PROGRESS REPORT ON LOAD-TRANSMISSION CHARACTERISTICS OF FLEXIBLE PAVING AND BASE COURSES

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SYNOPSIS

The load-transmission-test apparatus consists essentially of (1) a spring-supported mechanical subgrade upon which flexible-pavement test sections can be constructed, (2) a device for loading the pavement section through the use of tires or rigid plates, and (3) equipment for measuring the vertical movements of the mechanical subgrade during the loading process. It is designed to provide load-distribution data on full-sized pavement sections tested under laboratory conditions.

Such data should provide one major step forward in the ultimate development of a rational method for flexible-pavement design. The test results can also be used in emprical-design methods based on a maximum subgrade bearing strength at a given deflection.

Results from approximately 350 loading tests are presented in this progress report. Most of these tests were run on gravel base courses of varying thickness with rigid plates as the loading medium. A limited number of tests of single airplane tires and dual truck tires are included also. These were run on gravel bases covered with asphaltic-concrete surfacing, as well as on the bases alone.

It was found that the maximum vertical subgrade pressure varied widely with total load, loaded area, pavement thickness, and pavement shear strength. Shear strengths were measured by large-scale triaxial tests.

Graphs are presented to illustrate the possible use of load-transmission data for design purposes and to permit the approximate determination of maximum subgrade pressures for pavement and loading conditions other than those actually tested.

●THE JANUARY, 1950, issue of *Highway Research Abstracts* described briefly the load-transmission project of the Civil Aeronautics Administration. A similar description of project aims and equipment has been printed as *CAA Technical Development Report* No. 108.

This project is being conducted at the CAA Technical Development and Evaluation Center, Municipal Airport, Indianapolis, Indiana. The broad purpose of the investigation is to study the dissipation and distribution of concentrated loads applied on flexible pavements. The present paper, which also will be published in somewhat more detailed form as a CAA report, is intended as a progress report on the tests completed thus far.

Typical data on load transmission and distribution are presented, and the possible use of such data for pavement-design purposes is discussed. The paper also includes empirical graphs by which the maximum subgrade pressure can be predicted approximately for pavement sections and loading conditions other than those actually tested.

APPARATUS

The load-transmission apparatus consists essentially of (1) a spring-supported mechanical subgrade, (2) a device for loading a superimposed pavement section through the use of rigid plates or tires, and (3) apparatus for measuring the vertical movement of the mechanical subgrade during the loading process.

The mechanical subgrade is about 10 ft. square. It consists of 3,600 steel plates, each 2 in. square, mounted in 60 rows of 60 each. Each plate is supported by a plunger and calibrated spring. Provision is made for measuring the deflections of individual springs at any step in the loading process, thus determining the pressure distribution over the mechanical subgrade.

Figure 1 shows a partial section of gravel base course and asphaltic-concrete surface on the subgrade. The thin rubber mat used to prevent infiltration of foreign matter among the plungers and guide cylinders has been rolled back to show the bare subgrade itself.

An aircraft wheel is attached to the hydraulic jacks in position for loading.

TEST OPERATIONS

The first step in the testing procedure is to construct the desired pavement section on the mechanical subgrade. Most of the tests to date have used a fair-quality dense-graded-gravel base-course material, either alone or with a bituminous-concrete surfacing. Crushed-stone base was used for a few tests.

Base-course materials are obtained from regular commercial sources. In order to insure as much uniformity as practicable the materials are run through a pug-mill mixer, and water is added as needed to obtain proper moisture content for most-efficient compaction. Although ordinary care is used in maintaining a uniform product, no effort is made to establish precise laboratory controls which could not be duplicated in field construction.

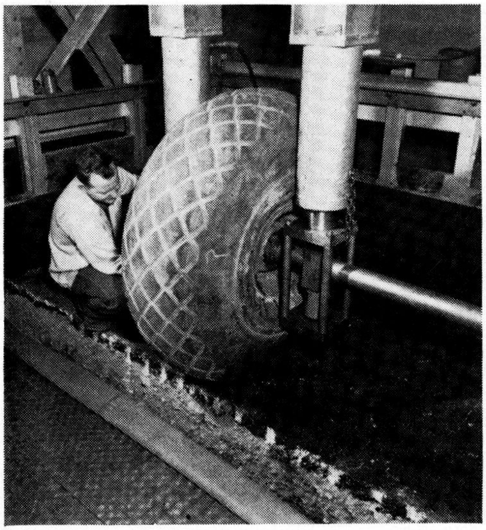


Figure 1. Load transmission apparatus: cutaway view of flexible pavement with airplane tire in place.

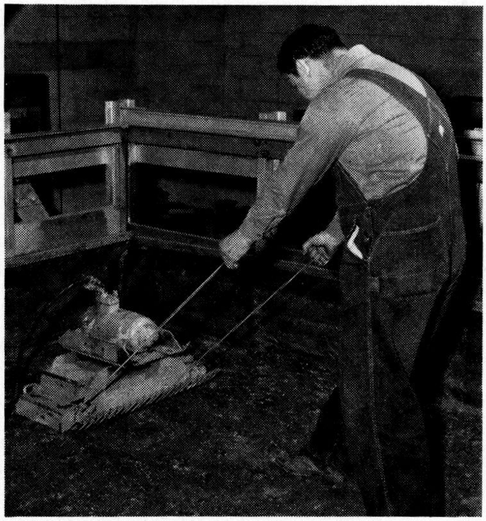


Figure 2. Vibratory compactor: compacting gravel base course on mechanical subgrade.

The material is spread by hand and compacted by vibratory equipment in layers of about 4 in. compacted thickness. The compactor is shown in Figure 2. With the gravel material it is fairly easy to obtain dry densities of 135 lb. per cu. ft. at moisture contents ranging from about 5 to 6 percent. A few pavement sections were constructed to densities as low as 122 and as high as 142 lbs. per cu. ft. Total pavement thickness has been varied from 4 to 24 in.

For each pavement section three corresponding triaxial compression specimens are prepared. These specimens are 10 in. in diameter and usually 20 in. high. They are compacted to the desired density by means of the vibratory tie tamper shown in Figure 3. More complete information on the triaxial testing is contained in *CAA Technical Development Report* No. 144.

The purpose of the triaxial samples is to establish a correlation between the load-distributing properties of a material as measured in the load-transmission test and its shear strength as determined by the simpler triaxial test. By comparing the triaxial-loading curve of each sample against an average curve for a large number of samples, it is possible to check the uniformity of the material and to establish a shear-strength rating for each pavement section.

In the earlier tests it was assumed the material for the triaxial samples would be sufficiently representative of that in the pavement section if both were taken from the same bin. Due to natural variations in large quantities of commercial material, it was found that this was not always the case. Beginning with Test No. 312, therefore, the triaxial specimens were prepared from a composite sample taken from the mixed material as placed in the pavement.

Vertical loads are applied to the paving section by means of hydraulic jacks, using various-sized tires or rigid plates as the load-transfer medium. Single plates (10- to 30-in. diameter), single airplane tires and dual truck tires have been used in the tests thus far.

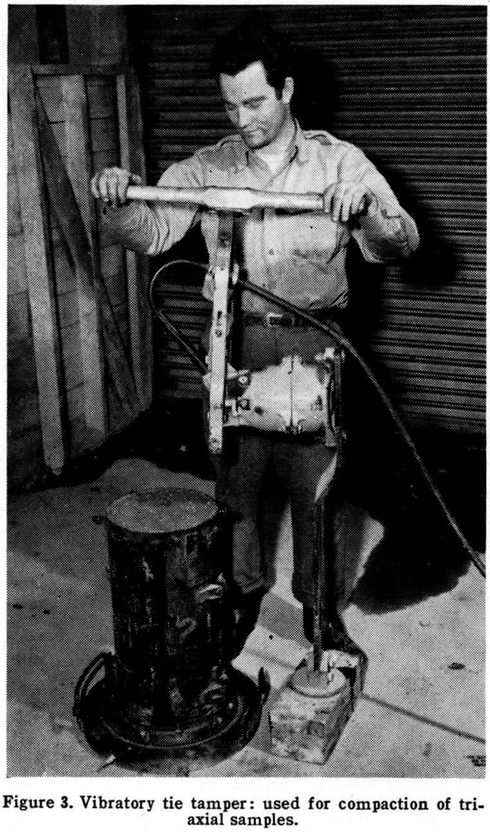


Figure 3. Vibratory tie tamper: used for compaction of triaxial samples.

Loads of increasing magnitude are applied until the subgrade deflection becomes excessive or until the load limit of the equipment is reached. Each load application is designated as a test, and the loads on a given test section constitute a test series. Due to a certain amount of permanent warping and residual stress in the pavement, it has been found impractical to use a section for more than one test series. A test series, including the time required for constructing and removing the test section, applying test loads, and molding and testing triaxial specimens, takes about a week.

The distribution of vertical load on the mechanical subgrade is determined by measuring the vertical deflection of the coil spring supporting each small subgrade element. The elevation of each segment is determined by readings taken immediately after construction of the pavement section and after application of each load increment. Differences between dead-load and live-load readings are converted

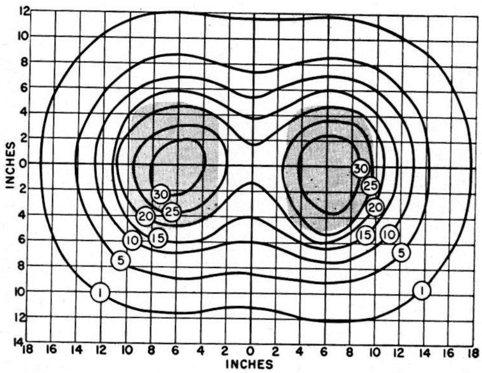


Figure 4. Typical pressure contours of 10 by 20 dual truck tires (70 psi. inflation pressure, 8.0 kips total load, 4-in. gravel pavement).

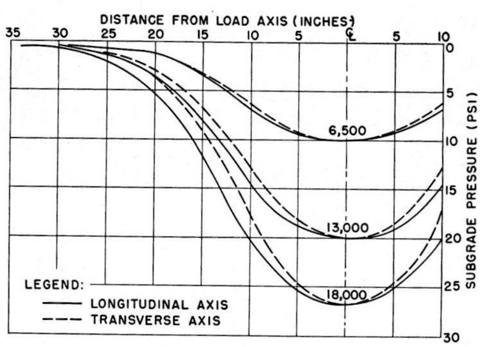


Figure 5. Subgrade pressure distribution along major load axes (47 in. single airplane tire, 12 in. gravel pavement).

to pressures by means of an appropriate calibration curve.

Although three sets of subgrade springs have been provided, only the weakest set has been used so far. These springs have an average rate of about 350 lbs. per in. deflection. As the area supported by each spring is slightly greater than 4 sq. in. this results in a value of 82 lb. per in. cubed for k, the modulus of subgrade reaction.

If the recorded pressures are shown on a facsimile chart of the artificial subgrade, it is possible to plot pressure contours as illustrated in Figure 4. Such a presentation is helpful in studying the pressure pattern resulting from any loading, especially with dual tires. For most tests, however, the general shape which the pattern will assume is quite apparent. Usually it is sufficient, therefore, to record the pressures only along the two major axes of the pattern and to display them in graphical form, as in Figure 5. This results in a considerable saving in the labor of recording and converting test data. Also it permits a certain amount of "smoothing" of the data as readings of corresponding plungers from each quadrant are averaged in computing ordinates for the curves.

TABLE 1

BREAKDOWN OF TEST SERIES BY TYPE AND THICKNESS OF PAVEMENT AND BY TYPE AND SIZE OF LOADING MEDIUM

Pavement	Loading Medium							
	Rigid Plates Diameter, In.				Single Airplane Tires		Dual Truck Tires	
	10	12	18	30	36 In.	47 In.	8½ x 20	10 x 20
4-in. Gravel					1			1
8-in. Gravel	1	5	7	4	2	2	1	1
12-in. Gravel		3			2	1		1
16-in. Gravel		1	1	1		1		
20-in. Gravel	1							
24-in. Gravel		1	1	1				
8-in Stone		2						
12-in. Stone		1						
8-in. Gravel + 2-in. A.C					1			
8-in Gravel + 3-in. A.C							2	1

Notes: Strength indices varied from 40 to 145 percent of normal Various inflation pressures were used with each tire. Al tests were run on 350 lb per in. subgrade springs, corresponding to $k = 82$.
Dual tire spacing was 10 8 in. c-c for the 8½ by 20 tires and 12.9 in. for the 10 by 20 tires

TEST RESULTS

At the time of this writing, a total of 400 load-transmission tests have been performed. It may be of interest to note that these tests involved about 475,000 individual deflection readings, with a corresponding amount of computation and plotting for reduction and presentation of the results. Tests of an exploratory nature and those run only for certain special purposes were eliminated from consideration at this time. The remaining 348 form the basis for this report.

In Table 1 this test group is broken down to show the number of test series corresponding to various combinations of loading medium and pavement. This indicates the extent to which each of these variables has been studied in the current program.

Data for individual tests are given in the Appendix. For convenience they are tabulated in subgroups according to the breakdown in Table 1, rather than by consecutive numbers. The maximum subgrade pressure or reaction is recorded for each test. Detailed load-distribution patterns and graphs are not shown for each test series, but typical patterns are illustrated by the various figures throughout the text of this paper.

All tests of single loads show a characteristic helmet-shaped distribution pattern, with the maximum subgrade reaction occurring immediately under the center of load. The maximum reaction and width of pattern vary widely, of course, with the pavement thickness and size of loading area. In dual loadings the patterns from the individual loads overlap, and the maximum may occur either directly under the loads or halfway between them, depending upon load spacing and pavement thickness.

The strength index, S, given in the tables, is a convenient measure of the inherent strength of the paving material in each test section as determined by the corresponding triaxial tests. Briefly, it represents the strength of a section as a percentage of the strength of a normal section. A standard or normal curve of lateral pressure versus maximum vertical pressure at failure was first prepared from triaxial tests of a large number of gravel specimens. The maximum vertical pressure for any individual triaxial test is then divided by the corresponding value from the curve in order to determine the strength index of the particular specimen involved. The value given for a load transmission test section usually is the average ratio from three triaxial tests.

Due to difficulties in maintaining accurate control of large quantities of material (as much as 15 tons in one test section) the triaxial specimens have not always been truly representative of the critical portions of the load transmission pavements. Arbitrary adjustments in the strength index have been made where they appeared to be justified by known differences in density, moisture content, or gradation. In other cases one can only assume that such differences existed by virtue of the observed differences in behavior of supposedly similar test sections.

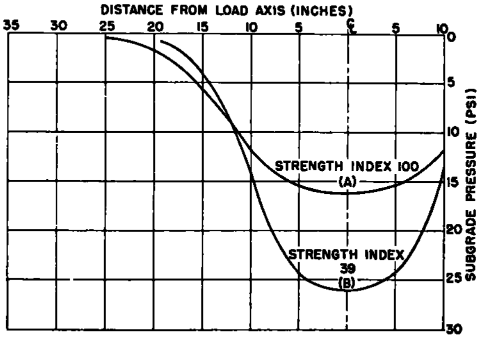


Figure 6. Effect of pavement strength index (8-in. gravel pavement, 9-kip load, 18-in. plate loading).

DISCUSSION

Method of Using Test Data—The ultimate aim of a project such as this is to provide information of value to the airport-pavement designer, and to provide it in a form which he can use conveniently. A more immediate use of the data is the direct comparison of the action of pavement sections which vary in physical characteristics or in the manner of loading. In some instances such a comparison is very obvious, at least from a qualitative standpoint; in others it is not so apparent. This can be best illustrated by reference to some typical test data.

Referring to Figure 6, there is no question that test section A is doing a better job of load distribution than section B, which has a much lower strength index. The total load, plate size, and pavement thickness are the same for both tests.

Figure 7 presents a different type of comparison, and one which is not so simple to make. In this example curve A shows the subgrade pressure distribution for a 24-kip load on a 24-in. pavement while curve B shows the distribution for a 6-kip load on an 8-in. pavement of comparable material. A 12-in. plate was used for both tests.

From the standpoint of subgrade protection and assuming that neither paving section fails internally, the 24-in. pavement obviously is the stronger of the two. In view of the fact that the maximum subgrade pressure is the same for both tests, one might say that the thicker pavement is four times as strong as the thinner one, this being the ratio between applied loads. Such a statement would be only approximately true, however, as the comparison should be on the basis of shear stresses and shear resistances in the subgrade rather than on the basis of vertical subgrade pressures.

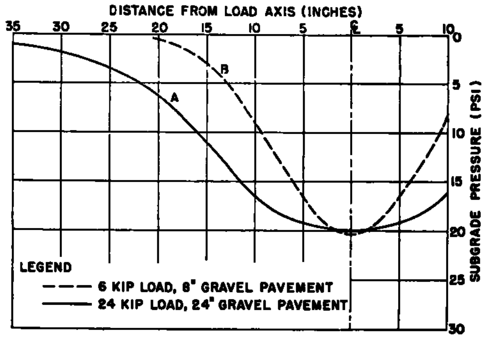


Figure 7. Effect of pavement thickness (gravel pavement normal strength, 12-in. plate loading).

The attainment of a truly rational design method for flexible pavements is a very difficult and complicated problem. Its solution will require knowledge of the load distribution on the subgrade and an understanding of the stress-strain relationships within the subgrade soil mass. The data available from the load-transmission apparatus will go far toward fulfilling the first part of this requirement. The Waterways Experiment Station at Vicksburg, Mississippi, is one organization, at least, which has made an encouraging start on the second phase of the problem through its stress distribution project. The ultimate solution, however, is still far in the future.

In the meantime, pavement designers are

faced with the necessity of making decisions on the basis of the best design methods now available. It has been suggested that the load-transmission data lend themselves readily to a design method based upon a limiting pavement or subgrade deflection. This is essentially the method used by many in designing pavement thicknesses on the basis of plate-bearing tests. If the modulus of subgrade reaction k and a desirable limiting deflection can be determined from test or assumed from experience, it is possible to give the subgrade a load rating in terms of vertical load per unit area. It then is a simple matter to determine from load-transmission data a pavement section which will limit the maximum subgrade pressure to this value for any given loading condition.

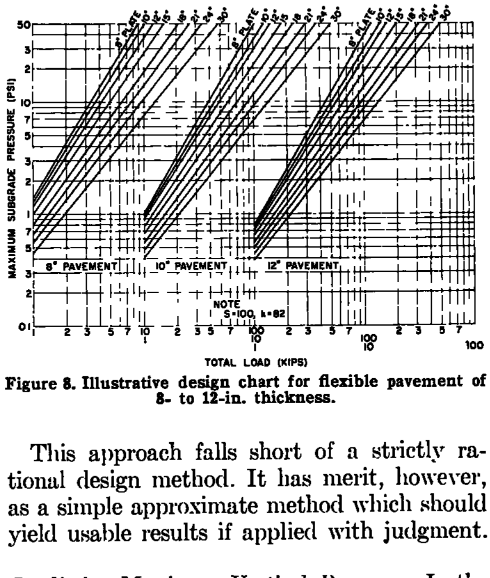


Figure 8. Illustrative design chart for flexible pavement of 8- to 12-in. thickness.

This approach falls short of a strictly rational design method. It has merit, however, as a simple approximate method which should yield usable results if applied with judgment.

Predicting Maximum Vertical Pressure—In the preceding subsection a method of design was suggested in which the vertical pressure on the subgrade would be limited to a given value. In order to use such a method one must be able to determine the maximum subgrade pressure for any given pavement and loading condition. As it would not be feasible to run several series of load-transmission tests for each design problem, the existing data were studied with a view toward setting up graphs or equations from which the maximum pressure can be predicted.

In this study it was assumed that the maximum pressure on the subgrade would be a function of (1) the total load on the pavement, (2) the loaded area, (3) the type of loading medium (rigid plate or pneumatic tire), (4) the pavement thickness, (5) the pavement strength, and (6) the flexibility of the subgrade. The effect of item (6) could not be studied as all tests to date have been run on the same subgrade. All results and conclusions reported in this paper will apply, therefore, only to a similar weak subgrade condition.

In order to reduce the number of variables under consideration at one time the first study was limited to test data from rigid plate loadings on gravel pavements of normal strength (S between 90 and 110 percent) and varying thicknesses. It was found that the relationship

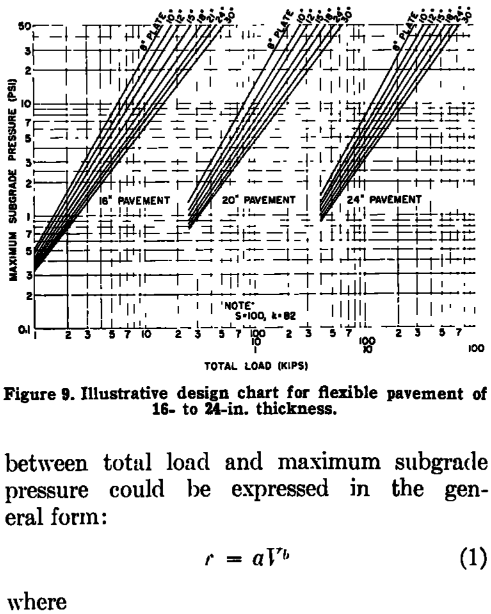


Figure 9. Illustrative design chart for flexible pavement of 16- to 24-in. thickness.

between total load and maximum subgrade pressure could be expressed in the general form:

$$r = aV^b \tag{1}$$

where

r = maximum subgrade pressure, or reaction;
a = a variable coefficient, dependent upon plate size and pavement thickness;
V = total applied vertical load; and
b = a variable exponent, dependent primarily upon plate size and to a slight extent upon pavement thickness.

Empirical relationships were worked out from the test data showing the variation of a and b with plate size and pavement thickness. It then was a simple matter to prepare the logarithmic graphs in Figures 8 and 9.

As these charts were constructed for pavements of normal strength ($S = 100$ percent) it is necessary to correct the computed values if a stronger or weaker pavement section is under consideration. This can be done by use of correction factors taken from the curve in Figure 10. These corrections apply to both the crushed stone and gravel sections tested thus far.

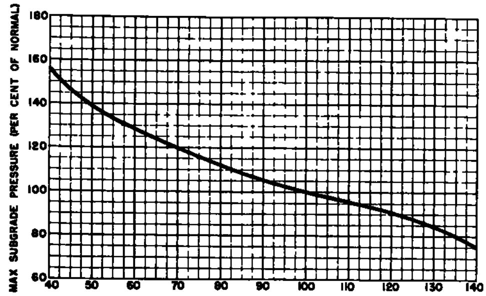


Figure 10. Chart for determining strength index correction factor.

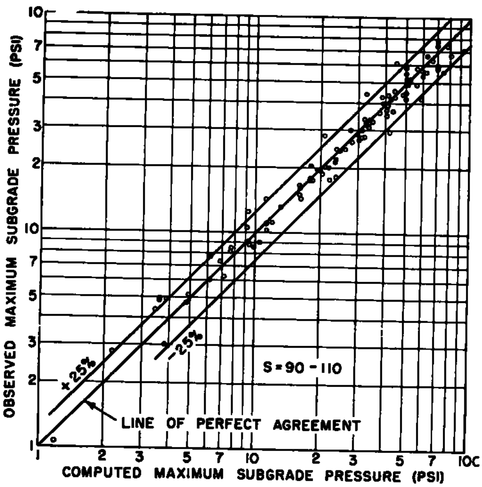


Figure 11. Comparison of computed and observed values of maximum subgrade pressure.

In about 90 percent of the tests on rigid plates, the values predicted from the graphs are within 25 percent of the recorded test values. See Figure 11 for the spread between computed and observed values from normal test sections. Most of the discrepancies are due to the abnormal behavior of certain test sections which, throughout an entire series of loads, consistently performed better or worse than the average of sections of supposedly similar character and strength.

This is illustrated in Figure 12, which compares the computed curve with the recorded results from three "normal" test sections. The computed curve does an excellent job of averaging the recorded results—yet only two-thirds of the individual points fall within 25 percent of the computed values. This simply emphasizes the variations which can be encountered in the stability of pavement sections, using normal construction materials and practices, and should serve as a caution to design and testing engineers.

One might well inquire why these differences in pavement behavior were not predicted or confirmed by the triaxial tests. In most cases

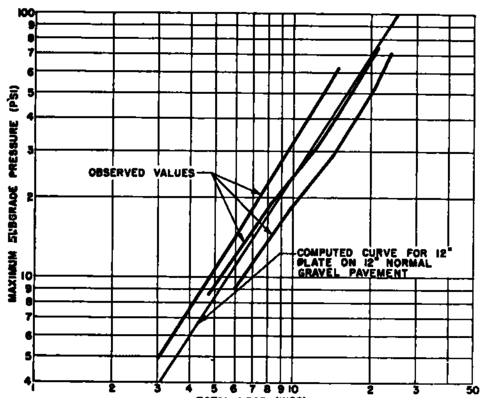


Figure 12. Illustration of erratic results from supposedly similar test sections.

they have been, but in about 20 percent of the sections they have not. Presumably the explanation for the latter lies in the difficulties of accurate sampling and mixture control which were mentioned previously, resulting in some triaxial samples which were not truly representative of the corresponding pavement section. Also, some triaxial tests were run at very low lateral pressures, and thus are of doubtful value in determining strength indices for base courses. These points can be established only through further tests under more closely controlled conditions.

The charts of Figures 8 and 9 are included in this paper only as an example of a possible use of load transmission data in a design problem. The relationships which they portray are applicable only to the weak subgrade and range of paving characteristics actually tested. Also, these particular graphs apply only to rigid-plate loadings. As further test data become available, it will be possible to construct charts of a similar nature applicable to a wide range of tire loadings, pavement strengths, and subgrade strengths.

The limited test information now available on single tires shows subgrade pressure distributions roughly comparable to those obtained with rigid plates of equal area. This is illustrated in Figure 13. In this figure, the results from both types of loading have been interspersed on one graph and the patterns are quite similar. The tire tests were selected at tire pressures such that the loaded contact area was approximately equal to that of the 18-in. plate. In cases where the pavement

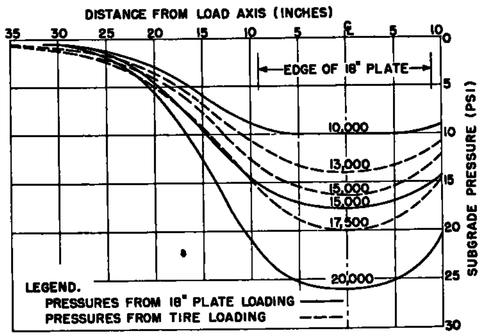


Figure 13. Subgrade pressure distribution from plate and tire loadings with equal loaded areas.

thickness is appreciably less than the plate diameter the distribution curve under the plate is noticeably flatter than that under the tire.

Dual-Tire Tests—Due to delays in procurement of certain loading equipment, the dual-tire tests were confined to the use of two sizes of truck tires at loads which are typical for highways but rather low for airports.

Based on a constant tire-inflation pressure the maximum subgrade reaction due to dual-tire loading logically should lie somewhere between a maximum value computed for the same total load on a single tire and a minimum value computed for half the same total load on a single tire. The degree to which the maximum recorded reaction would approach either the theoretical maximum or minimum should depend upon the pavement thickness, the spacing between dual tires, and possibly other factors. The available data cover only a small range of these variables. Further tests will be necessary, therefore, in order to determine the exact relationship among the various factors.

The tests are sufficient, however, to demonstrate the benefits of dual-tire use, even at close spacings. Referring to Figure 14, the

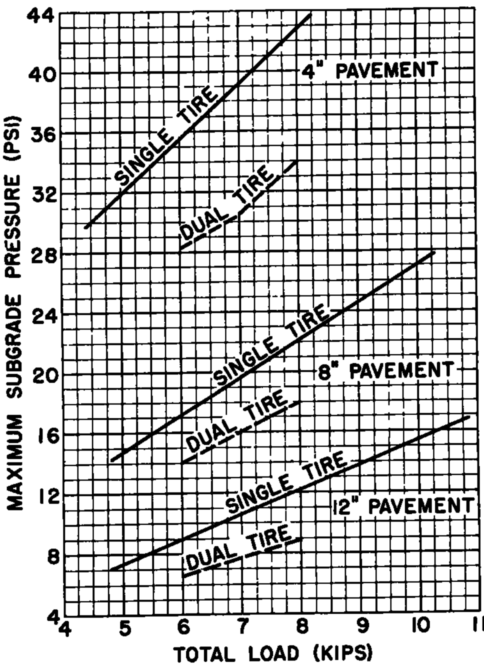


Figure 14. Effect of dual tires.

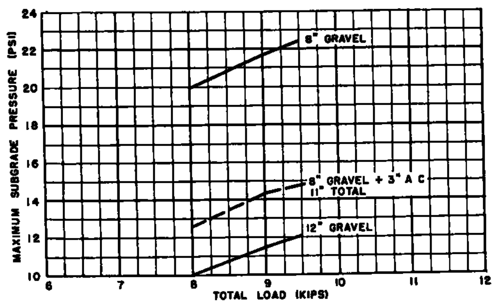


Figure 15. Effect of asphaltic concrete surfacing.

solid lines show average relationships between total load and maximum subgrade pressure as established by tests on single tires. The dotted lines show test results from loads on dual tires at approximately the same inflation pressures. From the standpoint of controlling the maximum subgrade pressure the use of dual tires in these tests was equivalent to a substantial increase in pavement thickness.

Effect of Asphaltic Concrete Surfacing—Each of the test sections discussed thus far was constructed of a single material, usually gravel. A relatively few two-layer sections were tested, with the gravel base covered with 2 to 3 in. of asphaltic concrete surface. These tests were intended to show the load-distributing characteristics of such surfacing as compared to that of the base material. Various investigators and designers have considered an inch of asphaltic concrete as equivalent to 2 or 3 in. of nonbituminous base course.

Here again, the data are not extensive enough to warrant general conclusions. There is some evidence, however, that asphaltic concrete has been somewhat overrated as a base-course material. In the actual loading curves of Figure 15 the performance of the 11-in. composite section is very close to what would be obtained by interpolating an 11-in. gravel section between the 8- and 12-in. ones. All data obtained to date tend to confirm this observation.

It should be borne in mind, however, that the normal gravel sections used in these tests were tested at densities and water contents more favorable than those often encountered in service. With triaxial strengths of the base course almost as high as those of the asphaltic-concrete (at lateral pressures in the range of 20 to 50 psi.) it is not surprising that thin coverings of asphaltic surfacing should fail to show any advantage in load distribution. It is logical that they should do better when compared to weaker base courses. This will be done in future tests.

CONCLUSIONS

The load-transmission-testing program is only well started. The following conclusions are indicated by the assembled data and discussions, but must be considered tentative pending confirmation by further tests:

1. The load-transmission apparatus provides a convenient and relatively accurate means for determining the load-distributing qualities of a flexible-pavement section.

2. For any single load, the vertical pressure pattern on the subgrade shows a helmet-shaped sectional distribution, with the maximum pressure under the center of load.

3. For pavement thicknesses equal to or greater than the width of loaded area, the vertical-pressure distribution on the subgrade is practically independent of the type of loading medium, provided that the loaded area is the same. For thinner pavements, loads on rigid plates show a somewhat flatter section than those on pneumatic tires.

4. Although the ultimate development of a rational design for flexible pavements must await the successful conclusion of extensive stress-distribution studies, it is possible to utilize the load-transmission data in a comparatively simple design method based on a subgrade-strength modulus and a limiting deflection.

5. The maximum subgrade pressure and area of load distribution vary widely with pavement thickness, pavement strength, and loaded area. The possible interrelated effect of subgrade strength has been considered but has not yet been investigated.

6. Within the range of variables tested thus far it is possible to predict approximately the maximum subgrade pressure by means of empirical curves. An extensive program of tests will be needed in order to establish curves for different subgrade, pavement, and loading conditions.

7. In a limited number of tests the use of dual truck tires at normal spacing reduced the maximum subgrade pressure materially from that obtained by application of equal loads through single airplane tires at the same inflation pressure.

8. In a limited number of tests the addition of asphaltic concrete surfacing to a gravel base did not improve the load distribution beyond that obtainable by adding the same thickness of base-course material. This conclusion should not be extended to materials or conditions other than those represented by these tests.

APPENDIX

TABLE A
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
10-in -Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		per cent	*kips*	*in.*	*psi.*
30	8-in. Gravel	45	2.6		9 4
31	8-in Gravel	45	5 1		24
32	8-in Gravel	45	7 6		51
33	8-in. Gravel	45	10 1		88
306	20-in Gravel	92	4 0	0.082	2.8
307	20-in Gravel	92	8 0	0 195	7 3
308	20-in. Gravel	92	12 0	0 333	13.1
309	20-in Gravel	92	16 0	0.532	20
310	20-in Gravel	92	20 0	0.756	27
311	20-in Gravel	92	24 0	1.312	39

TABLE B
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
12-in -Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
64	8-in Gravel	95	3 0	0 099	7.7
65	8-in. Gravel	95	6.0	0.241	17 9
66	8-in Gravel	95	9 0	0.454	33
67	8-in. Gravel	95	12.0	0.713	51
68	8-in. Gravel	95	15.0		78
69	8-in. Gravel	100	2 0	0 069	4.4
70	8-in. Gravel	100	4 0	0 159	8.5
71	8-in Gravel	100	6 0	0.280	20
72	8-in. Gravel	100	8 0	0.450	30
73	8-in Gravel	100	10.0	0.670	43
74	8-in Gravel	100	12.0	0.930	59
102	8-in. Gravel	104	3.0	0.131	6.0
103	8-in. Gravel	104	6.0	0 297	17.7
104	8-in Gravel	104	9 0	0 499	32
105	8-in Gravel	104	12.0	0 779	51
106	8-in. Gravel	104	15.0	1.139	75
107	8-in Gravel	122	3 0	0 118	5 8
108	8-in Gravel	122	6 0	0 241	14.1
109	8-in. Gravel	122	9.0	0 393	25
110	8-in. Gravel	122	12.0	0.586	40
111	8-in. Gravel	122	15.0	0.778	54
112	8-in. Gravel	122	18.0	1.057	75
211	8-in. Stone	135	3.8	0 190	11.3
212	8-in Stone	135	7 2	0 347	22
213	8-in Stone	135	9.8	0 505	33
214	8-in Stone	135	12.6	0.670	44
215	8-in. Stone	135	15.8	0.886	54
216	8-in. Stone	135	18.8	1.092	74
223	8-in. Stone	145	4.6	0 144	9 8
224	8-in. Stone	145	8 6	0.282	20
225	8-in. Stone	145	12 2	0 418	31
226	8-in Stone	145	15.4	0.578	43
227	8-in. Stone	145	18.6	0.788	52
228	8-in. Stone	145	21.8	1 027	77
132	8-in Gravel	70	2.0	0.147	7.4
133	8-in Gravel	70	4 0	0.217	17.2
134	8-in. Gravel	70	6 0	0.455	30
135	8-in. Gravel	70	8 0	0 757	45
136	8-in Gravel	70	10 0	1 137	61
137	8-in. Gravel	70	12.0	1.522	78
144	12-in. Gravel	92	3.0	0.087	4.9
145	12-in. Gravel	92	6 0	0 254	14.3
146	12-in Gravel	92	9 0	0 577	28
147	12-in. Gravel	92	12 0	1 019	44
148	12-in Gravel	92	15.0	1.609	62

TABLE B—(con't)
LOAD TRANSMISSION TEST DATA
Weak Subgrade (k = 82)
12-in.-Plate Loading—No Surface Course

Test No	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
187	12-in Gravel	100	4.7	0.141	8.5
188	12-in Gravel	100	8.3	0.276	17.6
189	12-in. Gravel	100	12.3	0.487	31
190	12-in. Gravel	100	15.5	0.705	44
191	12-in. Gravel	100	18.3	0.940	56
192	12 in Gravel	100	21.3	1.235	74
193	12-in. Gravel	100	5.9	0.170	9.0
194	12-in. Gravel	100	9.7	0.319	18.2
195	12-in Gravel	100	14.2	0.470	29
196	12-in Gravel	100	17.8	0.759	42
197	12-in. Gravel	100	20.9	1.000	56
198	12-in Gravel	100	24.1	1.278	71
217	12-in Stone	133	6.2	0.160	9.3
218	12-in Stone	133	10.4	0.316	20
219	12-in Stone	133	13.6	0.468	30
220	12-in. Stone	133	17.2	0.679	42
221	12-in. Stone	133	20.6	0.951	54
222	12-in Stone	133	24.2	1.210	68
90	16-in Gravel	50	5.0	0.116	5.5
91	16-in Gravel	50	10.0	0.293	14.8
92	16-in. Gravel	50	15.0	0.585	28
93	16-in. Gravel	50	20.0	1.133	45
94	16-in Gravel	50	25.0	2.422	72
312	24-in. Gravel	100	4.0	0.076	1.05
313	24-in Gravel	100	8.0	0.135	3.0
314	24-in Gravel	100	12.0	0.208	6.2
315	24-in Gravel	100	16.0	0.285	10.2
316	24-in Gravel	100	20.0	0.525	14.3
317	24-in. Gravel	100	24.0	0.692	20
318	24-in. Gravel	100	28.0	0.910	26
319	24-in Gravel	100	32.0	1.044	34

TABLE C
LOAD TRANSMISSION TEST DATA
Weak Subgrade (k = 82)
18-in.-Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
138	8-in. Gravel	39	3.0	0.079	6.2
139	8-in. Gravel	39	6.0	0.229	14.8
140	8-in. Gravel	39	9.0	0.470	26
141	8-in. Gravel	39	12.0	0.755	38
142	8-in Gravel	39	15.0	1.046	50
143	8-in Gravel	39	18.0	1.244	62
11	8-in Gravel	45	2.7	0.084	5.0
12	8-in. Gravel	45	5.5	0.132	9.8
13	8-in Gravel	45	6.9	0.216	14.0
14	8-in Gravel	45	8.1	0.240	18.5
15	8-in Gravel	45	10.8	0.312	23
16	8-in. Gravel	45	11.3	0.384	25
17	8-in. Gravel	45	13.4	0.504	37
18	8-in Gravel	45	15.1	0.600	43
19	8-in Gravel	45	16.2	0.696	50
20	8-in Gravel	45	16.7	0.852	60
75	8-in. Gravel	90	3.0	0.071	4.9
76	8-in. Gravel	90	6.0	0.135	9.1
77	8-in Gravel	90	9.0	0.213	15.0
78	8-in Gravel	90	12.0	0.298	22
79	8-in. Gravel	90	15.0	0.392	29
80	8-in. Gravel	90	18.0	0.497	37
81	8-in. Gravel	90	21.0	0.602	45
82	8-in. Gravel	90	24.0	0.729	55
113	8-in Gravel	100	3.0	0.063	4.8
114	8-in. Gravel	100	6.0	—	12.4
115	8-in. Gravel	100	9.0	0.221	16.1
116	8-in. Gravel	100	12.0	0.295	22

TABLE C—(*con't*)
LOAD TRANSMISSION TEST DATA
Weak Subgade (k = 82)
18-in.-Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
117	8-in Gravel	100	15.0	0.377	28
118	8-in Gravel	100	18 0	0 468	35
119	8-in Gravel	100	21 0	0 559	42
120	8-in. Gravel	100	24 0	0 713	54
121	8-in Gravel	100	27 0	0 762	58
122	8-in Gravel	100	30 0	0 880	67
158	8-in Gravel	108	6 0	0 144	10.5
159	8-in Gravel	108	9.0	0.226	16.3
160	8-in Gravel	108	12.0	0.339	25
161	8-in Gravel	108	15 0	0.457	34
162	8-in Gravel	108	18 0	0 596	44
163	8-in Gravel	108	21 0	0 745	55
164	8-in Gravel	108	24 0	0 883	67
199	8-in Gravel	113	6 0	0.150	9.2
200	8-in Gravel	113	11.2	0.285	19 0
201	8-in Gravel	113	16.2	0 424	30
202	8-in. Gravel	113	20.5	0 565	41
203	8-in. Gravel	113	25 9	0.719	52
204	8-in. Gravel	113	30 0	0 890	66
165	8-in Gravel	124	6.0	0.139	10 5
166	8-in Gravel	124	12 0	0 296	24
167	8-in Gravel	124	18.0	0 489	37
168	8-in. Gravel	124	21 0	0 585	45
169	8-in Gravel	124	24 0	0.697	54
95	16-in. Gravel	120	5.0	0.128	4.4
96	16-in Gravel	120	10.0	0.226	10.1
97	16-in. Gravel	120	15.0	0.334	17.1
98	16-in. Gravel	120	20.0	0 485	26
99	16-in. Gravel	120	25.0	0 641	36
100	16-in. Gravel	120	30.0	0 815	47
101	16-in Gravel	120	35 0	1.086	62
179	24-in. Gravel	85	12.0	0.122	5.9
180	24-in Gravel	85	18 0	0.206	10.8
181	24-in. Gravel	85	24 0	0.318	16.8
182	24-in Gravel	85	30.0	0 482	23
183	24-in Gravel	85	36.0	0.639	32
184	24-in. Gravel	85	42.0	0 868	40
185	24-in. Gravel	85	48 0	1.124	50
186	24-in. Gravel	85	54.0	1.589	65

TABLE D
LOAD TRANSMISSION TEST DATA
Weak Subgrade (k = 82)
30-in.-Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
34	8-in Gravel	50	7.0	0 132	8.6
35	8-in. Gravel	50	14.0	0 252	15.7
36	8-in. Gravel	50	21 0	0.468	24
37	8-in. Gravel	50	28 0	0 600	33
38	8-in. Gravel	50	35.0	0 612	43
39	8-in. Gravel	50	42.0	0.756	53
205	8-in Gravel	96	11.9	0 141	8.8
206	8-in. Gravel	96	22.7	0 280	18.8
207	8-in. Gravel	96	32.3	0.396	28
208	8-in. Gravel	96	41.9	0.518	37
209	8-in. Gravel	96	52.7	0.659	49
210	8-in. Gravel	96	62.9	0.848	60
83	8-in Gravel	100	7.0	0.078	5.1
84	8-in. Gravel	100	14.0	0.162	11.0
85	8-in. Gravel	100	21.0	0.244	17.5
86	8-in. Gravel	100	28 0	0.334	24
87	8-in. Gravel	100	35.0	0.440	33
88	8-in Gravel	100	42 0	0.549	42
89	8-in. Gravel	100	49.0	0.669	52

TABLE D—(*con't*)
LOAD TRANSMISSION TEST DATA
Weak Subgrade (k = 82)
30-in.-Plate Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Surface Defl.	Max. Subgrade Pressure
		percent	*kips*	*in.*	*psi.*
123	8-in Gravel	130	6.0	0 082	4 5
124	8-in. Gravel	130	12.0	0.162	9 0
125	8-in. Gravel	130	18 0	0 241	13 5
126	8-in Gravel	130	24.0	0.363	18 8
127	8-in. Gravel	130	30 0	0.389	24
128	8-in. Gravel	130	36.0	0 470	31
129	8 in Gravel	130	42 0	0.557	37
130	8-in Gravel	130	48.0	0 680	45
131	8-in. Gravel	130	54.0	0.782	53
149	16-in Gravel	90	12.0	0 151	8.2
150	16-in Gravel	90	24.0	0.314	18 4
151	16-in. Gravel	90	30 0	0 404	24
152	16-in. Gravel	90	36 0	0 498	30
153	16-in. Gravel	90	42.0	0.602	36
154	16-in. Gravel	90	48.0	0 717	43
155	16-in Gravel	90	54.0	0 821	50
156	16-in Gravel	90	60.0	0.923	57
157	16-in. Gravel	90	66.0	1 063	64
170	24-in Gravel	94	12.0	0.125	4 7
171	24-in Gravel	94	24.0	0 249	11.2
172	24-in. Gravel	94	36 0	0 395	19 5
173	24-in. Gravel	94	48 0	0 562	29
174	24-in Gravel	94	54.0	0.666	34
175	24-in Gravel	94	60 0	0 774	40
176	24-in Gravel	94	66 0	0 909	46
177	24-in. Gravel	94	72 0	1 033	52
178	24-in. Gravel	94	78 0	1.165	58

TABLE E
LOAD TRANSMISSION TEST DATA
Weak Subgrade (k = 82)
36-in. Single Airplane-Tire Loading

Test No.	Base Course	Strength Index	Surface Course	Total Load	Inflation Pressure	Maximum Subg. Pressure
		percent		*kips*	*psi.*	*psi.*
288	4-in Gravel	106		3.0	42	20
289	4-in Gravel	106		6 0	42	34
290	4-in Gravel	106		7.0	42	37
291	4-in. Gravel	106		4 0	57	26
292	4-in. Gravel	106		8 2	57	42
293	4-in Gravel	106		9.0	57	44
294	4-in Gravel	106		5.0	73	32
295	4-in. Gravel	106		10.5	73	52
296	4-in. Gravel	106		12.0	73	57
279	8-in Gravel	103		3 0	42	7 5
280	8-in Gravel	103		6.C	42	15 9
281	8-in Gravel	103		7 0	42	17 9
282	8-in Gravel	103		4.0	57	10 8
283	8-in. Gravel	103		8.2	57	21
284	8-in. Gravel	103		9 0	57	22
285	8-in Gravel	103		5.0	73	13.9
286	8-in Gravel	103		10.5	73	27
287	8-in Gravel	103		12 0	73	31
229	8-in Gravel	112		2.5	73	8 2
230	8-in. Gravel	112		5.0	73	15 6
231	8-in. Gravel	112		7.5	73	23
232	8-in. Gravel	112		10 0	73	29
233	8-in Gravel	112		12 5	73	33
392	8-in Gravel	105	2-in A C.	3.0	42	5.3
393	8-in Gravel	105	2-in. A C	6 0	42	10 8
394	8-in. Gravel	105	2-in. A C.	7.0	42	12 3
395	8-in Gravel	105	2-in A C.	4 0	57	7 2
396	8-in Gravel	105	2-in. A C	8 2	57	14.3
397	8-in. Gravel	105	2-in A C	9 0	57	15 9
398	8-in Gravel	105	2-in A.C	5 0	73	9.4
399	8-in Gravel	105	2-in. A C.	10 5	73	19.1
400	8-in. Gravel	105	2-in A C.	12.0	73	22

TABLE E—(*con't*)
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
36-in. Single Airplane-Tire Loading

Test No.	Base Course	Strength Index	Surface Course	Total Load	Inflation Pressure	Max. Subgrade Pressure
		percent		*kips*	*psi.*	*psi*
320	12-in. Gravel	95		3.0	42	3.7
321	12-in. Gravel	95		6 0	42	8.6
322	12-in. Gravel	95		7 0	42	9.9
323	12-in. Gravel	95		4.0	57	5.1
324	12-in Gravel	95		8.2	57	12.4
325	12-in Gravel	95		9.0	57	14.9
326	12-in Gravel	95		5.0	73	7.5
327	12-in. Gravel	95		10 5	73	16.3
328	12-in Gravel	95		12.0	73	19.8
270	12-in. Gravel	100		3.0	42	2.8
271	12-in Gravel	100		6.0	42	6.1
272	12-in Gravel	100		7 0	42	7 1
273	12-in. Gravel	100		4.0	57	3.9
274	12-in. Gravel	100		8.2	57	9.1
275	12-in. Gravel	100		9.0	57	10.1
276	12-in. Gravel	100		5.0	73	5.0
277	12-in. Gravel	100		10.5	73	13.0
278	12-in Gravel	100		12.0	73	15.1

TABLE F
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
47-in. Single Airplane-Tire Loading—No Surface Course

Test No.	Base Course	Strength Index	Total Load	Inflation Pressure	Max. Subgrade Pressure
		percent	*kips*	*psi.*	*psi.*
243	8-in. Gravel	40	6 5	54	18.0
244	8-in Gravel	40	13.0	54	32
245	8-in Gravel	40	18.0	54	42
246	8-in. Gravel	40	7 5	63	21
247	8-in. Gravel	40	15 0	63	36
248	8-in Gravel	40	19.0	63	43
249	8-in Gravel	40	8.8	73	25
250	8-in Gravel	40	17.5	73	42
251	8-in Gravel	40	20.0	73	46
252	8-in. Gravel	102	6 5	54	16.6
253	8-in Gravel	102	13 0	54	30
254	8-in Gravel	102	18 0	54	38
255	8-in Gravel	102	7.5	63	19 1
256	8-in. Gravel	102	15.0	63	33
257	8-in. Gravel	102	19.0	63	39
258	8-in Gravel	102	8 8	73	22
259	8-in Gravel	102	17.5	73	38
260	8-in Gravel	102	20 0	73	41
261	12-in Gravel	88	6.5	54	10.0
262	12-in Gravel	88	13.0	54	20
263	12-in. Gravel	88	18 0	54	27
264	12-in Gravel	88	7.5	63	11.3
265	12-in Gravel	88	15 0	63	22
266	12-in Gravel	88	19.0	63	28
267	12-in Gravel	88	8 8	73	13.8
268	12-in Gravel	88	17.5	73	26
269	12-in Gravel	88	20.0	73	29
234	16-in. Gravel	100	6 5	54	9.5
235	16-in. Gravel	100	13 0	54	14 2
236	16-in Gravel	100	18.0	54	20
237	16-in. Gravel	100	7.5	63	8.5
238	16-in Gravel	100	15 0	63	16.2
239	16-in. Gravel	100	19 0	63	21
240	16-in. Gravel	100	8.8	73	9 7
241	16-in. Gravel	100	17 5	73	19.6
242	16-in Gravel	100	20 0	73	22

TABLE G
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
8.25 by 20 Dual Truck-Tire Loading

Test No.	Base Course	Strength Index	Surface Course	Total Load	Inflation Pressure	Max. Subgrade Pressure
		percent		*kips*	*psi.*	*psi.*
365	8-in. Gravel	95		6.0	70	14.6
366	8-in Gravel	95		7.0	70	16 3
367	8-in Gravel	95		8 0	70	18 4
368	8-in Gravel	95		9 0	87	21
369	8-in. Gravel	95		10 0	87	23
370	8-in. Gravel	95		10 5	87	24
371	8-in Gravel	95		11.0	104	25
372	8-in Gravel	95		12.0	104	27
373	8-in Gravel	95		13 0	104	29
374	8-in Gravel	75	3-in. A C	6.0	70	10 9
375	8-in. Gravel	75	3-in. A C.	7.0	70	12.9
376	8-in. Gravel	75	3-in A.C.	8 0	70	15.4
377	8-in Gravel	75	3-in. A C.	9.0	87	17.5
378	8-in Gravel	75	3-in A C	10 0	87	19.5
379	8-in Gravel	75	3-in A C.	10 5	87	21
380	8-in Gravel	75	3-in A.C	11.0	104	22
381	8-in Gravel	75	3-in A C.	12 0	104	24
382	8-in Gravel	75	3-in. A C.	13.0	104	27
383	8-in. Gravel	96	3-in A.C.	4.0	70	6.0
384	8-in Gravel	96	3-in A C.	8.0	70	12 4
385	8-in. Gravel	96	3-in. A C	14 0	70	23
386	8-in Gravel	96	3-in A C	5 0	87	7.6
387	8-in. Gravel	96	3-in A C.	10 5	87	16 6
388	8-in Gravel	96	3-in. A C	15.0	87	24
389	8-in. Gravel	96	3-in A C.	6.0	104	9.2
390	8-in Gravel	96	3-in A C.	13 0	104	21
391	8-in Gravel	96	3-in. A C	16.0	104	26

TABLE H
LOAD TRANSMISSION TEST DATA
Weak Subgrade ($k = 82$)
10.00 by 20 Dual Truck-Tire Loading

Test No.	Base Course	Strength Index	Surface Course	Total Load	Inflation Pressure	Max. Subgrade Pressure
		percent		*kips*	*psi*	*psi*
347	4-in Gravel	90		6.0	70	28
348	4-in Gravel	90		7.0	70	30
349	4-in Gravel	90		8.0	70	34
350	4-in Gravel	90		9 0	87	36
351	4-in. Gravel	90		10 0	87	39
352	4-in Gravel	90		10.5	87	40
353	4-in Gravel	90		11.0	104	43
354	4-in Gravel	90		12 0	104	44
355	4-in Gravel	90		13.0	104	46
338	8-in Gravel	105		6 0	70	13 4
339	8-in. Gravel	105		7.0	70	15 6
340	8-in Gravel	105		8 0	70	17 5
341	8-in Gravel	105		9 0	87	20
342	8-in Gravel	105		10 0	87	22
343	8-in Gravel	105		10.5	87	22
344	8-in Gravel	105		11 0	104	24
345	8-in Gravel	105		12 0	104	25
346	8-in Gravel	105		13.0	104	28
356	8-in Gravel	104	3-in. A C	6 0	70	8 4
357	8-in Gravel	104	3-in A C	7.0	70	9 8
358	8-in Gravel	104	3-in A C	8 0	70	11 2
359	8-in Gravel	104	3-in A C.	9 0	87	12 6
360	8-in Gravel	104	3-in A C.	10.0	87	14 3
361	8-in Gravel	104	3-in A C.	10.5	87	14 7
362	8-in Gravel	104	3-in. A C	11 0	104	15 6
363	8-in Gravel	104	3-in A C.	12.0	104	17 0
364	8-in. Gravel	104	3-in. A C	13 0	104	18 6
329	12-in. Gravel	92		6.0	70	6 6
330	12-in Gravel	92		7 0	70	7.7
331	12-in. Gravel	92		8 0	70	8 9
332	12-in Gravel	92		9 0	87	10 0
333	12-in. Gravel	92		10.0	87	11.4
334	12-in Gravel	92		10.5	87	12.1
335	12-in Gravel	92		11.0	104	12.9
336	12-in. Gravel	92		12.0	104	14.1
337	12-in. Gravel	92		13.0	104	15.3

DISCUSSION

W. H. Campen, J. R. Smith, and K. R. Mellerop, *Omaha Testing Laboratories.* A number of the tentative conclusions reported in this paper pertain to fundamental factors involved in the design of flexible pavements. Therefore they are of unusual interest to those who have been researching along this line. We wish to discuss the paper to emphasize a few of the conclusions and to make suggestions relative to future tests and analyses.

Probably the most important conclusion is contained in this statement: "For pavement thicknesses equal to or greater than the width of loaded area the vertical pressure distribution on the subgrade is practically independent of the type of loading medium provided the loaded area is the same." Since the combined thickness of subbase, base, and wearing surface is usually at least equal the width of the loaded area, this conclusion means that a circular steel plate can be used to represent an inflated tire, provided the plate has the same area as the contact area of the tire.

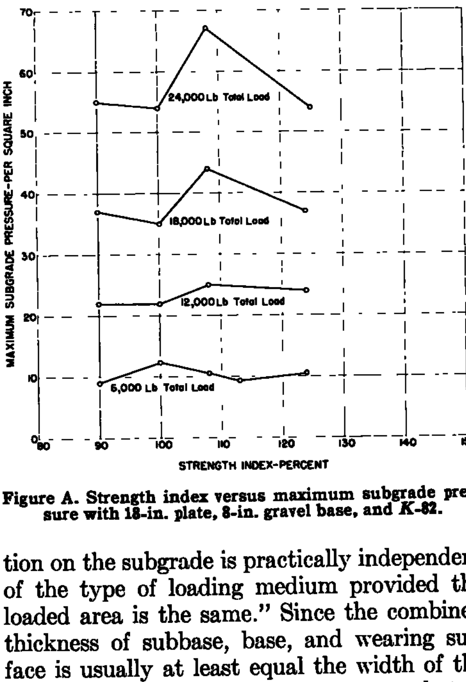


Figure A. Strength index versus maximum subgrade pressure with 18-in. plate, 8-in. gravel base, and *K*-82.

No doubt L. A. Palmer, N. W. McLeod, A. T. Goldbeck, and others join us in welcoming this conclusion, since we have previously assumed this representation to be correct.

The beneficial effect obtained by the use of dual tires at normal spacing is very impressive. In the three examples given in the paper the dual tires increase the load-carrying capacity of the bases by about one-third. For instance, the single tire on a 4-inch base produces a maximum subgrade pressure of 34 psi. when loaded with 6.1 kips, whereas 8 kips must be added to the duals to produce the same subgrade pressure. Similarly, loads of 6.3 and 8 kips, respectively, produce a subgrade pressure of 18 psi. on an 8-in. base. On a 12-in. base the single and dual tires require 5.4 and 7.25 kips, respectively, to produce 8 psi. on the subgrade. This type of information will be very useful in designing for thickness.

Another conclusion states that the load-distributive power of asphaltic-concrete mixtures is about the same as that of high quality gravel bases. This finding is in line with our own limited observations made in connection with evaluations of test sections and actual pavements.

We note also that considerable work has been done to study the effect of base quality, measured by the triaxial device. To bring out the relationship between base quality and distributive power we prepared a number of curves. A set of these is shown in Figure A. On this figure it will be noted that loads were applied on an 8-in. base through an 18-in. plate. Considering the curves as a whole it must be concluded that bases having qualities of from 90 to 125 percent are equally effective in distributing loads. This conclusion is very disappointing, since we are firmly convinced that base quality plays a very important part in distributing loads. We therefore question the method used in rating these bases. It may well be that if the base quality had been determined by the CBR method, or our own method as reported in 1942, a much different correlation might have resulted. We hope the additional correlations will be made before the experimental work is completed and that densities and moisture contents will also be reported.

Apparently no correlation has been established between maximum subgrade pressure and deformation at the top of the base. This correlation is extremely important, since it can be used to show if consolidation or plastic flow occurs in the base and thus produce a greater deformation at the surface of the base than at the top of the subgrade. The amount of surface deformation is a controlling factor, as it must be limited in order to prevent cracking and rutting.

In order to study the relationship of load versus maximum subgrade pressure, we have prepared the curves shown in Figure B. These curves show that the relationship is not lineal, which indicates that the distributive power of the bases changes with applied load. This behavior is very similar to that obtained on runway-layered systems in the field, except that the degree of curvature is less. The difference in curvature is explained by the fact that in the field total surface deformation is plotted against load, whereas in this report subgrade deformation is plotted against load.

The extent to which pressure is distributed laterally to the subgrade is of particular interest, because it confirms some results we obtained on test sections. The object of our tests was to determine the effect of loaded plates on the surfaces adjacent to the plates. In general, it was learned that even with very heavy loads the depressing effect did not reach more than 50-in. beyond the edges of the plates. The tests reported by Herner are not very inclusive on this point, but judging from the examples given it appears that the maximum distance of pressure distribution on the subgrade is about the same as the distance of surface depression in our field tests. Furthermore the shape of the surface depression surrounding the plates is very similar to the shape of the pressure distribution on the corresponding subgrade. If additional tests confirm this correlation, it will be possible to calculate subgrade-pressure distribution by first determining surface depression around the testing plate.

As a final comment on this paper, it is our opinion that the test results are much more useful for studying factors involved in the design of flexible pavement than for deriving formulas for the determination of thicknesses.

Raymond C. Herner, *Closure*—It is indeed gratifying to find that so many of the results obtained on the artificial subgrade in the load-transmission test have been confirmed by the experience of Campen and his co-workers in conducting load tests and designing flexible pavements. This should give us greater confidence in applying the results from the other tests which may be outside the scope of our own personal experience.

Campen, Smith, and Mellerop question the use of the triaxial test as a measure of pavement quality on the basis of the minor deviations in subgrade pressure shown in their Figure A. One would have to agree with them, of course, if these were the only data to be considered. Actually, the plotted data comprise only a small percentage of the total test results and are neither extensive enough nor representative enough to show the major trend. The indicated trend would have been very definite if the graphs had included Test Series 11–20 with a strength index of 45, and Test Series 138–143 with a strength index of 39.

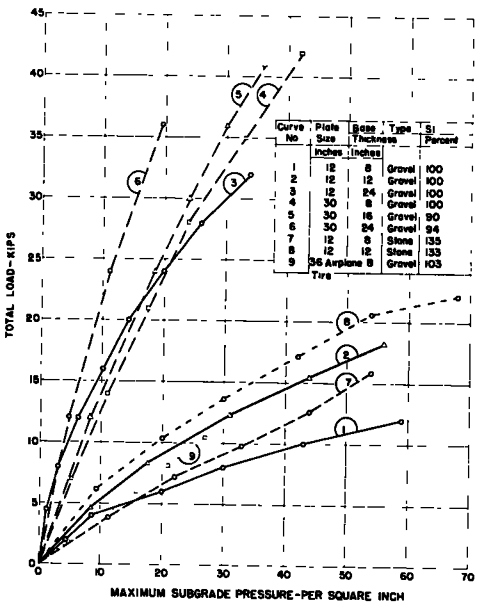
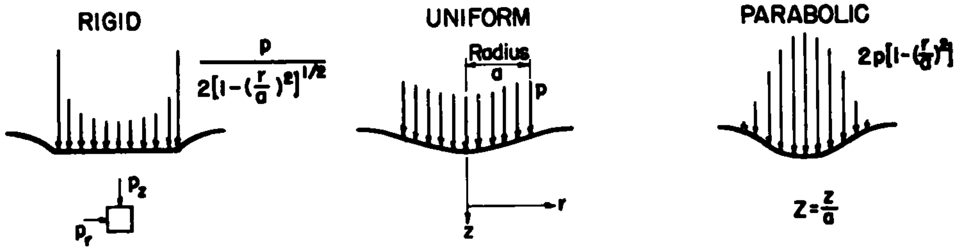


Figure B. Load and subgrade pressure relationships.

Figure 10 of the original paper shows the effect of the strength index when all of the test data from rigid plates are considered together. The average curve is somewhat flat in the center, indicating that the triaxial test is quite sensitive in this area, but steepens at both ends. A reduction of 60 percent in strength index corresponds to an increase of about 60 percent in subgrade pressure. Admittedly, there was considerable scatter in the points from which the curve was constructed, and a possible reason for the abnormal behavior of certain sections was discussed in the paper.

The writer heartily agrees that the load-transmission-test results should be considered as something more than an approach to another empirical-design formula. On the contrary, they represent basic information which can be studied to advantage by designers, regardless of their choice of design method.

E. S. BARBER, *Professor of Civil Engineering, University of Maryland*—Extensive data on measured pressures transmitted through granular base courses are presented. It is interesting to compare these with values calculated from elastic theory even though granular bases



$$\text{SETTLEMENT FACTOR}, F = \frac{\text{SETTLEMENT}}{pa \times \text{STRAIN COEFFICIENT}}$$

POISSON'S RATIO $= \mu$

Rigid:

$$\frac{p_z}{p} = \frac{1.5Z^2 + 0.5}{(1+Z^2)^2}$$

$$\frac{p_r}{p} = \frac{1+2\mu-(1-2\mu)Z^2}{4(1+Z^2)^2}$$

$$F = \frac{(1-\mu^2)}{2}\left[\frac{\pi}{2} + \sin^{-1}\frac{1-Z^2}{1+Z^2}\right] + (1+\mu)\frac{Z}{2(1+Z^2)}$$

Uniform:

$$\frac{p_z}{p} = 1 - \frac{Z^3}{(1+Z^2)^{3/2}}$$

$$\frac{p_r}{p} = 0.5+\mu-\frac{(1+\mu)Z}{(1+Z^2)^{1/2}} + \frac{0.5Z^3}{(1+Z^2)^{3/2}}$$

$$F = (2-2\mu^2)(1+Z^2) - (1+\mu)\frac{Z^2}{(1+Z^2)^{1/2}} + (2\mu^2+\mu-1)Z$$

Parabolic:

$$\frac{p_z}{p} = 2-4Z^2+\frac{4Z^3}{(1+Z^2)^{1/2}}$$

$$\frac{p_r}{p} = 1+2\mu+(6+4\mu)Z^2 - \frac{4Z+6Z^3+4\mu(Z+Z^3)}{(1+Z^2)^{1/2}}$$

$$F = (1-\mu^2)\frac{8}{3}\left[(1+Z^2)^{3/2}-Z^3-1.5Z\right] + (1+\mu)4\left[Z^3+.5Z-Z^2(1+Z^2)^{1/2}\right]$$

AT Z = 0

$$F = (1-\mu^2)\frac{\pi}{2} \qquad F = (1-\mu^2)2 \qquad F = (1-\mu^2)\frac{8}{3}$$

Figure A. Formulas for stresses and displacements on axis under vertical stress over circular area at surface.

have a variable modulus of elasticity, E_p, not anticipated in ordinary elastic theory.

Elastic formulas are shown in Figure A where strain coefficient is the reciprocal of modulus of elasticity Using data from Figure 8 for $p = 30$ psi., $a = 7.5$ in. and pavement thickness $z = 8$ in., E_p was calculated as 5000 psi. for Poisson's ratio $= 0$ from an influence chart[1] for an elastic layer supported by a heavy liquid which the mechanical sub-

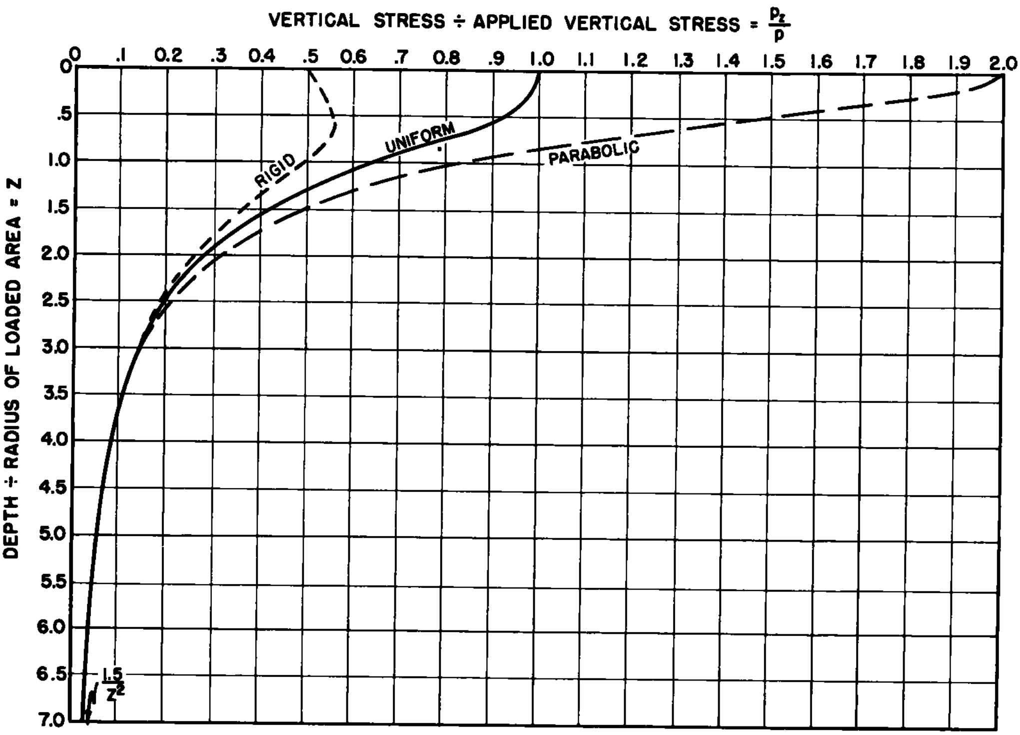


Figure B. Vertical stresses on axis below vertical stress over circular area at surface.

grade simulates. Since the subgrade coefficient, $k = \frac{\text{pressure}}{\text{settlement}}$, the corresponding modulus of elasticity, E_s, is proportional to ka. As an approximation, E_s is taken as $2ka$. Using these values of E, transmitted pressures, p_z, were calculated for various plate diameters and pavement thicknesses for $p = 30$ psi. The flexure of the base is allowed for by taking the effective depth as $z\sqrt[3]{E_p/E_s}$.[2] Thus, for $p = 30$ psi., $a = 15$ in. and $z = 16$ in.; $E_s = 2 \times 82 \times 15 = 2{,}460$, $z\sqrt[3]{E_p/E_s} = 16\sqrt[3]{\frac{5000}{2460}} = 20.3$, $Z = \frac{20.3}{15} = 1.35$, $p_z/p = 0.40$ from Figure B, and $p_z = .40 \times 30 = 12.0$. This is plotted in Figure C with other calculated values and observed values from Figures 8 and 9. A reasonable correlation with theory is indicated even though the cube-root factor is not as accurate for stress[3] as for displacement and the variation of E with base thickness was disregarded.

The same theory is useful in rigid-pavement design. For example, the effect of base courses on k is of interest. Values of $k = \frac{\text{stress}}{\text{settlement}}$ calculated with the aid of Figure D are shown in the top of Figure E. It is seen that, for the 30-in. diameter often used, k is increased only

[1] Influence Charts for Concrete Pavements by Gerald Picket and G. K. Ray ASCE *Proceedings* April 1950, p. 1.

[2] The Theory of Stresses and Displacements in Layered Systems by Donald M. Burmister, HRB PROCEEDINGS 1943, Discussion p. 146.

[3] Some Numerical Solutions of Stresses in Two- and Three-Layered Systems by R. J. Hank and F. H. Scrivner, HRB PROCEEDINGS 1948, p. 457.

ment stress by providing a more uniform k and may be essential to prevent pumping. The lower part of Figure E shows the effect of increased subgrade rigidity with depth which limits the reduction of k with increased plate diameters.[4]

Raymond C. Herner, *Closure*—Professor Barber's attempted correlation of load-transmission data with values calculated from

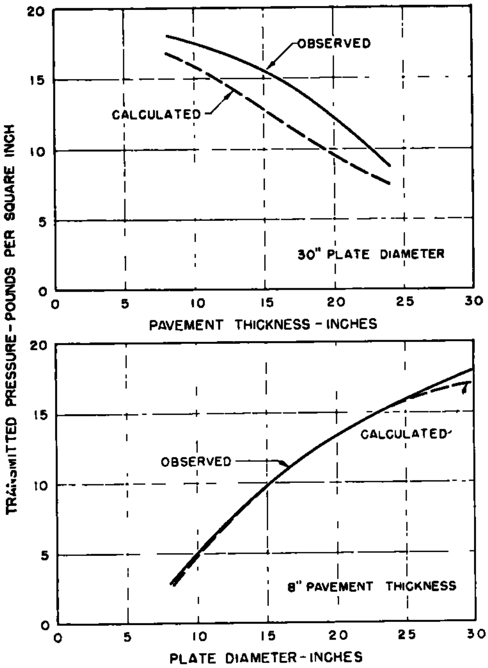


Figure C. Comparison of observed and calculated pressures from applied pressure of 30 lb. per sq. in.

moderately by thin base courses.[4] However, base-course construction may reduce pave-elastic theory is extremely interesting and should be encouraged. One should not be too disappointed, however, if such attempts are not always successful. Our own analyses have shown that the relationship between the external load and the internal stress at a given point varies not only with the material under test but also with the applied load. It is an exceedingly difficult task, therefore, to establish any general formula and set of as-

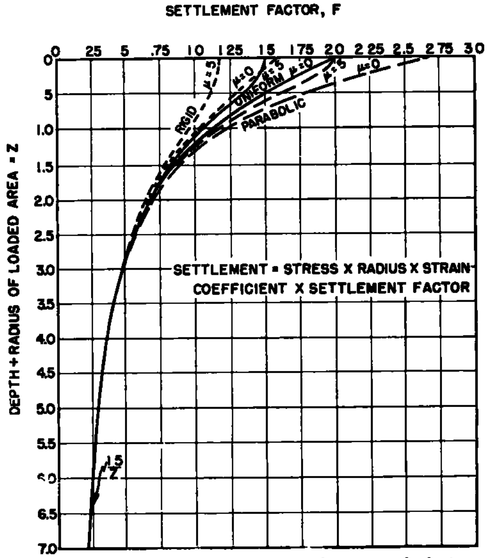


Figure D. Settlement factors on axis below vertical stress over circular area at surface.

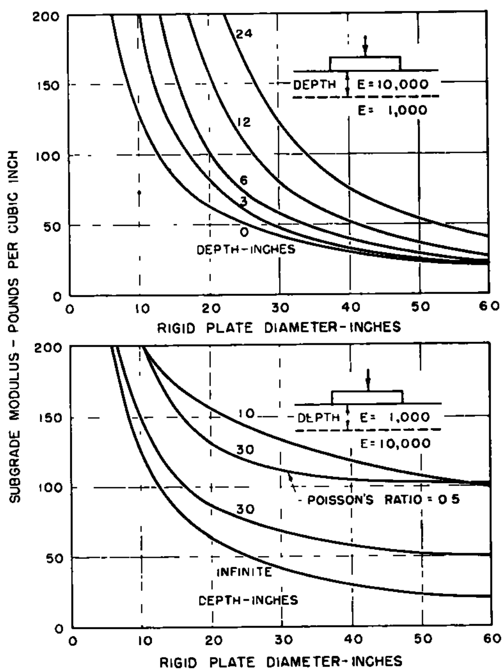


Figure E. Effect of layered system on subgrade modulus: Poisson's ratio = 0, except as noted.

sumptions which will give the correct answer under all conditions.

[4] The Structural Design of Concrete Pavements by L. W. Teller and Earl C. Sutherland, *Public Roads*, June 1943, p. 167.