve (1) pertains to a pavement thickness $T = \frac{r}{2} = 3$ inches throughout its entire length, curve (2) refers to a pavement thickness $T = r = 6$ inches, etc.

Figure 8 indicates the minimum value of pavement elastic modulus E_1 required for any given combination of pavement thickness T and subgrade elastic modulus E_2, when designing a flexible pavement for heavy traffic by a single wheel load of 9,000 pounds or equivalent, and a tire inflation pressure of 80 p.s.i. For example, when the subgrade elastic modulus E_2 is 1500 p.s.i. (C.B.R. = 5.5), and the pavement thickness is 18 inches, Figure 8 indicates that the minimum required pavement elastic modulus E_1 is 12,000 p.s.i.

Near the top of Figure 8, there is a broken line curve that represents a value of 35 for the pavement factor K (Equation (1) and Figure 2). The points on this curve were obtained by substituting the given values for T, P, and K in Equation (1) and solving for S. The corresponding values for S in kips at 0.1 inch deflection, and for T in inches, provide the coordinates required for locating the points on this broken line curve.

For flexible pavement thicknesses between T = 1:5r = 9 inches, and T = 5r = 30 inches (corresponding subgrade C.B.R. ratings 16 to 2), which covers the range of thicknesses currently employed for flexible pavements for heavy traffic composed of 9,000 pounds wheel loads or equivalent, it will be observed from Figure 8 that a value of 35 for the pavement factor K corresponds to an almost constant value of the pavement elastic modulus E_1, the actual range in E_1 values being only from 11,000 to 12,500 p.s.i. It is for this reason that in the application of Equation (1) to the design of flexible pavements, the use of a constant value of K for each size of loaded area, Figure 2, provides flexible pavement thickness requirements, Figure 3, that are very close to those indicated by other empirical approaches to flexible pavement design.

In Figure 9, the solid curved line indicates flexible pavement thickness requirements over subgrades with a wide range of C.B.R. values, that are currently recommended by The Asphalt Institute for very heavy traffic consisting of wheel loads of 9,000 pounds (single axle load 18,000 pounds). The crosses on Figure 9 represent pavement thicknesses of 6, 12, 18, and 24 inches (thicknesses equal to r, 2r, 3r, and 4r), taken from Figure 8 for corresponding subgrade strength values, and for a pavement material having an elastic modulus E_1 of 16,000 p.s.i. It is evident from Figure 9, that for a pavement elastic modulus E_1 of 16,000 p.s.i., the pavement thickness requirements for a 9,000-pound wheel load given by Figure 8, and based upon the elastic properties of a 2-layer pavement system, are almost identical with those specified by The Asphalt Institute for the same wheel load and subgrade strengths. Similar good agreement with the Asphalt Institute thickness requirements can be shown for subgrade strengths measured with a 12-inch diameter plate at deflections greater than 0.1 inch (smaller traffic values) and for corresponding pavement materials with elastic moduli E_1 less than 16,000 p.s.i.

The practical significance of Figure 8 may be more easily understood by reference to Figure 10. Six widely different combinations of pavement thickness T and corresponding minimum values of pavement elastic modulus E_1 are illustrated in Figure 10. Each of these combinations of T and E_1 is equally capable of carrying heavy traffic by a single wheel load of 9,000 pounds or equivalent at 80 p.s.i. tire inflation pressure, over a weak subgrade having a C.B.R. rating of 3, and a related elastic modulus E_2 of 1130 p.s.i. (0.1 inch deflection). These combinations of T and E_1 range from 36 inches of pavement with an elastic modulus of E_1 of 9,000 p.s.i. to 6 inches of pavement with an elastic modulus of E_1 of 185,000 p.s.i.

Figure 10 demonstrates that many different combinations of pavement thickness T and elastic modulus E_1 are capable of carrying a specified wheel load and traffic volume over a given subgrade. Furthermore, it is clear from Figure 10 that one way in which both low quality and high quality aggregates could be conserved and used more efficiently, would be to upgrade their load carrying capacities by increasing their E_1 values. This would enable much smaller pavement thicknesses to provide the same wheel load and traffic carrying capacity.

Methods employing additives to increase the load carrying capacity, or to otherwise improve the quality of inferior aggregates and soils, are ordinarily referred to as soil stabilization. The soil stabilization processes most widely used at present involve the incorporation of either bituminous materials or portland cement.

The effectiveness of these binders for upgrading the quality of inferior aggregates was demonstrated very dramatically by the results of the special base investigations at the A.A.S.H.O. Road Test[4]. For the traffic and other conditions at the A.A.S.H.O. Road Test, it was established for a single axle load of 18,000 pounds that one (1) inch of asphalt treated sandy gravel base had the same traffic carrying capacity as 1.3 inches of portland cement treated sandy gravel base, as 3 inches of high quality crushed stone, and as 4 inches of the untreated sandy gravel. Consequently, the incorporation of either asphalt binders or portland cement is a very effective means for upgrading the quality and load supporting capacity of inferior aggregates.

For the range of E_1 values that might be normally employed for flexible pavement design, bituminous materials have a number of very desirable characteristics as binders for increasing the E_1 values of aggregates and soils. By incorporating a bituminous binder into an aggregate, the resulting mixture has been waterproofed. Thoroughly compacted dense graded bituminous mixtures are impervious to water and do not have to be drained. They are unaffected by frost action. They are not attacked by salts which are present in high concentration in some areas, or that are applied to the paved surface for snow and ice removal. They develop a high elastic modulus E_1 under rapidly moving loads. Because they are quite cold at that time of year, they have a very high load carrying capacity during spring break-up, and this tends to compensate for loss of subgrade support during this period. Since the bituminous binder itself is relatively flexible, a well designed and constructed asphalt treated aggregate layer can adjust itself substantially within limits, to the strains imposed by load and environment without cracking. Furthermore, as illustrated by Figure 11, when the entire depth of material above the subgrade is treated with asphalt binder, the economies of a trench pavement cross-section become possible, in contrast with the expense of the common current practice of providing untreated aggregates for the full pavement depth from ditch slope to ditch slope, or from one shoulder to the other.

By how much the E_1 value of an aggregate material should be increased by incorporating a bituminous binder, will be determined partly by the technical and partly by the economic considerations associated with each project. Figure 10 has demonstrated that for any given wheel load, the higher the E_1 value achieved, the smaller is the pavement thickness T required. Consequently, for each project, there will be an optimum combination of improved E_1 value attained by processing available aggregate with asphalt binder, associated with a corresponding reduced thickness requirement T, that will result in satisfactory pavement performance at lowest pavement cost.

Where aggregate materials of acceptable quality but lower E_1 values are available in almost unlimited quantities, economy may indicate the use of a greater thickness T of untreated aggregate. On the other hand, in areas where aggregates are scarce and expensive, or require upgrading because of their inferior quality, a cost analysis may show that treatment of the aggregate for the full depth above the subgrade with sufficient asphalt binder to provide a high E_1 value, Figure 11, along with the correspondingly smaller thickness T, would be the most economical solution to the flexible pavement design problem.

It should be emphasized in conclusion that Figures 8 and 10 demonstrate one of the great advantages of this layered system elastic approach over any of the current empirical methods of flexible pavement design. In the case of an empirical method, if the strength of a granular material were improved substantially by the incorporation of a binder, a costly full scale road test section, including controlled traffic by a range of axle loads, similar to the procedure employed for the special base sections at the A.A.S.H.O. Road Test, would be required to determine the permissible reduction in thickness of the treated as compared with the untreated aggregate. (It should be noted that practically all of our accumulated experience in flexible pavement design has been with untreated granular materials, and that our present empirical methods of design for flexible pavements are based on the use of untreated aggregates.) Furthermore, this type of expensive trial and error testing program would be required to determine the effectiveness of incorporating a binder into the aggregate from each different aggregate source, and into each of the many possible aggregate blends. It would also be required to establish the effectiveness of different quantities and types of binders. The cost of obtaining even reasonably comprehensive strength data on treated versus untreated aggregates by means of this trial and error procedure, which is always associated with empirical methods of design, would obviously become astronomical.

For the elastic layered system approach to flexible pavement design, on the other hand, Figures 8 and 10 demonstrate that for any given subgrade, wheel load, and traffic volume, as soon as the elastic modulus E_1 of either the treated or untreated granular aggregate has been measured, the corresponding pavement thickness T on the basis of either the treated or untreated material can be quickly **calculated**, or, easier still, can be read from an appropriate chart like that of Figure 8.

It is true that the methods presently available for measuring either the static or dynamic moduli of elasticity E_1 and E_2 of pavement and subgrade materials respectively, are not entirely satisfactory. However, if even a small portion of the current annual expenditure on highway research were devoted to the development of simple, rapid, and precise methods for this purpose, one or more satisfactory procedures would undoubtedly be quickly evolved.

SUMMARY

1. All the currently employed methods for flexible pavement structural design are completely empirical.
2. Attempts being made to develop rational methods of flexible pavement design fall into three categories:
   (a) elastic theory methods,
   (b) visco-elastic theory methods,
   (c) ultimate strength or shear strength methods.
3. This paper attempts to demonstrate that the layered system elastic theory approach to pavement design can be correlated with and has important advantages over current empirical methods.
4. It is shown that the flexible pavement design equation, $T = K \log \frac{P}{S}$, developed from the analysis of a large number of plate bearing tests conducted by the Canadian Department of Transport, belongs to the elastic theory category.
5. Analysis of plate bearing test data from the Hybla Valley Road Test project indicates that the pavement factor K in this design equation varies with size of loaded area and with pavement thickness, and that its value goes through a minimum when the pavement thickness is roughly equal to the diameter of the loaded area.
6. It is demonstrated that there is a mathematical relationship between the design equation $T = K \log \frac{P}{S}$ and the design equation based on the elastic properties of a layered pavement system developed by Burmister on a purely theoretical basis.
7. It is shown that by means of the Burmister equation it could have been predicted that the pavement factor K would vary with size of loaded area and with pavement thickness, and that its value would go through a minimum.
8. On the basis of the elastic properties of a 2-layer pavement system, a flexible pavement design chart is presented for heavy traffic of a single wheel load of 9,000 pounds or equivalent, and a tire inflation pressure of 80 p.s.i. This chart shows the relationship between the elastic modulus E_2 of the subgrade, the pavement elastic modulus E_1, and the required pavement thickness T.
9. This chart demonstrates that for a given subgrade, there are many combinations of pavement elastic modulus E_1 and pavement thickness T that are capable of supporting a 9,000-pound wheel load. As the pavement elastic modulus E_1 is increased, this chart shows that the required minimum pavement thickness T is decreased.

10. It is shown that the pavement thickness requirements of this chart based on a 2-layer elastic system are almost identical with the pavement thicknesses recommended by The Asphalt Institute for a wheel load of 9,000 pounds and heavy traffic.

11. The elastic modulus E_1 of an inferior granular material can be increased from several to many times by the incorporation of asphalt binders. When the pavement elastic modulus E_1 is increased, the required pavement thickness T can be reduced. Consequently, in areas where granular aggregates are scarce and expensive, or are of low quality, the incorporation of asphalt binders to increase their elastic modulus E_1 values, and thereby reduce the pavement thickness requirement, can be economically attractive. In addition, the paper lists a number of important practical advantages that asphalt treated aggregates have over untreated aggregates for flexible pavements.

12. A serious disadvantage of present empirical methods of design is that they are based on average strength characteristics of granular base course materials that have been gradually acquired by experience over many years. These empirical methods are unable to determine by how much pavement thickness can be reduced as the strength characteristics of granular materials are increased by the incorporation of asphalt binders, except by means of the costly trial and error approach employing full scale road tests and controlled traffic. On the other hand, as indicated in this paper, by utilizing the layered system elastic theory method of pavement design, the permissible reduction in pavement thickness can be calculated as the strength characteristics (elastic modulus E_1) of a granular material are increased by incorporating asphalt binders.

13. It is pointed out that the greatest single current obstacle to the immediate application of the elastic theory layered system approach to flexible pavement design, is the lack of simple, rapid, and precise methods for obtaining representative working values for the dynamic and static moduli of elasticity E_1 and E_2 of pavement and subgrade materials respectively. However, it is suggested that seriously applied highway research could very quickly develop acceptable procedures for this purpose.

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TABLE 1

DATA FOR ESTABLISHING RELATIONSHIP BETWEEN PAVEMENT FACTOR K AND PAVEMENT THICKNESS T

RATIO $E_1/E_2 = 10$

Pavement Thickness T	Deflection Factor F_w	$-\log F_w$	$K = \frac{T}{-\log F_w}$
0.25r	0.900	0.0458	5.46r
0.5r	0.760	0.1192	4.00r
1.0r	0.492	0.3080	3.27r
1.5r	0.373	0.4283	3.50r
2.0r	0.308	0.5114	3.91r
2.5r	0.269	0.5686	4.40r
3.0r	0.242	0.6144	4.88r
4.0r	0.208	0.6819	5.87r
5.0r	0.183	0.7376	6.82r
6.0r	0.173	0.7620	7.85r

TABLE 2

Corresponding values for E_1, E_2, and T for Pavement Design for

Single wheel load	—	9000 pounds
Tire inflation pressure	—	80 p.s.i.
Traffic volume	—	heavy
Tire contact area	—	equivalent to 12" diam. bearing plate
Radius of contact area	—	6 inches
Critical pavement deflection	—	0.1 inch

Wheel Load P Pounds	Subgrade Support S Pounds	Subgrade Elastic Modulus E_2 p.s.i.	Deflection Factor $F_w = \frac{S}{P}$	Values of E_1/E_2 for Pavement Thicknesses Shown							
				Pavement Thicknesses							
				0.5r	1.0r	1.5r	2.0r	3.0r	4.0r	5.0r	6.0r
9000	500	310	0.055	—	6600	2250	950	350	170	103	77
9000	1000	630	0.111	6300	950	280	135	70	37	24	19.5
9000	2000	1250	0.222	900	115	42	21	11.8	8.7	7.2	6.8
9000	3000	1880	0.333	240	37	13.5	8.6	5.5	4.5	4.0	3.85
9000	4000	2500	0.444	92	14	6.6	4.5	3.4	3.02	2.8	2.65
9000	5000	3130	0.555	37	7	3.75	2.85	2.35	2.25	2.15	2.00
9000	6000	3760	0.666	17.5	3.8	2.4	2.0	1.75	1.70	1.65	1.60
9000	7000	4380	0.777	8.2	2.4	1.7	1.52				
9000	8000	5010	0.888	3.1	1.48						
9000	8500	5320	0.944	1.6							

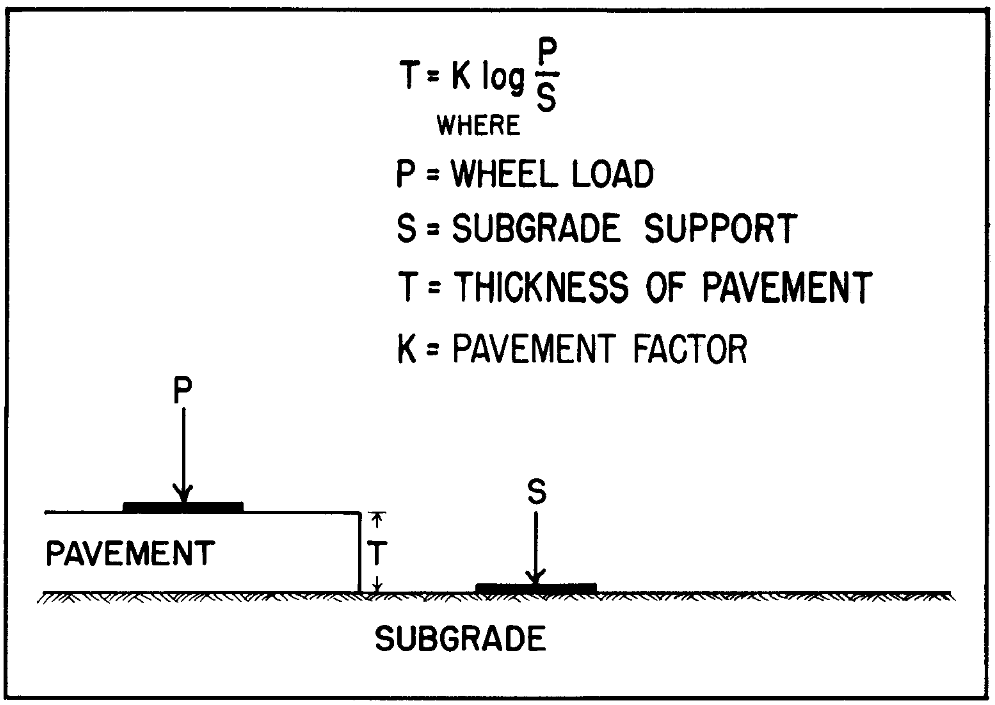


FIG. I LAYOUT OF LOAD TESTS FOR CANADIAN DEPARTMENT OF TRANSPORT'S INVESTIGATION OF AIRPORT RUNWAYS.

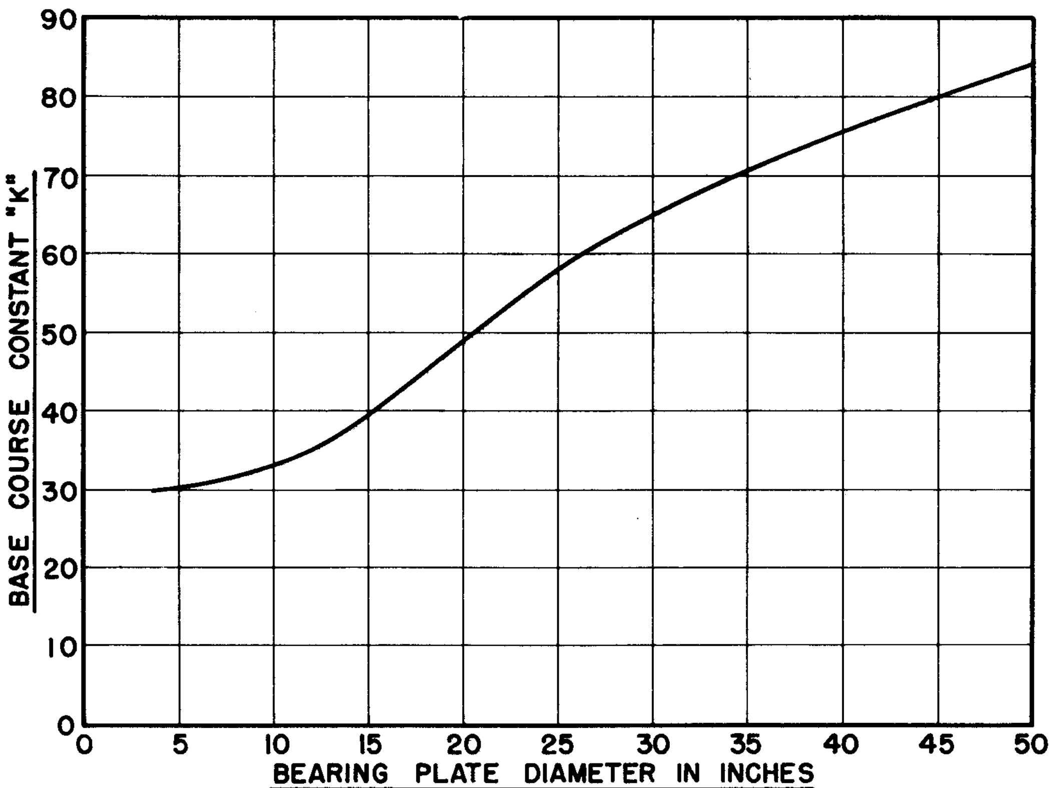


FIG.2 INFLUENCE OF BEARING PLATE DIAMETER ON VALUE OF "K" IN FLEXIBLE PAVEMENT DESIGN EQUATION $T = K \log(P/S)$.

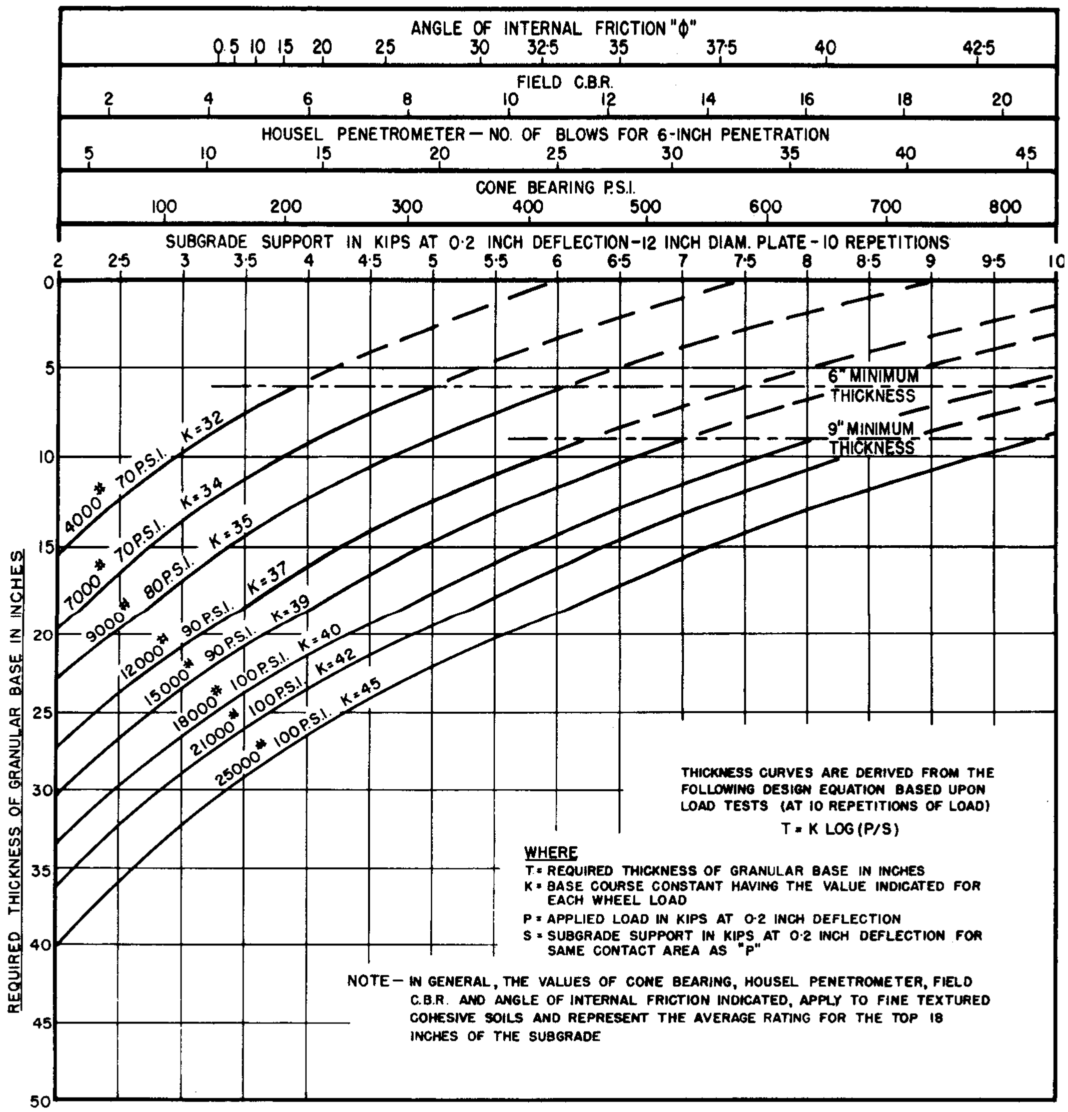


FIG.3 FLEXIBLE PAVEMENT THICKNESS REQUIREMENTS FOR HIGHWAYS CARRYING MAXIMUM TRAFFIC VOLUME (FULL LOAD ON SINGLE TIRE).

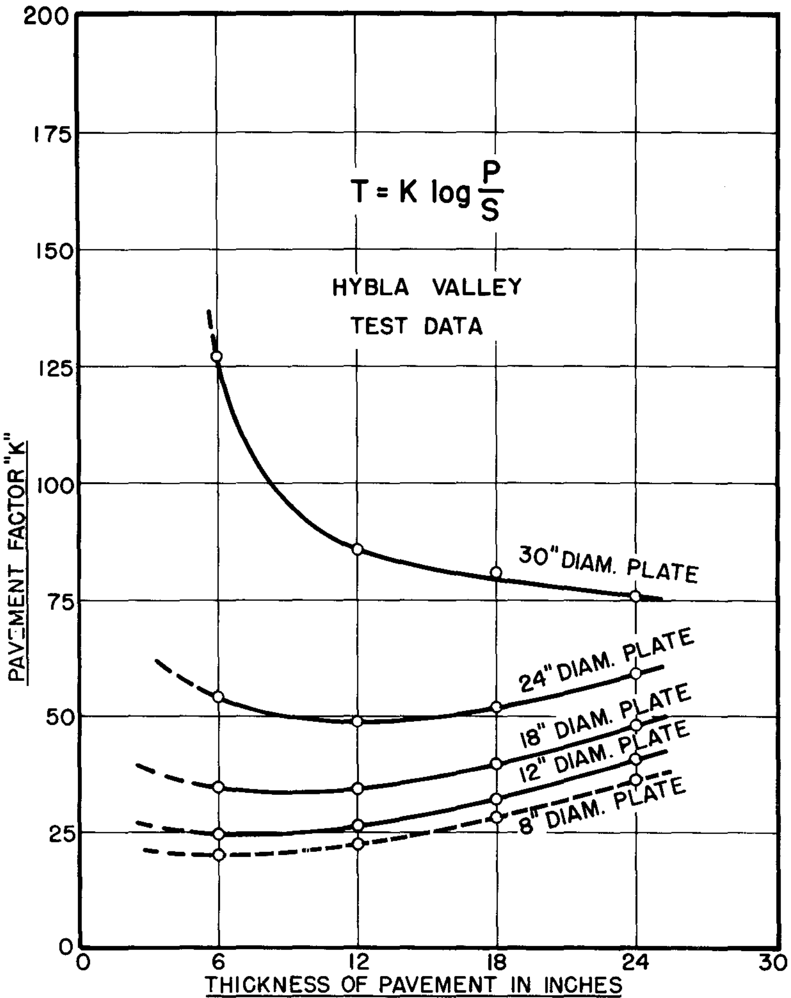


FIG.4 INFLUENCE OF PAVEMENT THICKNESS AND BEARING PLATE DIAMETER ON PAVEMENT FACTOR "K".

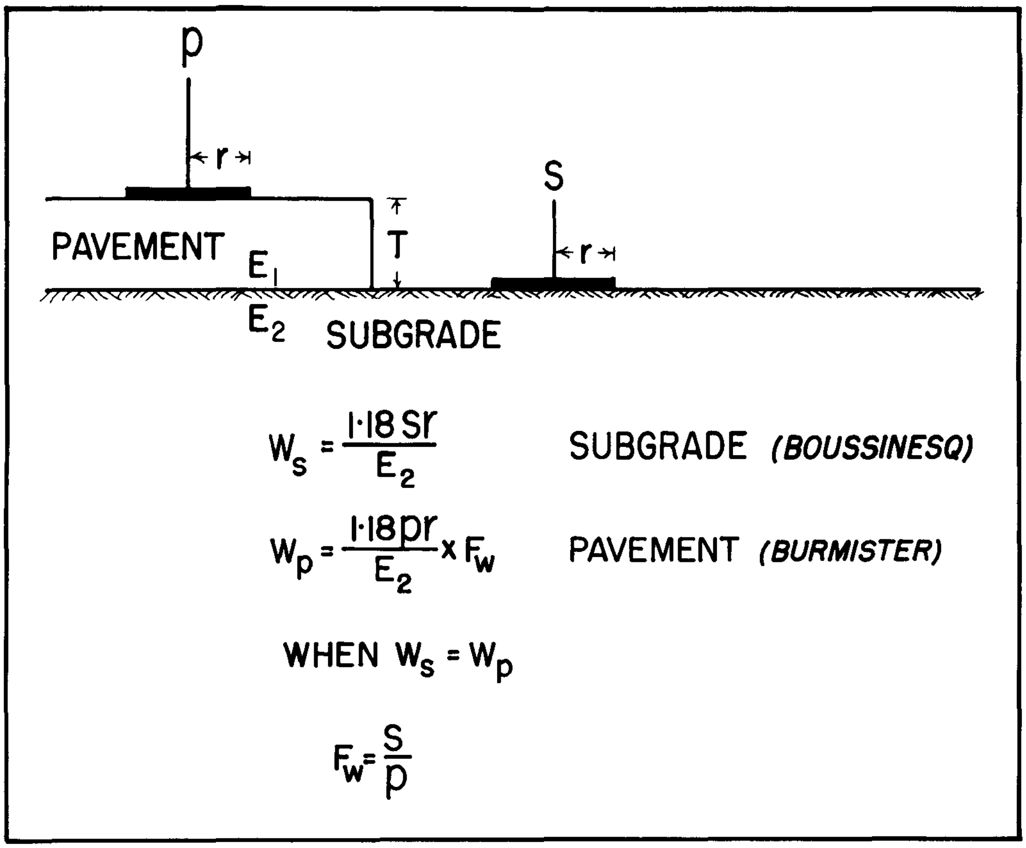


FIG.5 ILLUSTRATING BURMISTER'S LAYERED SYSTEM ELASTIC THEORY APPROACH TO PAVEMENT DESIGN.

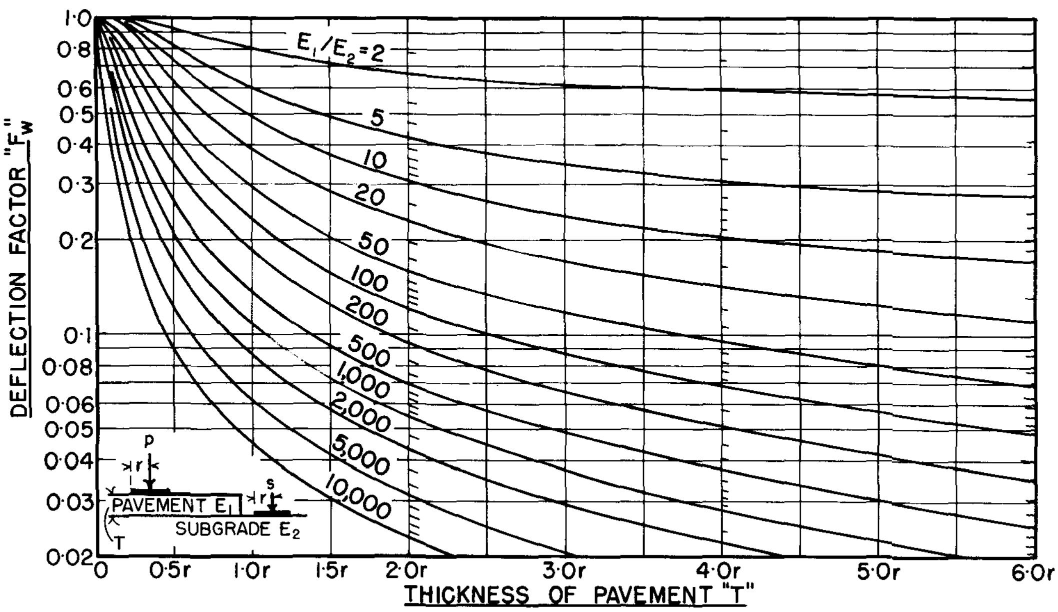


FIG.6 RELATIONSHIP BETWEEN DEFLECTION FACTOR, PAVEMENT THICKNESS, AND E_1/E_2 RATIOS, FOR A 2-LAYER ELASTIC SYSTEM.

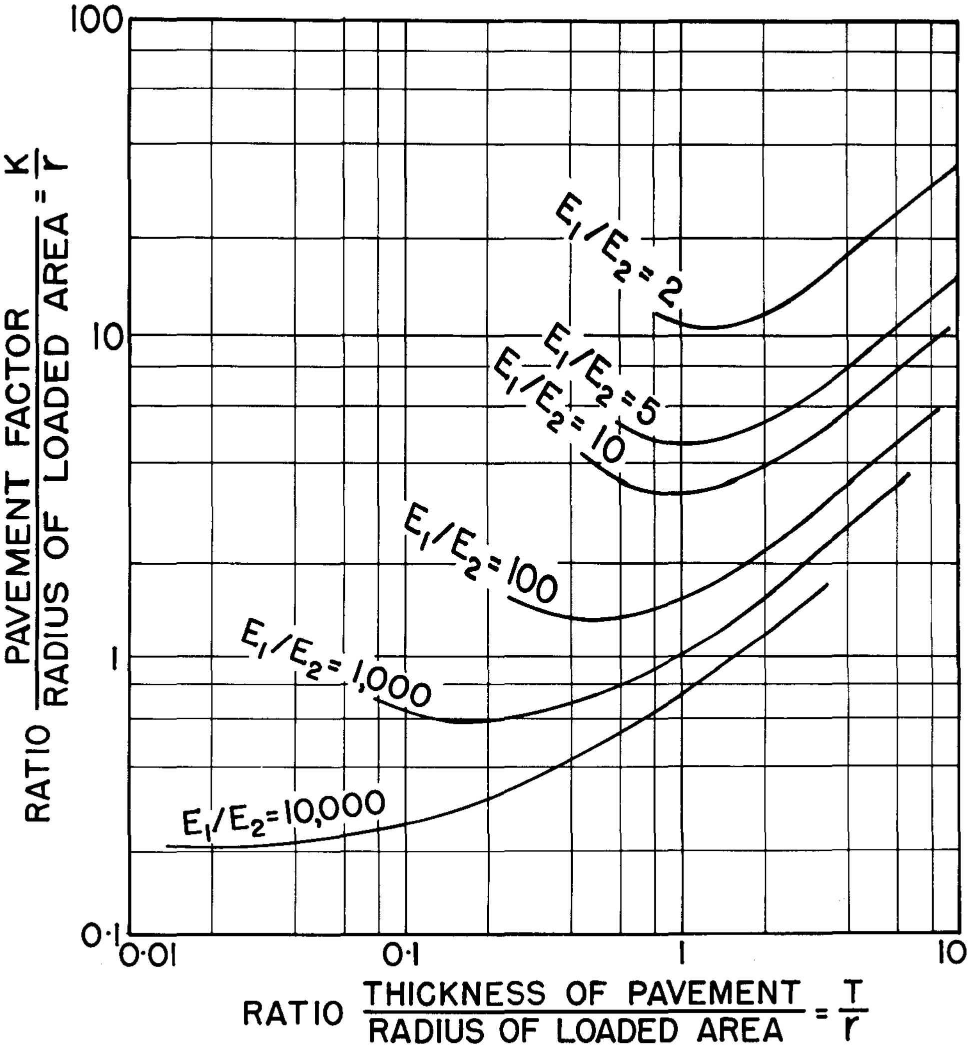


FIG.7 THEORETICAL RELATIONSHIP BETWEEN PAVEMENT FACTOR "K" AND PAVEMENT THICKNESS "T."

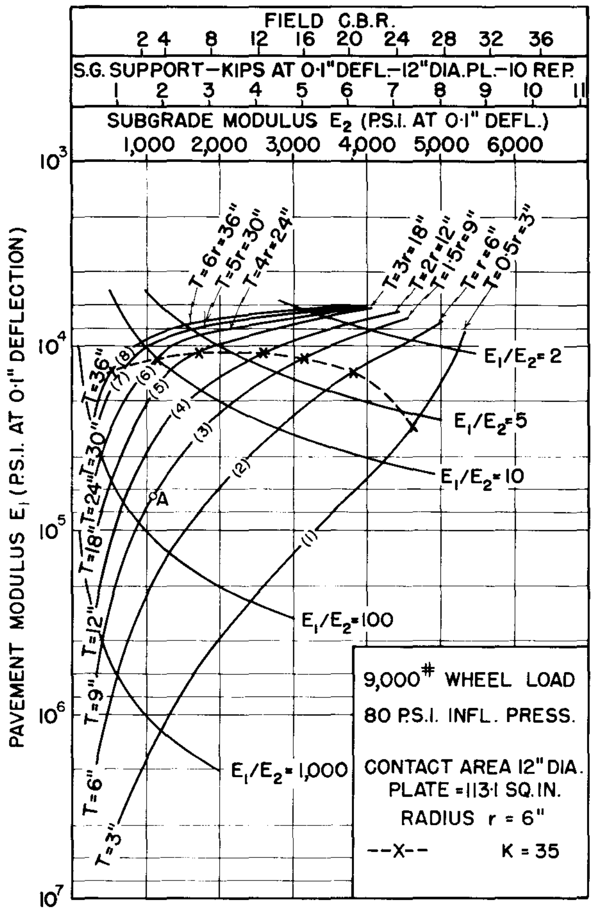


FIG.8 INFLUENCE OF PAVEMENT MODULUS E_1 AND SUBGRADE MODULUS E_2 ON FLEXIBLE PAVEMENT DESIGN FOR A 9,000-LB. WHEEL LOAD (CRITICAL DEFLECTION 0·1").

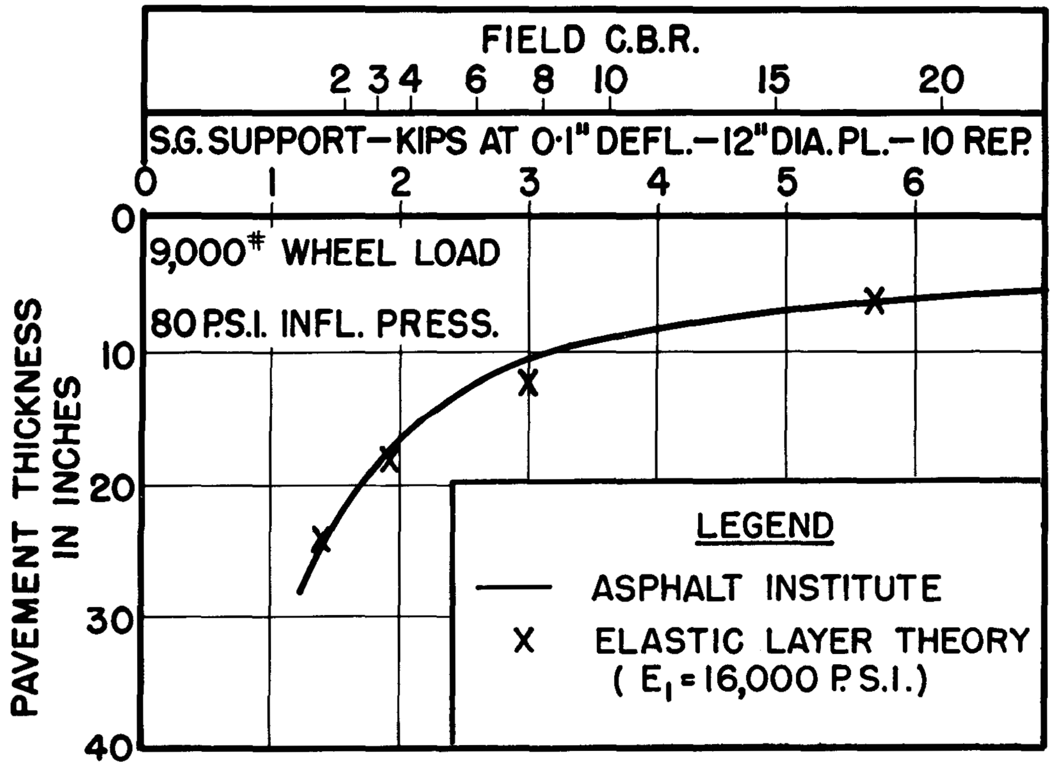
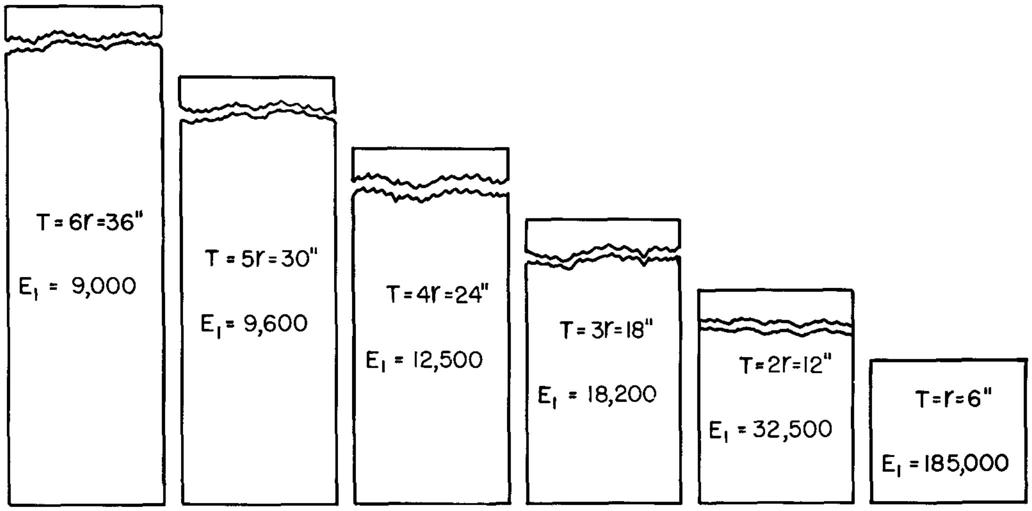


FIG. 9 COMPARISON OF ASPHALT INSTITUTE VERSUS ELASTIC LAYER THEORY THICKNESS REQUIREMENTS FOR A 9,000-LB. WHEEL LOAD.



WHEEL LOAD 9,000 LBS.
80 P.S.I. INFLATION PRESSURE
CONTACT AREA 12" DIAM. CIRCLE

SUBGRADE MODULUS E_2 = 1,100 P.S.I.
SUBGRADE C.B.R. = 3
0·1" DEFLECTION

FIG.10 ILLUSTRATING VARIOUS COMBINATIONS OF E_1 AND T REQUIRED TO SUPPORT A WHEEL LOAD OF 9,000 LBS. ON A PAVEMENT OVER A C.B.R. 3 SUBGRADE.

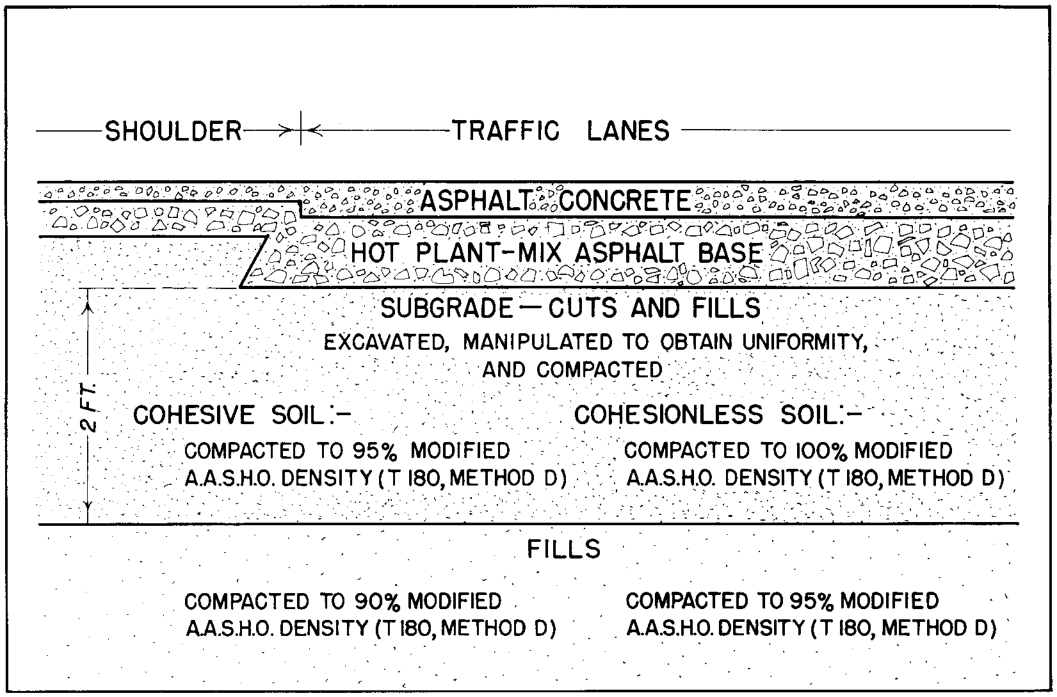


FIG.11 SUGGESTED ASPHALT PAVEMENT CROSS SECTION.