Effect of Base-Course Quality on Load Transmission Through Flexible Pavements

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REPRESENTATIVE test data from the Load Transmission Project illustrate the relative effectiveness of typical base and subbase materials in protecting the subgrade from overstress. Angular materials such as crushed stone or crushed slag are particularly effective in the lower layers of the pavement where their shearing resistance is greatly augmented by the confining effect of the upper layers.

Relative effectiveness of a wide variety of materials can be predicted qualitatively by reference to triaxial tests, and there is hope that such correlation can be established on a quantitative basis. It is important that the triaxial loading rate and the condition of the specimens at time of test be consistent with service conditions expected in the pavement.

Knowledge of the comparative values of available paving materials will enable the designer to establish alternate designs of flexible pavements which are truly equivalent. Natural competitive forces then will determine the best design for a given construction area. Significant savings may be possible by intelligent selection of the most economical materials.

● MOST organizations engaged in the design and construction of flexible pavements have developed empirical or semi-empirical methods for determining the total thickness of pavement considered necessary to protect the subgrade from high stresses imposed on the pavement surface. They also have prepared specifications for the surface, base, and subbase materials in order to be sure that the various layers of the pavement will have the minimum strength necessary to resist internal failure. Surprisingly little thought appears to have been given to the possibility of decreasing the total pavement thickness by using materials of a quality somewhat higher than these minimum requirements.

In fairness, it should be noted that a few individuals have consistently championed the cause of pavement quality versus thickness, and at least one organization has made an effort to incorporate this factor into its design method.* Also, when designs are based on load-bearing tests of trial pavement sections, the effect of pavement quality is included automatically, provided the trial section uses the same materials contemplated for possible use in construction. Despite these encouraging exceptions, however, the effect of pavement quality has been generally ignored in the consideration of pavement thickness.

Through the operation of the Load Transmission Project by the Civil Aeronautics Administration and by the Navy Bureau of Yards and Docks,* quantitative data on the effectiveness of typical base and subbase materials are now becoming available. A study of triaxial tests of the same materials also indicates the encouraging possibility of direct correlation between the two test procedures. This would mean that the value of a material in protecting the subgrade from overstress could be determined by use of the comparatively simple triaxial test. Such information, combined with cost data on available materials, would enable the design engineer to select the most economical design for any given condition.

Although the testing and analysis of data are far from complete, sufficient progress has been made to warrant a progress report at this time. The purposes of this paper are (1) to focus attention on the need for considering

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* The CAA Airport Paving Manual (1948) states, "In instances where it might prove economical from a construction standpoint, the depth of bituminous surface may be increased and substituted for base course on the ratio of 1½ inches of base for 1 inch of surface. Also, the thickness of base course may be increased and substituted for subbase on the ratio of 1½ inches of subbase for 1 inch of base."

* Since February 15, 1954, the project has been sponsored by BuDocks under a research contract.

pavement quality as well as thickness, (2) to indicate quantitatively the comparative effectiveness of some common paving materials when used as base or subbase, and (3) to indicate the possibilities of correlating triaxial and load transmission test results from a wide variety of materials. More complete data and analyses will appear in subsequent reports.

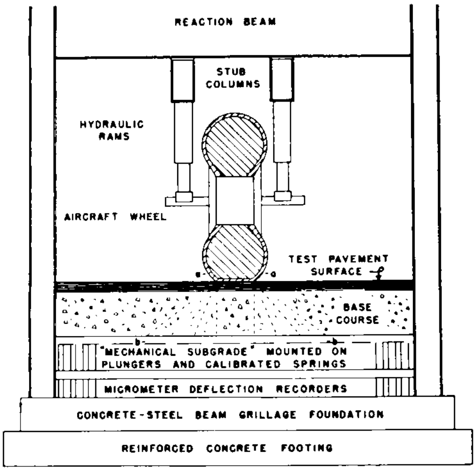
TESTING APPARATUS AND METHODS

The Load Transmission Project is being carried out at the CAA Technical Development and Evaluation Center at Indianapolis. In simplest terms, the project consists of a series of static loading tests on full-scale pavement sections, conducted under laboratory conditions. The natural subgrade is replaced by a flexible platform ten feet square. This is composed of 3,600 steel plungers, placed in 60 rows of 60 each, each plunger being supported by a calibrated steel spring. The sides of the platform are confined by wooden bulkheads. Provisions are made for measuring the deflection of each plunger under any loading condition.

In operation, a test pavement is constructed on the artificial subgrade, load is applied through an airplane tire or rigid plate, and deflections of the individual subgrade segments are measured. Deflections are converted to values of vertical stress by means of calibration curves. Fig. 1 is a schematic sketch of the apparatus and Fig. 2 is a general photograph of the artificial subgrade with a partial pavement section in place and a tire in loading position.

If the contact area of the loading medium is simple and symmetrical in shape—as in the case of a circular plate or the oval imprint of an airplane tire—it is necessary to measure the subgrade pressures only along the major axes of loading in order to get an adequate picture of the pressure distribution. Fig. 3 is a typical graph showing the longitudinal and transverse distribution of vertical pressure on top of the artificial subgrade caused by a loaded airplane tire on top of the pavement section.

Had the pavement been more effective in distributing the applied load—due to greater thickness of the same material or use of a better material—the load would have been spread over a larger area of subgrade and the maximum stress under the center of load would have been less. This maximum subgrade reaction (*r*) then becomes a convenient inverse measure of pavement effectiveness under any given loading condition. Conversely, the load required to produce a given value of *r* will give a direct comparison of pavement effectiveness. Although the value of *r* for any specific test is a function of many variables, this report will be concerned only with the effect of pavement quality versus pavement thickness.



LOAD TRANSMISSION TESTING RIG

A WHEEL LOAD APPLIED TO THE PAVEMENT SURFACE OVER AN AREA a--a IS TRANSMITTED AND DISTRIBUTED THRU THE SURFACE AND BASE COURSE. THIS PRODUCES VARYING PRESSURES AND DEFLECTIONS OVER A LARGER AREA b--b ON THE SUBGRADE. IN THIS TEST THE NATURAL SUBGRADE IS REPLACED BY A "MECHANICAL SUBGRADE" OR FLOORING COMPOSED OF 3600 SMALL STEEL PLATES. THESE ARE MOUNTED ON PLUNGERS AND CALIBRATED SPRINGS IN SUCH A MANNER AS TO SIMULATE A SUBGRADE OF THE DESIRED STRENGTH AND TO PERMIT MEASUREMENT OF THE UNIT PRESSURES TRANSMITTED TO THE SUBGRADE.

Figure 1

The triaxial test is used to measure the physical strength of the materials used in the load transmission testing program. An attempt is made to prepare triaxial samples corresponding to each pavement test section in gradation, density, and moisture content. Specimens composed of granular materials are usually constructed 10 inches in diameter and 20 inches high, but most of the asphaltic concrete specimens have been 4 inches in diameter by 8 inches in height.

In the early part of the program an attempt was made to determine the cohesion and angle of internal friction of the materials by means of the Mohr diagram. In most cases, however, these values were indeterminate because of the fact that the Mohr envelope was curved. It was decided, therefore, that the simplest

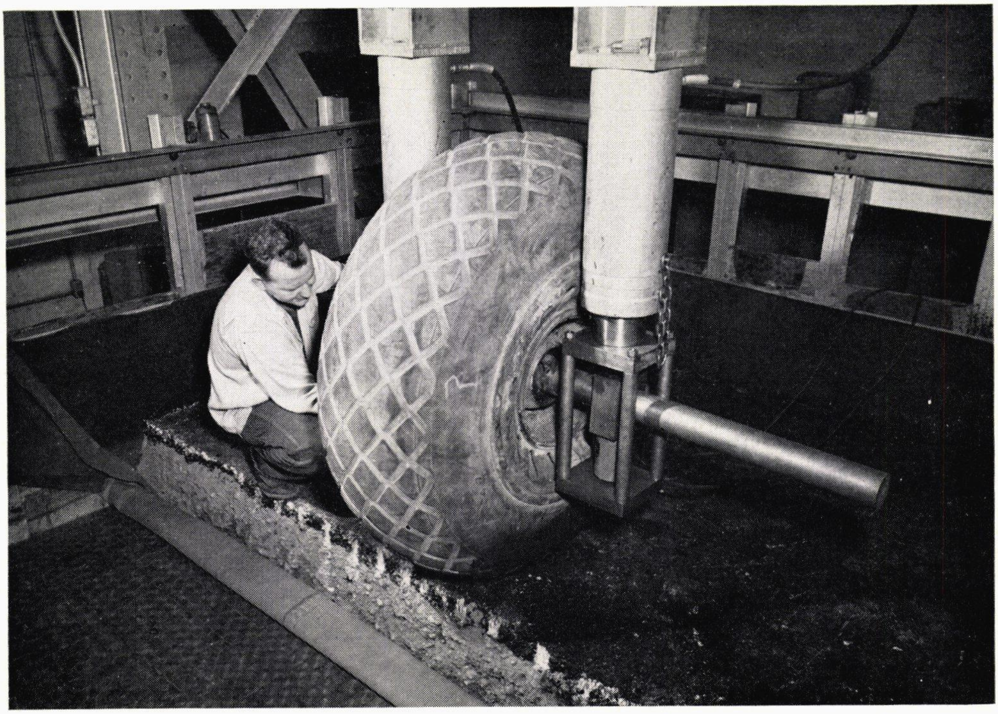


Figure 2. General view—load transmission apparatus.

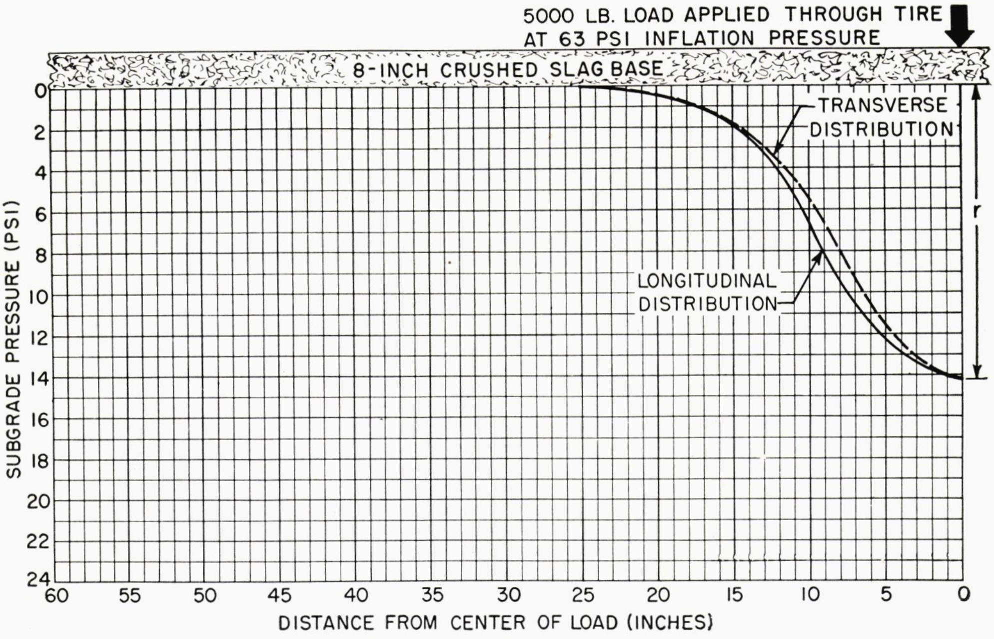


Figure 3. Typical pressure distribution pattern.

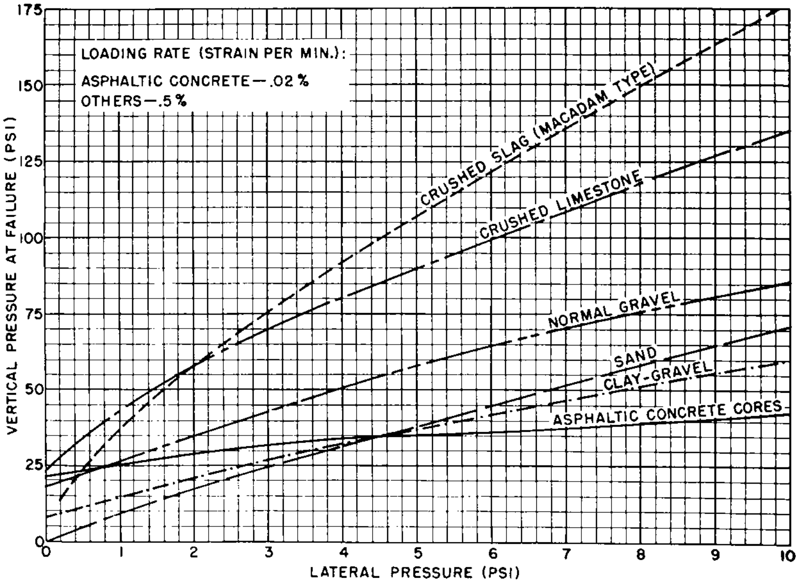


Figure 4. Triaxial test data—relationship of principal stresses.

method of describing the strength characteristics of a material was to construct graphs showing the relationship of principal stresses at failure. Typical curves are given in Fig. 4.

The above information has been condensed from material appearing in previous reports (*1*, *2*, *3*, *4*) to which the reader is referred for more complete information.

DESCRIPTION OF MATERIALS TESTED

Normal Gravel

The material used in a large number of the tests was a partially crushed pit gravel, reasonably well graded, with practically 100 per cent passing the 1-inch sieve and an average of about 10 per cent passing the No. 200 sieve (by washing). It is typical of base course material used extensively in the United States. For this reason, it was chosen as the "standard" material against which other materials were rated.

This proved to be a rather unfortunate choice, as there was considerable variation in gradation of the gravel received in different shipments. This, together with variations in density and moisture content which occurred in mixing and placement of some pavement sections, resulted in rather wide strength variations in the "standard" material. This makes it necessary to exercise great care in using for direct comparison only those gravel pavements which actually were normal in composition and behavior. In this paper the descriptive term "weak" has been added to a couple of gravel sections which were definitely below average in the triaxial tests.

Clay-Gravel

In addition to the gravel sections which were weak from accidental causes, there were a few which were made intentionally weak by addition of surplus fine material and a higher amount of water. These were intended to represent the poorer clay-gravels often used for subbase—and sometimes allowed in base course construction.

Sand

The sand used in these tests was a relatively clean concrete sand, selected to represent fine non-cohesive materials. It would pass many subbase specifications.

Crushed Stone

The crushed limestone was well graded, with a top size of 1½ inches and about 10 per cent pasing the No. 200 sieve. Although possessing little true cohesion as used, it showed high strength at low lateral pressures in the triaxial test because of good particle interlock.

A blend of three fractional sizes of stone was used in these tests in order to insure uniformity. The resultant material was typical of a well-graded, high-grade crushed stone base course.

Crushed Slag

The crushed slag was of the same top size as the crushed limestone, but with practically no minus-200 material and with no cohesion. The particles also were more blocky in shape.

In order to avoid segregation due to lack of cohesion the slag was placed in two sizes, using a macadam type of construction. The coarse fraction, 1-inch to 1½-inch size, was placed in 4-inch layers; then fine slag, all passing the No. 4 sieve, was vibrated into place. The resulting mixture had a dry density of about 130 pounds per cubic foot, which was adequate for a gap-graded material practically devoid of fines passing the No. 200 sieve. The triaxial specimens would hardly stand when unconfined but increased rapidly in strength as the lateral pressure was increased.

Asphaltic Concrete

A rather open-graded binder-course material was used for the asphaltic concrete pavement tests reported in this paper. It was obtained from a commercial hot-mix plant in regular production for street and highway work. The aggregate for this mixture was a blend of partially crushed gravel and sand. The resulting blend was gap-graded, with very little material in the No. 4 to No. 8 range and very little passing the No. 200 sieve. Five per cent of 80-penetration asphalt cement was used. A density of 145 pounds per cubic foot was obtained by means of vibratory compaction and pneumatic tamping.

The average Marshall stability of the mixture was 1,170, with a flow of 28 which is higher than allowed by many specifications. Triaxial specimens, tested at room temperature, showed a wide variation in strength when tested at different rates of loading. This will be discussed later.

EFFECT OF PAVEMENT QUALITY ON SUBGRADE PRESSURES

Fig. 5 portrays graphically the effect of pavement quality in reducing the vertical pressures transmitted to the subgrade. Each curve shows the measured distribution of subgrade pressure, along the longitudinal axis of the tire contact area, for a different test pavement. In each case the applied load is 20 kips, the tire inflation pressure is 100 psi, and the total pavement thickness is 24 inches.

Each curve represents data from only one

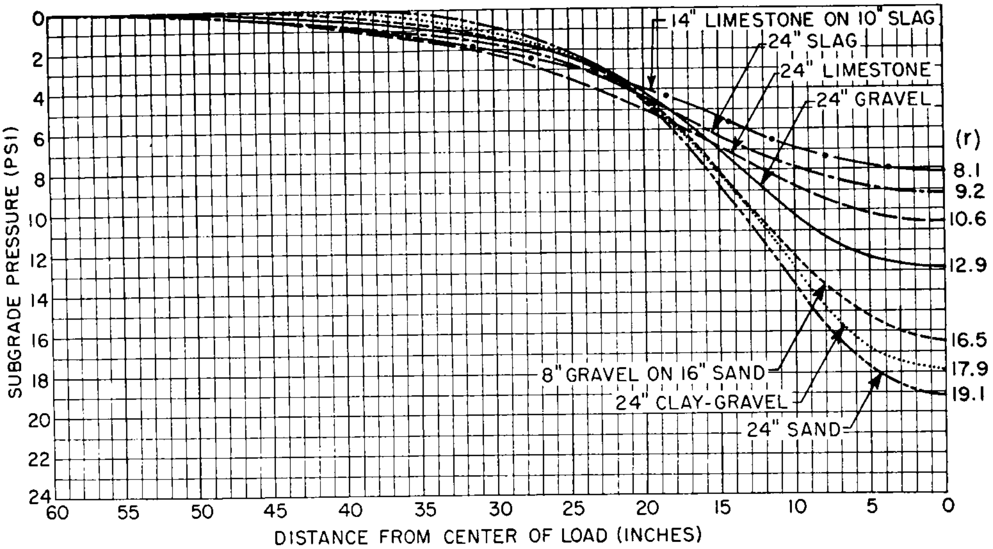


Figure 5. Longitudinal load distribution pattern for various base course materials—24-inch thickness, 20-kip load, 100-psi inflation pressure.

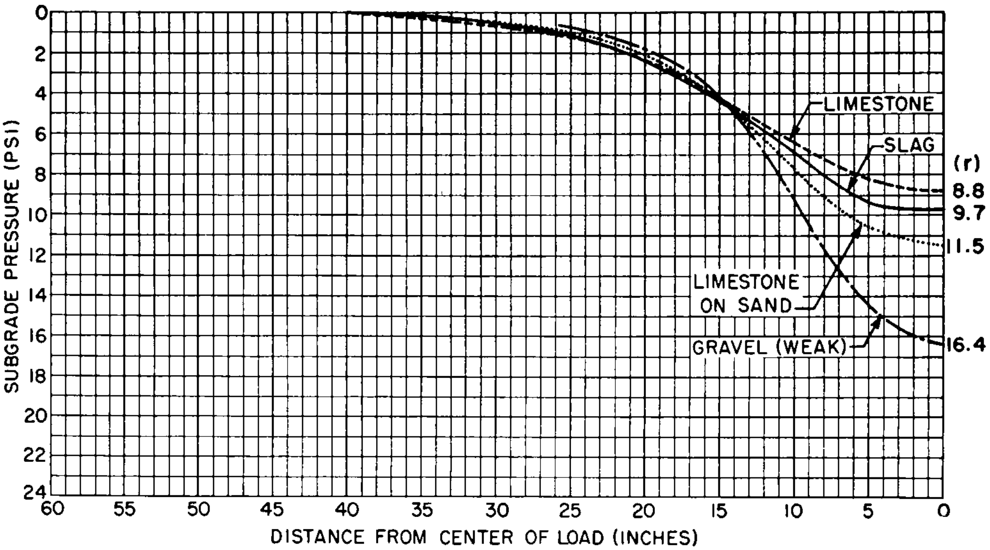


Figure 6. Longitudinal load distribution pattern for various base course materials—16-inch thickness, 10-kip load, 100-psi inflation pressure.

test section, and may be subject to minor revision as more test data are accumulated and averaged. The indicated differences in performance are large enough, however, to overshadow any probable experimental error. Moreover, the differences appear very logical when one considers the nature of the materials.

The pavement section composed entirely of sand, with consistently low strength at all confining pressures in the triaxial test, is also the weakest in the load transmission test. The clay-gravel, with excess fines and moisture, is little better. On the other hand, the crushed slag and limestone—with sharp angular particles—show up well under the high degree of confinement present in the 24-inch depth of pavement. The normal gravel is intermediate in effectiveness, and the composite section with an 8-inch gravel base on a 16-inch sand subbase very properly falls between the values for these two materials.

Similar information from 16-inch pavement sections is given in Fig. 6. A 10-kip load is used for these comparisons.

Here again, the crushed slag and stone are the most effective materials but have changed places in the rating. Although this difference is minor and may not be significant, it is logical in view of the lower degree of confinement in the 16-inch pavement and the cohesionless nature of the slag. The weak gravel section (density a little low and moisture a little high) gave the poorest performance of the 16-inch group, while the composite stone and sand section fell into its logical intermediate position.

The differences found in comparisons of 8-inch pavements (Fig. 7) are not quite so great as those found in the thicker pavements. This is only natural, as the thin pavement does not provide sufficient confinement to bring out the potential effectiveness of the angular crushed slag and limestone materials. The crushed stone still is the best material, due to its good interlock even at low degrees of confinement. The slag, however, is now hardly as effective as the normal gravel. The weak gravel and clay-gravel are relatively ineffective. Although there is no corresponding section constructed of sand, there are data available from tests at other inflation pressures indicating that such a section would be very ineffective also.

The performance of the 8-inch asphaltic concrete section barely equalled that expected of normal gravel, which confirms limited test results previously reported (*4*). These results, whicy may prove surprising to many, may be explained by the differences in properties of the various materials tested. The granular materials, which support loads largely through interaction between discrete particles, tend to

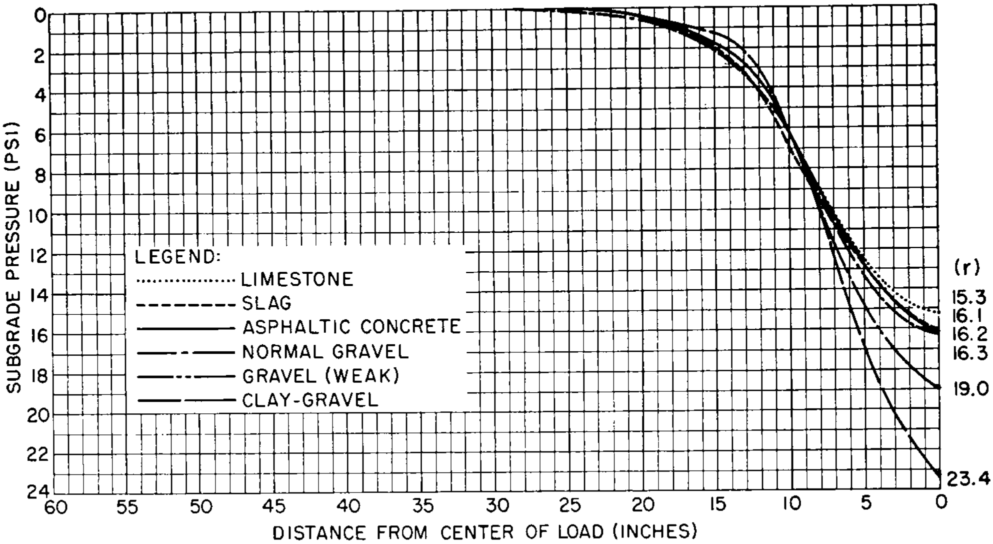


Figure 7. Longitudinal load distribution pattern for various base course materials—8-inch thickness, 5-kip load, 100 psi inflation pressure.

behave in a semi-elastic manner when loaded. Movement ceases soon after loading, and there is measurable rebound when the load is removed. The asphaltic concrete, on the other hand, behaves as a very viscous solid. On application of a static load, as in the load transmission test, plastic flow may continue for several hours before a state of equilibrium is approached. In triaxial tests, with load applied at a constant rate of strain, there is a wide variation in apparent shear strength, depending upon the loading rate selected.

This phenomenon of viscous flow in asphaltic concrete has been discussed quite thoroughly in excellent papers by Nijboer (*5*) and McLeod (*6*). Nijboer gives values of dynamic shear moduli more than five times as high as those for static loads. It is apparent, therefore, that the quantitative data on paving materials presented herein can be applied directly only to those design problems where the critical loads are either static or slow-moving.

CORRELATION OF LOAD TRANSMISSION AND TRIAXIAL TEST RESULTS

A further study of Fig. 4 reveals the excellent manner in which the protection of the subgrade by various pavement sections has been predicted by triaxial tests of the same materials. The strength curves for crushed stone, normal gravel, and sand are generally parallel and definitely separated throughout the range of lateral pressures used in the triaxial tests. If these tests are indicative of what may be expected in the pavement loading tests, the crushed stone should give the best performance of these three materials, regardless of pavement depth, and the sand should give the worst. It has been shown that this was consistently true.

The triaxial curve for slag starts low, crosses the gravel curve at about 0.5 psi lateral pressure, and continues upward to cross the crushed stone curve at about 2 psi lateral pressure. Referring again to the load transmission data given in Figs. 5 to 7, it appears that comparative performances of 8-inch pavements could be predicted qualitatively at least by running triaxial tests of the materials at a lateral pressure of about 0.5 psi. Similar comparisons for 16-inch pavement could be made by running tests at about 1.5 psi, while comparisons for 24-inch pavements would require triaxial tests at about 2.5 psi.

In the preceding paragraph an attempt has been made to select a single lateral pressure in the triaxial test which reflects the average over-all degree of confinement existing in a pavement of given depth. This would be applicable only to a single-layered pavement, using the same material for its entire depth. In multiple-layered pavements, composed of

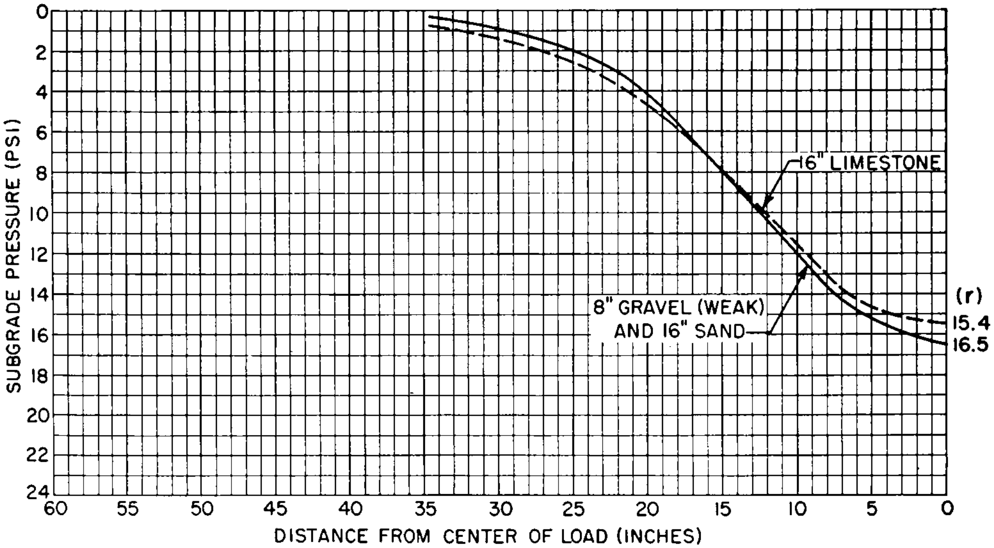


Figure 8. Quality vs. thickness for equal load distribution—20-kip load, 100 psi tire pressure.

different surface, base, and subbase materials, it will be necessary to establish the lateral pressure corresponding to the degree of confinement at any depth in the pavement structure. After evaluating each layer of material according to its position in the pavement, it then will be necessary to combine these figures into an over-all rating for the entire pavement structure.

Enough work has been done to warrant a hope that such a quantitative method of evaluation can be worked out, and that it will be simple enough for practical use. More testing and analysis remain to be done, however, before this phase of the project can be reported.

When asphaltic triaxial specimens were tested at the same rate of strain (0.5 percent per minute) used for granular materials, the apparent strengths were too high for correlation with load transmission test data. This was due to the viscous effect previously mentioned. Through a series of supplementary tests it was found that increasing the rate of strain by a factor of 10 increased the apparent strength of the asphaltic specimens by 50 to 100 percent, whereas a similar change in rate for granular specimens increased the values by only about 10 to 20 percent. In order to obtain comparable results it was found necessary to reduce the rate of strain to about 0.02 percent per minute when testing asphaltic samples. The asphaltic concrete curve shown in Fig. 4 was obtained by interpolating between tests run at higher and lower rates of strain.

ECONOMIC SIGNIFICANCE OF DIFFERENCES IN BASE COURSE QUALITY

The comparative effectiveness of different materials is illustrated very forcibly in Fig. 8. Here are two pavements supporting the same load (20 kips) with the same tire inflation pressure (100 psi) and yielding very nearly the same pressure pattern on the subgrade. One pavement, of conventional construction, is 24 inches thick; the other, using superior material, is only 16 inches thick but is doing a slightly better job of protecting the subgrade.

By interpolating between test values given in this paper—and with some reference to other test data not included herein—it is possible to arrive at thicknesses of different materials and combinations of materials which might be considered equivalent in value under a given design condition. Fig. 9 shows such equivalent designs for a 15-kip load on a soft subgrade, the subgrade pressure to be limited to a maximum of 12 psi. Estimated costs per square yard for each type of construction are given also. These are based on prices in the

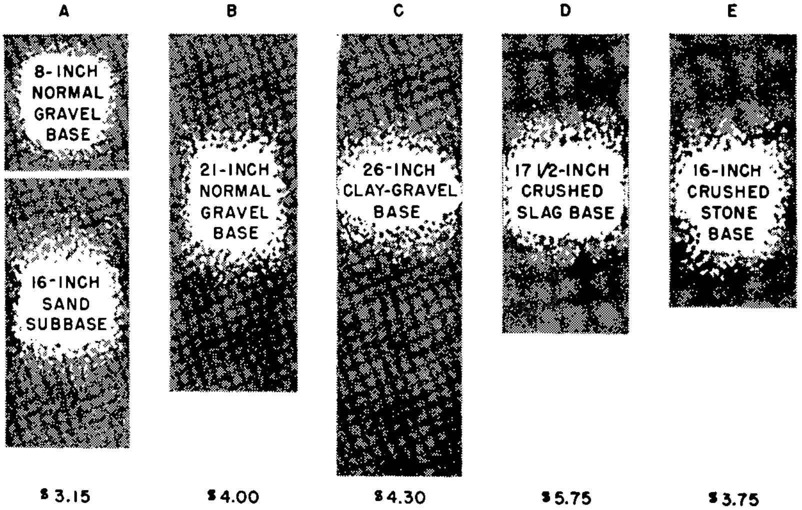


Figure 9. Economic comparison of equivalent pavement sections.

Indianapolis area, and are intended only for purposes of illustration.

Because of the fact that sand is very cheap in this area, being a plentiful byproduct of gravel production, the composite section using sand as a subbase is estimated as the cheapest construction shown. Crushed stone should be competitive with gravel, even at a higher price per unit of volume. There would be no advantage in specifying clay-gravel in this area, as the natural product is relatively clean and the price differential is small. The crushed slag would be out of the question due to high shipping costs.

The reader can visualize readily how the picture might change for other areas, particularly those where the better materials are locally available and do not have to overcome a large differential in freight costs. In any event, we now are obtaining data which will allow the paving engineer to prepare designs which are really equivalent from the standpoint of subgrade protection. The normal forces of competition then may be depended on for selection of the most economical design for any given locality.

CONCLUSIONS

The principal points in this paper may be summarized as follows:

1. Subgrade pressure distribution caused by application of static loads to a pavement structure is affected to an important degree by the physical characteristics of the base and subbase materials.
2. Angular coarse-graded materials are particularly effective in the lower layers of the pavement structure due to the confining action of the upper layers.
3. Comparative performance of various materials in protecting the subgrade can be predicted qualitatively by study of triaxial data. With sufficient test information there is hope that the comparison may be made quantitative.
4. The performance of viscous materials, such as asphaltic concrete, varies widely with the rate of loading. The ratings of such materials under short-duration dynamic loads should be much higher, therefore, than their ratings under static loads.
5. These findings are of economic significance in any construction area where high quality materials are available at prices approaching those of inferior materials.

In applying the above data and conclusions to his own specific problems, the pavement designer is urged to keep in mind that the load transmission data reported herein were obtained from *static* loads, with the pavement sections supported by a *weak* mechanical subgrade. He should remember also that there may be wide differences in physical characteristics of materials of the same general type.

Any material contemplated for use should be tested triaxially, therefore, under conditions approaching those expected in actual service. If these limitations are observed, the data have great potential value in pavement design.

ACKNOWLEDGMENT

This report would not have been possible without the efforts of many engineers who have been active in the operation of the load transmission project. While it is impractical to list all of them, special recognition is due William M. Aldous whose foresight and perseverance made the project possible.

Personnel of the Navy Bureau of Yards and Docks also deserve credit and thanks, both for their close technical cooperation and for provision of financial support of the project.

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DISCUSSION

W. M. ALDOUS, *Consulting Engineer, Ann Arbor, Michigan*—The paper by Raymond C. Herner, Airport Division, Civil Aeronautics Administration, Technical Development and Evaluation Center, Indianapolis, Indiana, provides the subject for this discussion. It was presented at the annual meeting of the Highway Research Board in January 1955, at Washington D.C.

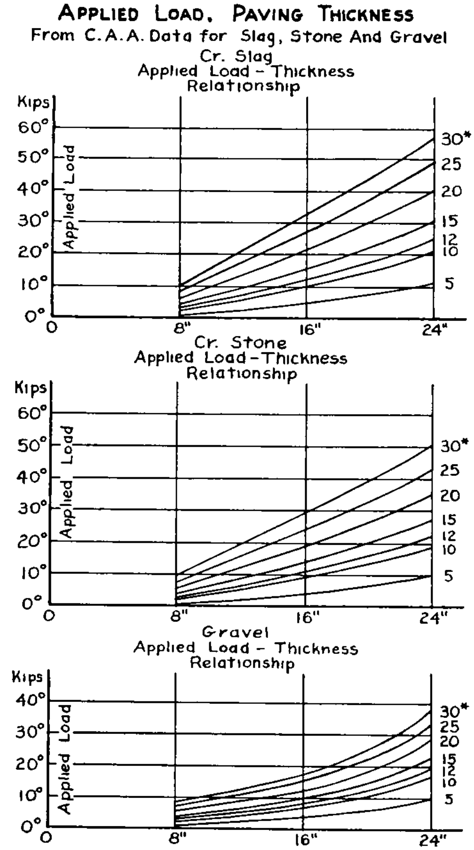
There are numerous statements throughout the paper which indicate that the method of interpreting factual load transmission test data is the underlying cause of the major differences making this discussion necessary. Complete rebuttal would require extensive documentation and will not be attempted in this discussion.

The principal objection to certain portions of Herner's paper is relative to his comparison of the structural properties and cost of crushed slag and crushed stone. These data are shown in Figures 5, 6, 7 and 9. He has supplemented these figures in the text on page 227 (Crushed Stone), page 228, (Crushed Slag), and in Economic Significance of Differences in Base Course Quality on page 231. Of particular interest is the statement contained in a paragraph on page 230, quoted as follows: "A further study of Fig. 4 reveals the excellent manner in which the protection of the subgrade by various pavement sections has been predicted by triaxial tests of the same materials. The strength curves for crushed stone, normal gravel and sand are generally parallel and definitely separated throughout the range of lateral pressure used in the triaxial tests. If these tests are indicative of what may be expected in pavement loading tests, the crushed stone should give the best performance of these three materials, regardless of the paving depth, and the sand should give the worst. It has been shown that this was consistently true." Although unmentioned, triaxial results on slag are very favorably located on Figure 4.

From data contained in previous C.A.A. reports and papers, and employing performance values of the material as obtained from direct load transmission test observations, without recourse to any doubtful or unnecessary interpretation of unrelated triaxial test results, it is possible to compare the structural performance of the materials under consideration. By the use of the section in the Engineering News Record of March 10, 1955, covering Materials and Labor Prices, authentic costs per ton of slag, stone, gravel and sand may be obtained. This cost information is presented, not to refute the figures Mr. Herner considers representative of his testing operations, but to correct any impression that the paving costs shown in Figure 9 of his paper are representative.

Herner has employed the following design criteria to develop the information shown in Figure 9:

Applied load—15.0 kips (15000 lbs.)



Note (*) Figures and curves show range of subgrade pressure

Figure 1

Maximum allowable subgrade pressure—12.0 psi.

Load medium—Very necessary but not mentioned. We have assumed that a 47″ S.C. aircraft tire at 100.0 psi inflation pressure has been used.

Preparatory to our solution we have assembled the applied load, base course thickness and range of subgrade pressure for slag, stone and gravel. These data are shown graphically on Figure 1, this discussion. Such information requires that a minimum of three tests be performed on three different thicknesses of a selected base course, in order that the curves may be developed. Only one test was run on the composite gravel-sand section referred to on Herner's Figure 9. This made it necessary to employ the equation showing the relationship between applied load (V_k) and subgrade reaction (r) to check the adequacy of

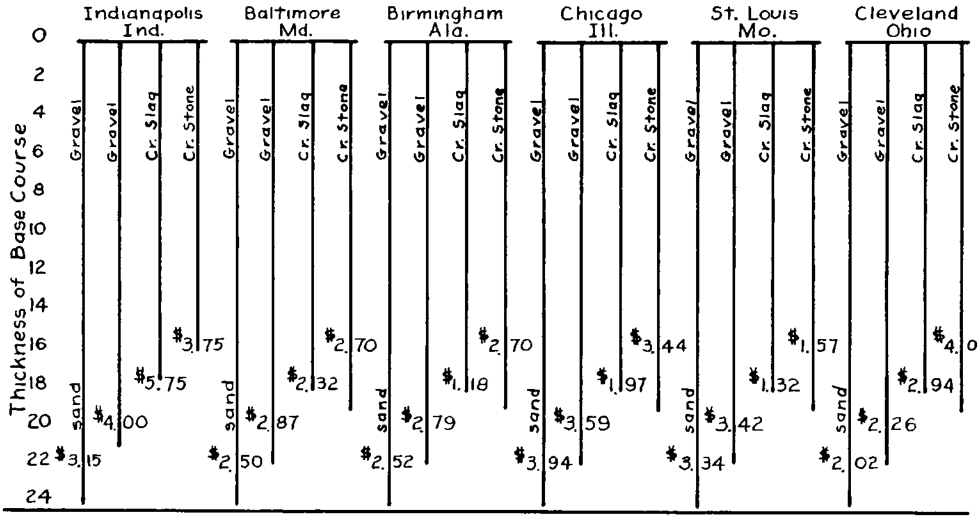
TABLE A

Slag	Stone	Gravel	Composite section	
			Gravel	Sand
Required Thickness of Compacted Base Course Material, inches				
18.0	19.0	21.8	8	16
Recorded Load Transmission Test Densities in Lbs. per Cu. Ft.				
130.0	138.0	135.0	135.0	120.0
Weight per Square Yard of Compacted Material, lbs.				
1755	1966	2208	814	1436
Yield in Square Yards per Ton of 2000 Pounds				
1.140	1.017	0.906	2.457	1.393

Cost of Slag, Stone, Gravel and Sand At Locations Shown

Location	Slag		Stone	
	Price—ton	Cost, sq. yd.	Price—ton	Cost, sq
Baltimore	$2.65 Dld.	$2.32	$2.75 Dld.	$2.70
Birmingham	1.35 Plt.	1.18	2.75	2.70
Chicago	2.25 Dld.	1.97	3.50 Dld.	3.44
St. Louis	1.50 Plt.	1.32	1.60 Plt.	1.57
Cleveland	3.35 Dld.	2.94	4.10 Dld.	4.03
Avg.	$2.22	$1.95	$2.94	$2.89

Location	Gravel		Composite section—8″ gravel, 16″ sand		
	Price—ton	Cost, sq. yd.	Type	Price—ton	Cost, sq.yd.
Baltimore	$2.60 Dld.	$2.87	(G) (S)	$2.60 Dld. 2.00 Dld.	$1.06 1.44 } $2.50
Birmingham	2.53 Cars	2.79	(G) (S)	2.53 Car 2.08 Car	1.03 1.49 } $2.52
Chicago	3.25 Dld.	3.59	(G) (S)	3.25 Dld. 3.65 Dld.	1.32 2.62 } $3.94
St. Louis	3.10 Trk.	3.42	(G) (S)	3.10 Trk. 2.90 Trk.	1.26 2.08 } $3.34
Cleveland	2.05	2.26	(G) (S)	2.05 1.65	0.83 1.19 } $2.02
Avg.	$2.71	$2.99		$2.58	$2.86



Note Indianapolis Ind. data from Herner's paper. Others from data in discussion. Vertical lines denote base thickness for identical design conditions. Dollars & cents across each vertical line represent cost per square yard. Method used by Herner not explained in his paper. Discussion costs based on material costs. for details, see text.

GRAPH SHOWING BASE COURSE THICKNESS AND COST PER SQ. YD. AT VARIOUS LOCATIONS
See Herner's Paper & Discussion Text

Figure 2

the selected section to handle the applied load in accordance with the imposed design conditions.

The applicable equation is $V_k = 1.838\ r^{0.85067}$. Using logarithms for most expeditious solution, $\log V_k = 0.26429 + 1.07918 \times 0.85067 = 1.18232$. The anti-log is 15.22 which is the allowable load in kips which this section will carry. This checks closely with design requirements.

Another factor which complicated our discussion was the failure to include any test information relative to crushed stone in the original paper. In absence of these data, it was necessary to make interpretations from such as was available from previous reports. It is believed that this will have but little effect upon the accuracy of our presentation.

Using the stipulated 12.0 psi allowable subgrade pressure from the graphical values for slag, stone and gravel and the 8 inch gravel and 16 inch sand thickness for the composite section, the information of Table A is obtained.

The comparison of prices and cost in Table A is based on material only. The handling and placing on actual construction is not included, but is reasonable to assume that any construction operation would be so equipped as to handle either material equally well.

Although it is my belief that the presentation of construction costs based upon test or assumed conditions are of little significance in a technical article concerning the structural properties of material, a graph shown in Figure 2, this report, will be presented as a basis for comparison with the data shown by Mr. Herner in his Figure 9, original report.

In conclusion, I would like to express my conviction that the Load Transmission Test, if properly conducted and if results are presented strictly upon a factual basis, can be of great benefit to those who believe that rational design, in lieu of empirical methods, is necessary to the efficient and economical design of paving for both highways and airports.

NORMAN W. MCLEOD, *Engineering Consultant, Department of Transport, Ottawa, Canada*—Engineers concerned with flexible pavement design are indebted to Mr. Herner and the Civil Aeronautics Administration for continuing research with the load transmission apparatus at Indianapolis. The Bureau of Yards and Docks of the U.S. Navy also deserves our gratitude for the financial support which made the continuation of this project possible at a critical time.

So little is known about the fundamental mechanism of failure of flexible pavements when overloaded, that every reasonable approach should be squeezed dry of any information it can contribute to the solution of this problem. The load transmission equipment at Indianapolis is a unique instrument for investigating certain phases of flexible pavement design. The development of the device itself required several years of painstaking, patient effort by Mr. William Aldous and his associates, as Mr. Herner has generously pointed out. Those of us who are interested in flexible pavement design are looking forward to additional papers on the further information that is gradually developed by this large scale apparatus.

Mr. Herner's paper and this discussion are confined to consideration of the thickness of base course needed to prevent failure within the subgrade. Mr. Herner's data point to the very definite conclusion that the thickness of flexible pavement required to carry any specified wheel load over any given subgrade should be varied (within limits) with the quality of the base course material. For relatively cohesionless base course aggregates, his paper indicates that the thickness of the base course can be decreased as the angle of internal friction of the base course material is increased; that is, as the inherent strength or stability of the base course aggregate is increased.

Mr. Herner's conclusions in this respect are based upon test data provided by his load transmission apparatus at Indianapolis. From an entirely different starting point outlined in a paper on "An Ultimate Strength Approach to Flexible Pavement Design," prepared for the annual meeting of The Association of Asphalt Paving Technologists in February, 1954, the writer arrived at the same conclusion, which is illustrated in Figure A.

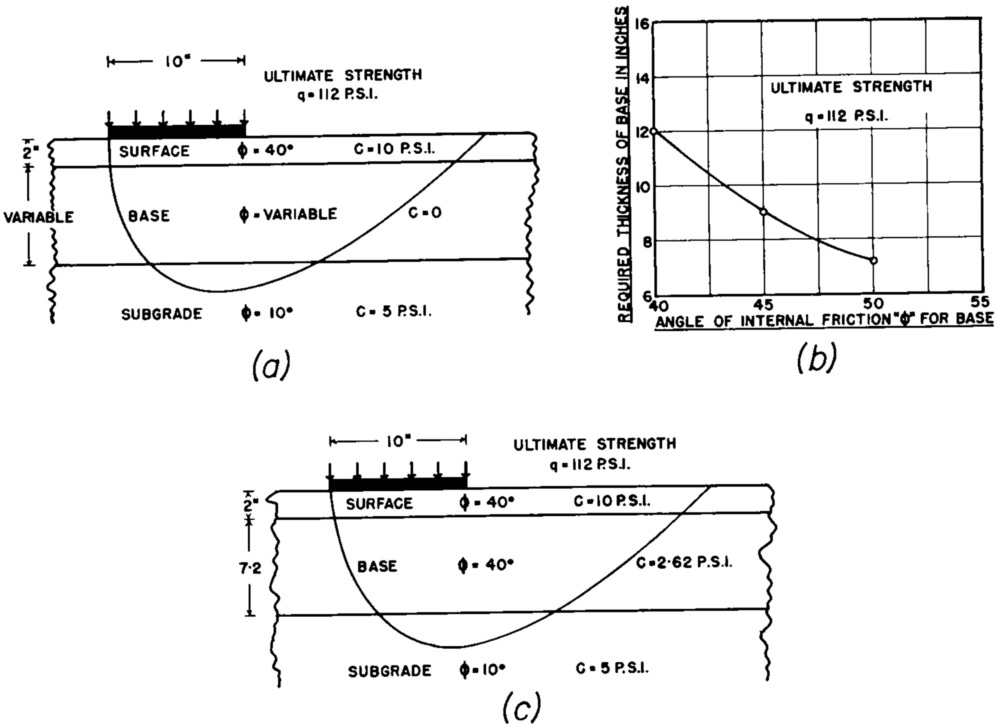


Figure A. Influence of base course strength characteristics on base course thickness requirements.

Figure A(b) indicates that if the angle of internal friction of the cohesionless base course material were increased from 40° to 50° (equivalent to changing from an inferior pit-run gravel to crushed stone), the required base course thickness could be decreased from 12 to 7.2 inches, all other factors being constant. This represents a 40 percent decrease in base course thickness requirement due to the use of a higher quality base course aggregate.

Figure A, together with Mr. Herner's data, provide evidence that flexible pavement thickness requirements should be influenced by base course quality. In actual practice, however, engineers generally refuse to reduce the thickness of granular base, even if crushed aggregates of unusually high quality are to be employed for the full depth. For example, neither the U.S. Corps of Engineers nor the Canadian Department of Transport would permit any reduction in base thickness even if high quality crushed aggregates were to be used for the entire depth of base course and subbase of a flexible pavement. Mr. Francis Hveem from California appears to be of like mind, provided the various cohesionless granular base course materials are of approximately the same weight per cubic foot. To Mr. Hveem, the surcharge effect of a base course is its most important property. He believes that if the densities of different cohesionless base course aggregates in place are nearly identical, variations in their quality in terms of some strength factor such as stability, angle of internal friction, etc. are without significance insofar as thickness design is concerned. In view of Mr. Herner's data and Figure A, the question arises as to whether or not engineers responsible for the actual design of flexible pavement thickness are justified in their present attitude toward base course quality.

Insofar as cohesionless granular base course aggregates are concerned, the writer agrees with current practice in which base thickness is not influenced by base course quality. (It is understood, of course, that the quality of the base course material, that is, its shearing strength, must exceed the minimum at which failure under load would occur within the base itself.) While Mr. Herner's data and the writer's Figure A show that marked differences in base course quality can be demonstrated *by means of laboratory tests*, it has *not* yet been shown that these same differences in base course quality can be developed *consistently in the field.* There is considerable evidence to the contrary. This may be due to the inability of current compaction equipment and compaction procedures to develop in the field the large differences in base course quality that can be made so obvious by means of laboratory tests, such as the triaxial.

It needs to be kept clearly in mind that, other factors being equal, the stability or strength of cohesionless base course aggregates depends upon two fundamental characteristics, (a) particle shape and surface roughness, and (b) relative density.

The properties of aggregates produced entirely by crushing, such as angular shape and surface roughness, which cause them to develop high angles of internal friction (excellent quality) when tested by means of laboratory apparatus, are the same properties that make it difficult to compact these aggregates to high relative density under the amount of compaction ordinarily given to base course materials in the field. On the other hand, pit-run and even many crusher-run gravels usually have less particle angularity and surface roughness. Nevertheless, under the kind and amount of compaction ordinarily provided in the field, they can be rolled to a high relative density. Consequently, although their angular shape and surface roughness might be expected to give thoroughly crushed aggregates greater load carrying capacity per unit thickness than aggregates consisting of more rounded particles, this does not necessarily occur under field compaction as carried out at the present time. In general, the two types of aggregates seem to develop roughly the same supporting value per unit thickness. The explanation seems to be that the higher relative density of the more rounded aggregates tends to compensate for the greater angularity and surface roughness of the highly crushed materials. This situation is likely to continue until compaction equipment and procedures are developed that provide thoroughly crushed base course aggregates with the same relative density as that of pit-run or crusher-run gravels. When this development occurs, engineers may be able to progressively decrease the base course thickness requirement as aggregates of higher and higher quality are selected.

Considerable evidence supports the usual current practice of permitting no reduction in base thickness due to the use of high quality base course aggregates for the full depth of base.

As a result of traffic tests on experimental sections, the U.S. Corps of Engineers arrived at this conclusion some years ago. It is expressed in several of their reports, for example "Certain Requirements for Flexible Pavement Design for B-29 Planes."

Plate bearing tests on runways in Canada that have been in service for a number of years, conducted by the Canadian Department of Transport, have not indicated greater supporting value for crushed stone per unit thickness than for less angular crusher-run gravels. At the present time, therefore, the Department of Transport's method of flexible pavement thickness design assumes that one hundred percent crushed stone, mechanically stabilized gravel bases, crusher-run gravel, and even the more angular pit-run gravels, have equal load supporting value per unit of thickness.

The only failure within the base course that the writer has observed to date on a runway in Canada developed where the full depth of base consisted of one hundred percent crushed stone. Due to wet weather, the subgrade strength was low at the time of construction. On the soft subgrade, it was not possible to compact the crushed stone to a high relative density. Trenching across the failed area proved that failure under airplane traffic occurred entirely within the base. The base course was deeply rutted with accompanying upheaval at the sides. The underlying subgrade showed no rutting or upheaval. Here was a classic example where the potentially high stability of a thoroughly crushed base course material was being only partially developed because of its low relative density.

It is fully recognized, as Mr. Herner's data and Figure A so clearly demonstrate, that one hundred percent crushed stone with angular particles and rough surfaces is potentially capable of developing greater supporting value per unit thickness than less angular crusher-run gravels. However, on the basis of the evidence just outlined, insofar as subgrade protection is concerned, unless an engineer has satisfied himself that with the compaction equipment and procedure to be used on any given flexible pavement project, he can develop *in the field* the difference in stability that can be shown for these materials *in the laboratory*, he should be very cautious about assigning greater load supporting value per unit thickness to one material than to the other. It is to be hoped that this situation can be reversed, and that compaction equipment and methods will be developed that will enable engineers to take advantage of the potentially greater supporting capacity of highly crushed aggregates when designing the thickness of flexible pavements.

Mr. Herner has included asphaltic concrete among the base course materials he has investigated. In spite of what would appear to be a rather poorly designed asphalt paving mixture, his Figure 7 indicates that the asphalt concrete he was using was equivalent in load supporting value to the highest quality cohesionless aggregates.

The principal criticism of the asphaltic concrete used by Mr. Herner concerns its high flow index, which is reported to be 28. In the writer's experience, the flow index is a more important criterion of the strength of an asphalt paving mixture than the so-called "stability" value given by the Marshall test. As shown in a discussion by the writer on pages 240–1, Volume 20, Proceedings of the Association of Asphalt Paving Technologists, 1951, there appears to be a relationship between the flow index and the angle of internal friction of an asphalt paving mixture. A high flow index corresponds to a low angle of internal friction and vice versa. There is considerable evidence that the flow index for heavy duty highway and airport traffic should not exceed from 16 to 18. The writer prefers to keep the flow index within a range of 12 to 15. If Mr. Herner had employed a thoroughly compacted asphaltic concrete having a flow index below 18, it is believed that the curve representing its load supporting value on his Figure 7 would have been well above those of the best of the aggregates tested.

Figures A, B, and C, taken from the writer's paper already referred to, confirm Mr. Herner's general conclusion concerning the high load supporting value of asphaltic concrete. Figures A, B, and C actually present a more optimistic comparison in this respect than is portrayed by Mr. Herner's test data. This is believed to be due to the high flow index, and therefore relatively weak asphalt mixture employed for the Indianapolis tests.

For the specific conditions pertaining to Figure A, it has already been pointed out that Figure A(b) indicates that by substituting a base course material with an angle of internal friction of 50° for one with an angle of internal friction of 40°, the base course thickness can be reduced by 40 percent (from 12 to 7.2 inches). Base course aggregates with a high angle of internal friction may not always be available and the question of improving the stability of the inferior cohesionless aggregate at hand arises. Figure A(c) demonstrates that this improvement might be obtained by adding a bituminous binder to introduce cohesion *c* into the inferior aggregate. For the cohesionless aggregate with an angle of internal friction of 40°, if the addition of bituminous binder develops cohesion $c = 2.62$ psi, Figure A(c) indicates that only 7.2 inches of base course are required. Consequently, for the conditions illustrated by Figure A, a bituminous-bound base course 7.2 inches thick for which $\phi = 40°$ and $c = 2.62$ psi develops the same ultimate strength as the identical thickness of cohesionless aggregate having an angle of internal friction of 50°. In this case, using a binder to introduce cohesion $c = 2.62$ psi into an inferior cohesionless base course material for which $\phi = 40°$, confers on it the same strength as that developed by a high quality base course aggregate for which $\phi = 50°$.

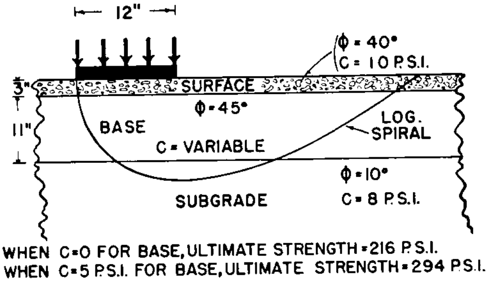


Figure B. Influence of magnitude of base course cohesion on ultimate strength of a flexible pavement.

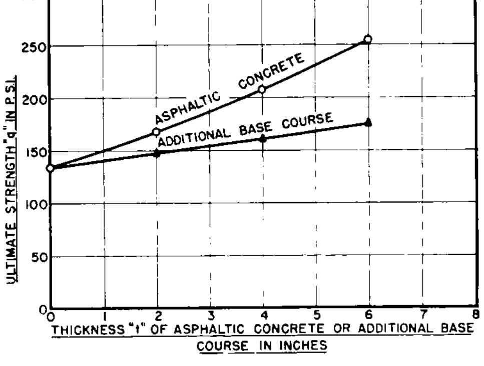


Figure C. Relative influence of thickness of asphaltic concrete or additional base course on the ultimate strength of a flexible pavement.

Similar conclusions are illustrated by Figure B, in which the use of 11 inches of cohesionless base course material, for which $\phi = 45°$, results in an ultimate strength of 216 psi for the flexible pavement as a whole. By adding a binder to this base course aggregate to provide it with cohesion $c = 5$ psi, the ultimate strength is increased to 294 psi. In this case, through the addition of a binder to increase the cohesion of the base course from $c = 0$ to $c = 5$ psi, the ultimate strength of the flexible pavement has been increased by 36 percent.

Figure C compares the use of several thicknesses of an asphaltic concrete versus the same additional thicknesses of a cohesionless base, for increasing the ultimate strength of a flexible pavement. It shows that for zero thickness of asphaltic concrete on the 6-inch base, the ultimate strength is 134 psi, while the addition of 6 inches of this particular asphaltic concrete increases the ultimate strength to 255 psi. The addition of 6 inches of the cohesionless base, on the other hand, increases the ultimate strength to only 176 psi. For the conditions illustrated in Figure C, therefore, 6 inches of asphaltic concrete increased the ultimate strength by $255 - 134 = 121$ psi, while 6 additional inches of the cohesionless base course increased the ultimate strength by only $176 - 134 = 42$ psi.

It should be mentioned that the data illustrated by Figures A, B, and C result from a theoretical study of the flexible pavement thickness problem. Nevertheless, they seem to agree at least qualitatively with observed field performance.

It has been suggested above that the reason that engineers currently refuse to permit base course quality to influence base course thickness requirements is because of the inability of present field compaction equipment and procedures to compact top quality aggregates to high relative densities. This criticism does not seem to apply when the stability of an aggregate is increased by incorporating a bituminous binder.

When properly handled, bituminous paving mixtures can be compacted to very high relative densities. For example, the U.S. Corps of Engineers' specifications require that bituminous mixtures be rolled to 98 percent of the laboratory compacted density (Marshall). Consequently, it might in many cases be easier to obtain high base course stability or supporting value in the field and corresponding reduction in base course thickness by adding a bituminous binder to an inferior aggregate (low angle of internal friction), than by endeavoring to compact top quality crushed cohesionless aggregates, having large angles of internal friction, to high relative densities.

An outstanding example of the increase in overall load supporting value of a flexible pavement obtained by adding asphalt binder to a base course material is provided by one of the few findings concerning the WASHO Test Road that have been published so far. Under identical traffic, and for the same total thickness of base and surface, test sections with 4 inches of asphaltic concrete surface course have shown superior performance to those surfaced with 2 inches of asphaltic concrete. The difference in thickness of surfacing, amounting to 2 inches in this case, could be looked upon as 2 inches of base course to which an asphalt binder has been added.

The current large scale use of sand asphalt stabilization provides another practical illustration of the marked increase in stability that occurs when the proper amount of an asphalt binder is added to a cohesionless aggregate. Combining an asphalt binder with an unstable sand, for example, can result in a base course material equal in stability to high quality aggregates. Sand asphalt stabilization usually provides an economical solution to the base course problem in areas where large deposits of unstable sandy soils occur, but where high quality aggregates are not available unless imported from long distances.

Where it is economical to do so, the sand asphalt stabilization solution might be advantageously extended to other aggregates. For example, under the high tire pressures of military jet aircraft, the addition of asphalt binder might be effectively employed to increase the shearing resistance of base course aggregates that are satisfactory for tire pressures up to 100 psi, but are deficient in stability under tire pressures of 200 psi, 300 psi, etc.

C. W. Johnson, Howard Nunez, and Hardy Swayze, *New Mexico State Highway Department*—As Mr. Herner points out in his introduction, most organizations design a total pavement thickness entirely on the supporting power of the subgrade and make no attempt to reduce that thickness by taking advantage of superior base or subbase materials.

The purpose of the research and testing as presented in this paper was solely to compare the load transmission abilities of various types of base course materials onto a given subgrade. The effect of poor or superior subgrade qualities did not enter the investigation. A further objective of the test series was an attempt to establish a criteria using the triaxial test as a basis whereby the relative merits of various materials under a given set of conditions could be evaluated.

That the tests described in the paper are of a limited value in highway designing are at once apparent. In the first place, the tests were all of a static nature, which is perhaps the only practical method of conducting such a series of experiments. While loads of a static or slow-moving nature are of primary concern in airport design where the most frequent failures are caused by standing aircraft, such is not the case in highways where failures are induced by numerous repetitions of heavy fast moving loads. Secondly, the pavement thicknesses investigated were, with the exception of the 8-in. thickness, all much greater than is common practice in highway construction, and the test results as presented for the 8-in. pavements were of somewhat erratic nature, i.e., the trend of subgrade reaction is not consistent. Mr. Herner has explained this rather logically as being due to insufficient confinement of the thin layers. Undoubtedly, more research is needed on these thinner sections for a better correlation of capacities of materials.

Test results obtained on the asphaltic concrete pavement were undoubtedly dependent in a large measure upon the temperature of the pavement when tested. In our estimation the loading rate (strain per minute) being reduced from 0.5% for all other pavement materials tested to 0.02% for asphaltic concrete does not give a reasonable basis for comparison of the relative value of the asphaltic concrete. This reduction in rate of loading is misleading and should have been given more emphasis.

In addition, practically all the tests reported were conducted on a thickness of like material. Further study is in order to determine the effect of layered materials and to develop correlations between the triaxial test and layered materials.

The methods employed by Mr. Herner are ingenious but apparently quite capable of accomplishing the job they were designed for. I am of the opinion that Mr. Herner's basic premise that the subgrade reaction can be taken as in inverse measure of the effectiveness of the pavement is a sound one. Likewise, for a given material, I believe there should be a definite means of determining this effectiveness in the laboratory. However, I should like to see more conclusive evidence before accepting the triaxial lateral pressures given as those on which to compare various thicknesses of material.

L. A. Palmer, *Engineering Consultant, Bureau of Yards and Docks, Department of the Navy*—This splendid paper by Mr. Herner is a progress report of research which will go far in establishing the relative load distributing powers of different layered materials on subgrades of different moduli in compression and with variable sizes of plates.

The simple fact that different subbase and base courses vary widely with respect to load distributing power is not fully appreciated as yet by paving technologists generally and the principle has been applied in the design of flexible type pavements by relatively few paving engineers.

The load applied on a very small plate supported by say a foot of good base may barely be transmitted through the base to the subgrade whereas the same unit load applied on a very large plate on the same foot of base may be transmitted practically undiminished to the subgrade. This principle is very elementary, but yet it is not sufficiently appreciated and utilized in design. Oversimplification in application of this principle, for example, expressing the unit load reduction from plate through base in terms of pounds per inch thickness of base or, vice versa, expressing the load capacity of the base in terms of pounds per inch thickness of base, diverts one from an adequate analysis of load test data. The relationship is not linear. The load distribution

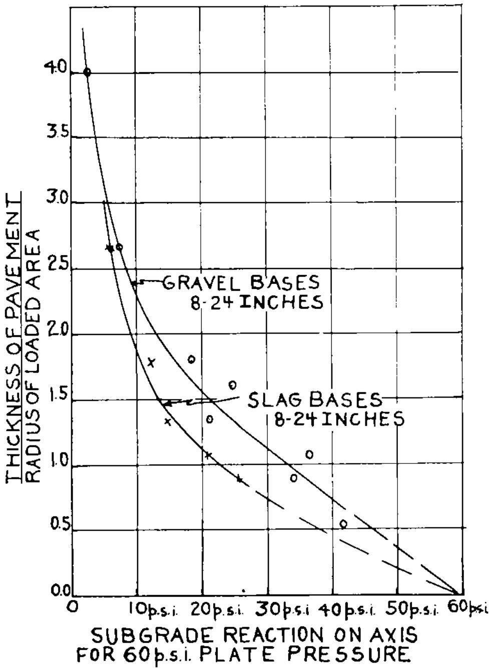


Figure A. Relationship between h/a and subgrade reaction.

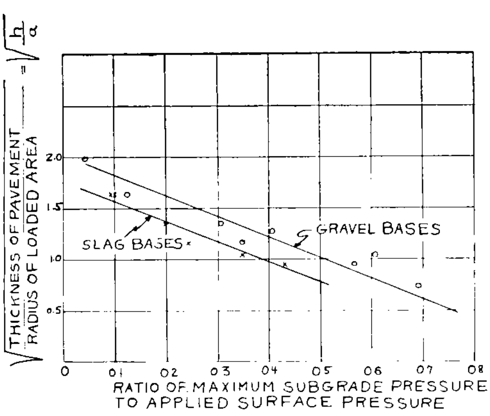


Figure B. Relation between $\sqrt{h/a}$ and subgrade reaction.

"lines" are very definitely curves as shown in Figure A. The same data are replotted in Figure B which shows a linear relation between the *square root* of the ratio of pavement thickness, *h*, to the plate radius and the pressure transmitted to the springs ("subgrade"), these data being taken from Mr. Herner's reports.

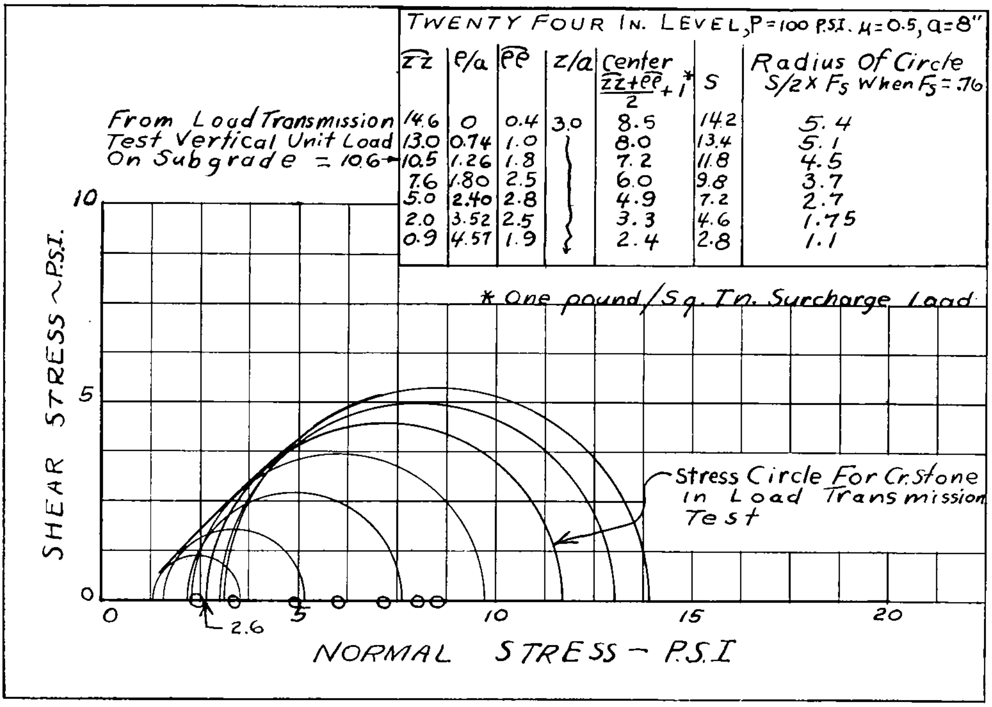
It is not considered desirable at this time to show application of mathematical analysis to Mr. Herner's interesting and valuable test data. Such analysis has been made and has shown that the mathematical theory of D. M. Burmister leaves little to be desired. However, presentation of this analysis must necessarily be very incomplete pending the time that the tests are repeated with stronger "subgrades" (springs).

Since the "subgrade" in Mr. Herner's experiments deflects in the vertical direction only and is not displaced laterally under load, one must consider its Poisson's ratio as zero. Thus its behavior is that of a saturated subgrade undergoing consolidation by egress of water. This does not in any way detract from the practical considerations and utilization of the results in pavement design. The important point is that with a constant and unchanging subgrade in these tests, we can vary the quality and thickness of bases and subbases and determine with reasonable accuracy their relative load distributing characteristics.

W. H. Campen, *Manager, Omaha Testing Laboratories*—As many of you know, it has been my contention for years that the quality of the base is one of the factors to be considered in the estimation of thickness to be superimposed on subgrades or subbases. My own actual experience has borne this out. Naturally I am very pleased to know that Herner's work verifies my contention.

The tests reported in this paper were conducted on top of a weak subgrade. No doubt they will be repeated on top of stronger subgrades.

Chester McDowell, *Senior Soils Engineer, Texas State Highway Department*—My first impression was that differences in depths indicated in the report due to use of different base materials were overemphasized. Therefore, an attempt was made to check Herner's results

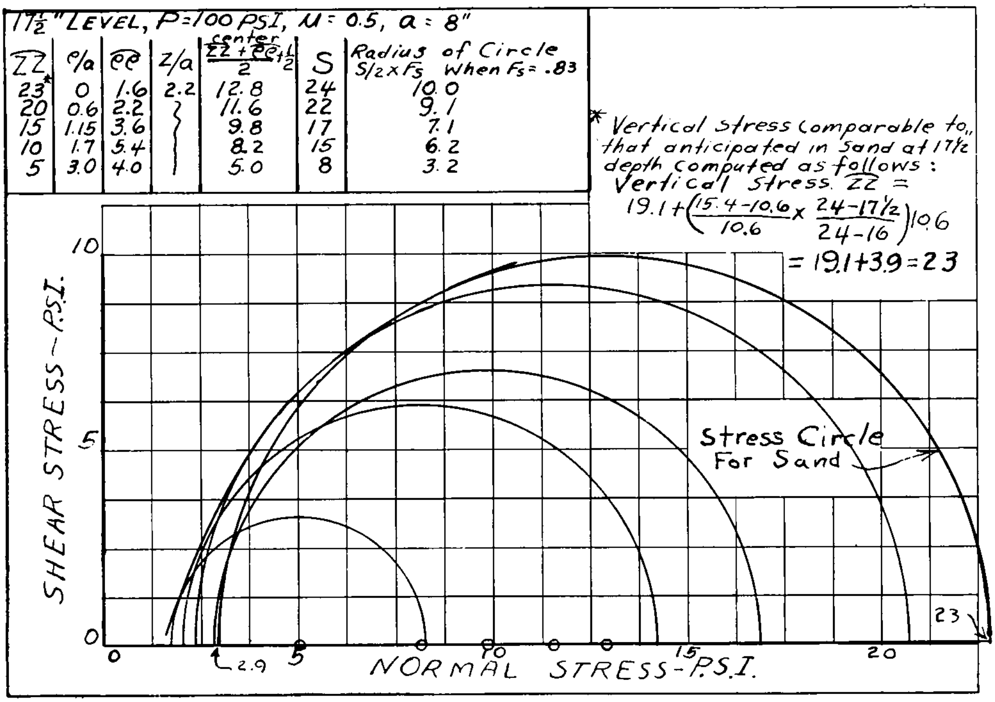


TWENTY FOUR IN. LEVEL, $P = 100$ P.S.I. $\mu = 0.5$, $a = 8''$

$\widehat{zz}$	ρ/a	$\widehat{\rho\rho}$	z/a	Center $\frac{\widehat{zz}+\widehat{\rho\rho}}{2}+1^*$	S	Radius Of Circle $S/2 \times F_S$ When $F_S = .76$
14.6	0	0.4	3.0	8.5	14.2	5.4
13.0	0.74	1.0		8.0	13.4	5.1
10.5	1.26	1.8		7.2	11.8	4.5
7.6	1.80	2.5		6.0	9.8	3.7
5.0	2.40	2.8		4.9	7.2	2.7
2.0	3.52	2.5		3.3	4.6	1.75
0.9	4.57	1.9		2.4	2.8	1.1

* One pound/Sq. In. Surcharge Load

Figure A



$17\frac{1}{2}$" LEVEL, P=100 PSI, μ= 0.5, a = 8"

$\widehat{ZZ}$	e/a	$\widehat{ee}$	Z/a	center $\frac{\widehat{ZZ}+\widehat{ee}}{2}+\frac{1}{2}$	S	Radius of Circle S/2×Fs When Fs= .83
23*	0	1.6	2.2	12.8	24	10.0
20	0.6	2.2		11.6	22	9.1
15	1.15	3.6		9.8	17	7.1
10	1.7	5.4		8.2	15	6.2
5	3.0	4.0		5.0	8	3.2

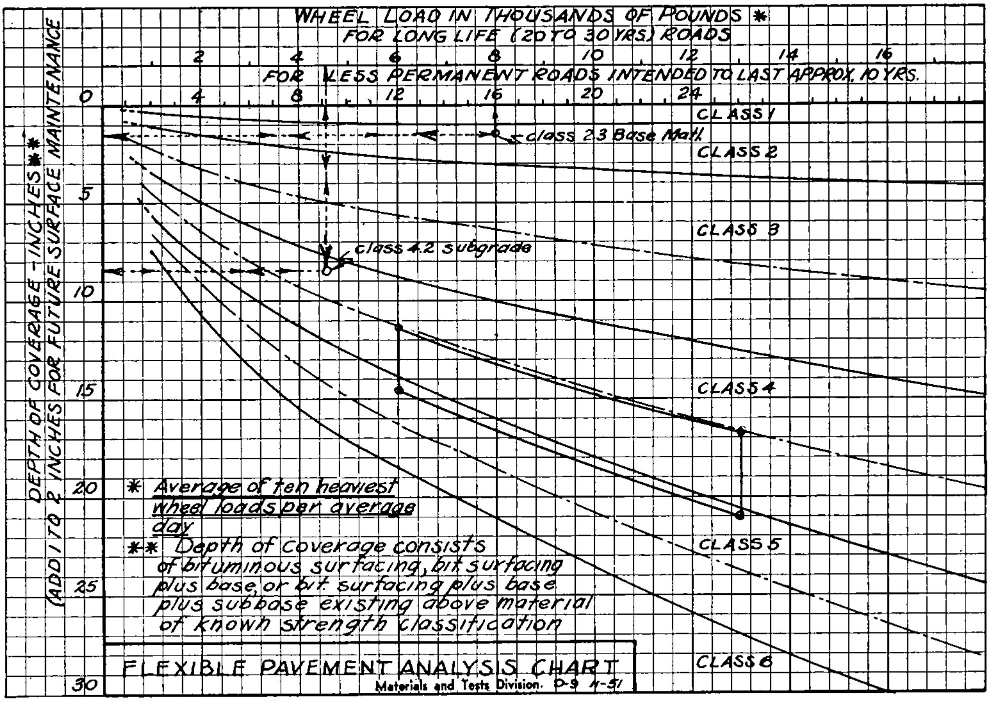
* Vertical stress comparable to" that anticipated in Sand at 17½ depth computed as follows:

Vertical Stress $\widehat{ZZ}$ =

$$19.1+\left(\frac{15.4-10.6}{10.6}\times\frac{24-17\frac{1}{2}}{24-16}\right)10.6$$

$$=19.1+3.9=23$$

Figure B



* Average of ten heaviest wheel loads per average day

** Depth of coverage consists of bituminous surfacing, bit surfacing plus base, or bit. surfacing plus base plus subbase existing above material of known strength classification

Figure C

by the use of the theory of elasticity and the assumptions given in my report, entitled: "Wheel Load Stress Computations Related to the Texas Highway Department's Triaxial Method of Flexible Pavement Design," (see Vol. 34, H.R.B. Proceedings). The attached charts were prepared. Figure A shows stress conditions calculated at a depth level of 24 inches. Fortunately, the stress conditions are similar to those measured with the load-transmission equipment when crushed stone was used. The stresses developed by use of load transmission tests through sand were excessive for this level. Figure B shows that stresses produced through the sand would be comparable to theoretical level of 17½ inches. This means to me that the crushed stone protected the subgrade from overstress when it was 24 inches below the surface. Although not plotted, stresses produced through the sand are such that they would overstress this theoretical envelope. Figure B shows that the sand produced stresses as should be found from theory preventing overstress at a depth of only 17½ inches. Therefore, the crushed stone offers adequate protection to subgrades at depths which are 6½ inches greater in depth than could be expected of similar loadings on the sand. This difference is perhaps a little less than Herner obtained, but considering all things involved, it is a close check.

For loads larger than 20 kips up to 50 kips the difference probably would vary from 6½ to 10 inches; for highway loadings, such as we now have, (Figure C) the difference is only 3 or 4 inches. Mention of this is made because some experiments were made using small wheel loads in which differences may have been only 1 or 2 inches. I am sure other factors were so involved that such small differences were not observable in their track tests.

We are indebted to Herner and his associates for the excellent studies they are making.

Raymond C. Herner, *Closure*—The importance of the flexible paving design problem is amply attested by the volume of comments and discussions, both verbal and written, which have followed the author's paper. These expressions of interest in the problem and in our load transmission project at Indianapolis are deeply appreciated and gratefully acknowledged. This closure will be limited to a slight amplification of certain phases of the original paper and brief coverage of certain points raised by others in the discussions.

There is no need for concern over the fact that some of the data and opinions offered in the discussions do not agree entirely with those of the author or with each other. If all testing and service data were in agreement and if there was unanimity of opinion among pavement designers, there would be no need or excuse for further studies. A primary purpose of our project is to provide facilities for measuring the influence of each design variable independently and objectively so that existing differences of opinion may be gradually eliminated. The present paper is but a single step toward this ultimate goal.

It is evident, from both formal and informal discussions, that the author's presentation suffered somewhat from the attempt to keep it brief and pointed. For instance, test results were given from only one test pavement of a particular type and thickness, and the reader was asked to accept these as representative of all tests of that material. He will have a chance to verify or modify this assumption for himself as other data appear in succeeding reports.

Most of the original paper is a mere recital of facts and, therefore, not arguable. The interpretation of these facts was based on the premises that: (1) many pavement failures and displacements are caused by excessive deformations in the subgrade; (2) these deformations are caused by stresses transmitted through the pavement from concentrated surface loads; (3) the subgrade stresses and deformations may be reduced to tolerable limits by an adequate pavement; (4) the proper measure of pavement adequacy (from the standpoint of subgrade protection) is the reduction in transmitted stress; (5) there is a qualitative relationship between two test methods if both rate the same materials in the same relative order; (6) rate of load application must be considered in rating viscous materials; and (7) different materials vary in price at different locations.

These assumptions were not stated specifically in the original paper as they were considered obvious and axiomatic. If they are accepted, the original conclusions follow automatically from the factual data presented.

McLeod refers to field tests of the U. S. Corps of Engineers and the Canadian Department of Transport as evidence that the use of high-quality granular base course material may not warrant any reduction in total pavement thickness. Certainly, the results of these investigations cannot be ignored entirely. On the other hand, they should not be assigned an undue importance as they are adequately rebutted by reported experiences and design practices of the Civil Aeronautics Administration and the Department of the Navy, plus those of many highway departments and consultants. Neither can we ignore indications from the earlier experimental studies of Goldbeck (*1*), Burggraf (*2*), and others, nor the theoretical treatments by Burmister (*3*) and by Palmer (*4*) and Barber. It may be significant also that Dr. McLeod still favors a theoretical approach based on use of the logarithmic spiral despite the lack of agreement between this approach and his own earlier field data.

The existence of some doubt in the matter is indicated by this comment from his original report (*5*):

> "When all the available information is considered, there is no positive evidence that for similar conditions of density and moisture content, all other factors being equal, that any one type of granular base material has a greater supporting value per unit of thickness than any other type. However, this matter merits considerable further study before a final conclusion can be stated."

A similar lack of conviction is found in the Airfield Pavement Design Manual (1951) of the Corps of Engineers which states:

> "There may be some difference in stress-distributing characteristics of subbases and bases with different CBR values."

While the above references are heartening, as evidence of an open-minded attitude by everyone concerned, they still do not explain the discrepancies in reported test results. McLeod offers the suggestion that the differences are caused by greater difficulty in achieving adequate field density of the angular materials which showed to advantage in certain phases of the load transmission tests. This suggestion must be rejected as, (1) the densities used in the laboratory are easily obtained in the field, and (2) the angular materials did not require greater compactive effort for higher strengths in the laboratory tests. Although adequate compaction of any material is essential in order to achieve optimum benefits from its use, one should not rely upon density as a criterion in comparing materials of different types. For example, the open-graded slag base courses used in these experiments were much more effective at a unit weight of 131 pcf than the clay-gravel sections were at 137 pcf.

The base failure described by McLeod is a glaring example of poor construction, but as the failure was in the base rather than the subgrade, it is irrelevant in this discussion. Actually, such failures should not exist. Adequate equipment and techniques for proper compaction are available. It is the engineer's responsibility to see that they are used.

The author prefers to believe—at least until further evidence is forthcoming—that the inconclusive results from many field investigations are caused by the wide range of uncontrolled variables affecting the test data. Even under relatively good control, some of the load transmission test sections yielded test results which varied 20 percent or more from the average. Much greater variations can be expected under field tests with widely varying subgrade conditions and hidden construction flaws.

One might inquire then, whether it is worthwhile to study the effect of pavement quality if this effect can be obscured by other variables. The answer is definitely affirmative if we only realize that any design problem is partially a statistical study of probabilities. If careful tests in the laboratory show that use of a certain material increases the strength of a structure by 30 percent, the use of that material in the field will increase the factor of safety against failure by a corresponding amount.

No defense is offered to McLeod's criticism of the asphaltic concrete used in the load transmission tests. It was a commercial mixture, representative of that used locally. In this connection, it should be emphasized perhaps that the project is aimed at a study of the variables affecting flexible pavement design. Any comparison of specific materials is purely incidental. Certain materials were selected for test because they exhibited certain physical characteristics which were of interest. The materials used were not necessarily the best of their respective kinds, and the reader is urged to review the original paper for cautions on application of the test data.

It often is possible to improve a material by addition of asphalt cement, as suggested by McLeod. One must remember, however, that an increase in cohesion may be accompanied by a loss in internal friction. The comparative value of the two must be determined by the proposed use of the material. Load transmission tests indicate that cohesion may be the more important factor in thin pavements or in the upper portions of thick pavements. The situation appears to be reversed in the lower portion of thick pavements. The WASHO test track results are an excellent example of the benefits of adding cohesion where it was badly needed.

The author is indebted to Aldous for furnishing comparative cost data from areas in which crushed slag is more favorably situated from a competitive standpoint than it is at Indianapolis. His discussion emphasizes the point made in the original paper, that local competitive conditions will govern selection of the best design for a given location.

The discussion by Johnson, Nuney, and Swayze, of the New Mexico Highway Department, brings out two closely related points which are very important to the design engineer. The first is the relative effect of static and dynamic loads. Our own tests, as well as information available from others, show that materials of a plastic or semi-plastic nature tend to offer more resistance to loads of short duration than to static loads. As previously noted, the asphaltic concrete is very sensitive in this respect.

This brings us to the second point of the discussion—the reason for using different rates of deformation in the triaxial tests. The purpose in performing the triaxial tests is to develop a correlation with results from the load transmission tests. As the latter are static tests, the corresponding triaxial tests should logically be run at a very low rate in order to avoid any dynamic effect. Indications are that the rate of compressive strain should be as low as 0.01 per cent for correlation with the static load tests. As this is impractical from a production standpoint, the rates have been increased, each in such ratio as to maintain the same relative rating of materials.

The problem of loading rate is a very important one both in the laboratory and in the field. As triaxial tests can be performed over a rather wide range of loading rates, there is hope that practical correlation with field performance will be possible. The author did not intend to imply that all problems had already been solved.

The different discussions by Palmer and by McDowell and by Campen are welcome as they add substantial corroboration to the original paper, both from a theoretical and a practical standpoint. As they raise no controversial questions, it does not appear desirable to extend this closure any further for the sake of additional comments.

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