A Summary of Load Transmission Tests on Flexible Paving and Base Courses

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The load transmission apparatus provides a means of conducting load tests on full-scale pavement sections under laboratory conditions. A segmented loading platform supported by coil springs is substituted for the natural subgrade to insure constant test conditions over long periods, and to permit quick and accurate measurement of vertical stresses transmitted through the pavement. For a given applied load, the maximum stress on the subgrade provides a convenient means of comparing the efficiencies of various pavement sections or evaluating the effects of various design variables.

The relationship of subgrade stress to applied load should vary with pavement thickness, contact area, and respective strengths (or stiffnesses) of the pavement and subgrade. An analysis of 814 loading tests on 123 pavement sections verifies the essential correctness of theoretical studies and provides numerical values for use in design or for futher study. These values are given in chart form, and represent a generalization of all pertinent test data. They may be used directly in a method of pavement thickness design based on a limiting subgrade stress or deflection, or to extend empirical designs into areas not adequately covered by service experience.

The triaxial test was used to compare strengths of the various materials (gravel, clay-gravel, sand, limestone, slag, and asphaltic concrete) used in the pavement sections. Although further correlation studies are in progress, the method outlined in this and previous papers is considered adequate for design purposes. The validity of the test data for use in highway pavement design will be checked by correlation with results of traffic tests on the AASHO Test Road.

THE LOAD TRANSMISSION testing project consists fundamentally of a series of static loading tests on full-scale flexible pavement sections. The pavements are supported by a mechanical subgrade in lieu of the natural earth. This provides a constant and uniform degree of support, and also facilitates measurement of vertical stresses and deflections transmitted to the subgrade.

Such an arrangement permits orderly long-term studies of pavement behavior under load, with each major variable controlled independently in a planned schedule of operations. The basic testing program has been underway for approximately seven years. During this period the relationship of load to subgrade deflection has been measured for almost 1,800 load applications on approximately 250 pavement test sections.

Several progress reports have been published (1, 2, 3, 4, 5, 6, 7, 8, 9). The present paper summarizes and discusses the results from all of the single-wheel loadings on various pavement sections supported by either a weak, medium, or strong subgrade. Major variables ranged within the following limits:

Applied load	2.5 to 60 kips
Pavement thickness	3 to 24 in.
Tire inflation pressure	40 to 200 psi

Pavement strength index	22 to 246%
Subgrade modulus	82, 150, and 300 lb/cu in.

Some of the detailed test data used in this analysis have already been recorded in CAA Technical Development Reports (4, 8); the remainder will be published in the near future.

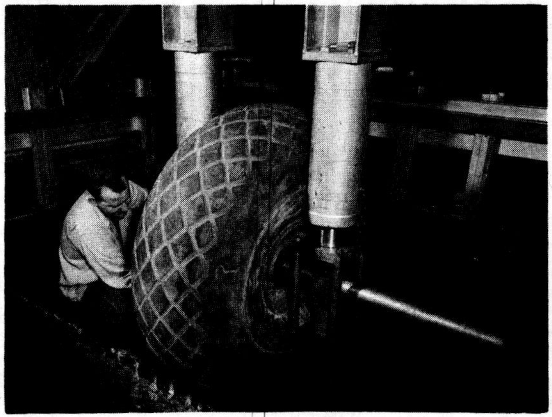

Figure 1. General view of load transmission apparatus.

APPARATUS, MATERIALS, AND PROCEDURE

The mechanical subgrade is about 10 ft square, with 3,600 segments supported individually by calibrated springs. The interior view (Fig. 1) shows a portion of the subgrade and a cutaway section of pavement, with an airplane tire in loading position. The subgrade pressure pattern is determined by reading spring deflections before and after loading the pavement. Each pavement section is subjected to a series of loads, increasing in magnitude, with the subgrade deflections measured after each load increment.

The tire inflation pressure is set at the desired value while the tire is entirely free of load, and is allowed to increase normally during the loading cycle. The actual inflation pressure at the heavier loads may be as much as 10 psi above the nominal pressure.

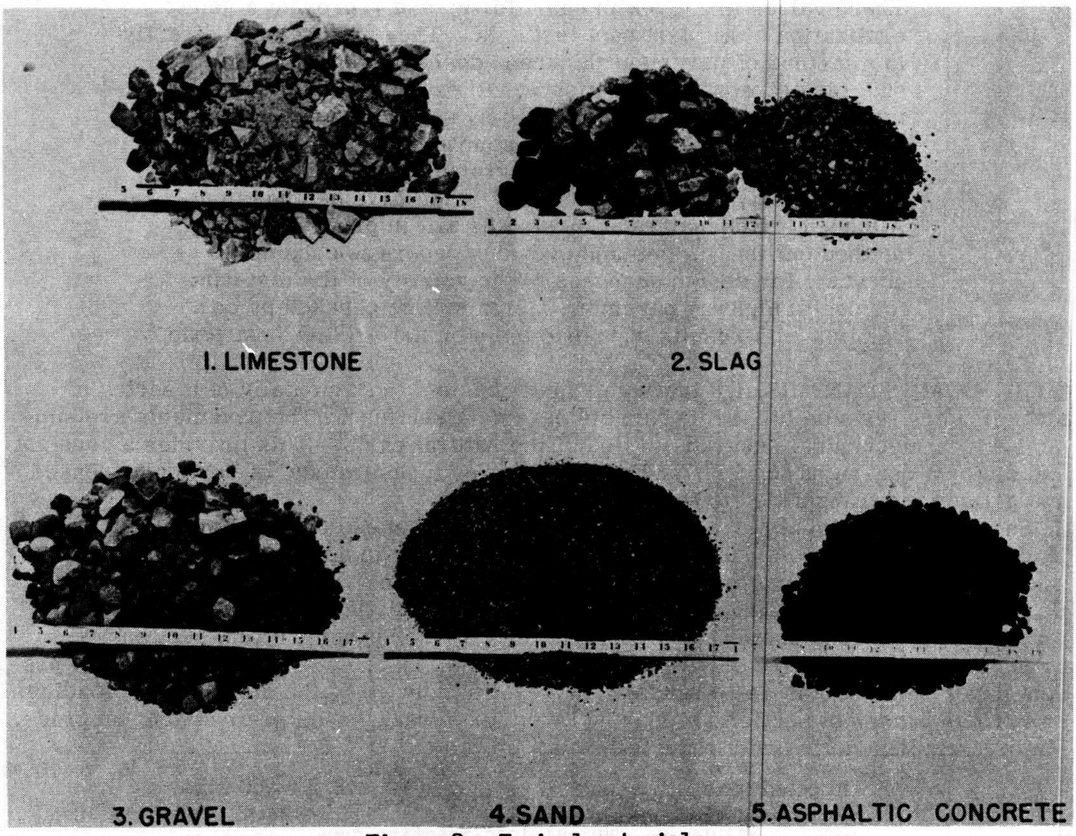

Figure 2. Typical materials.

A number of different airplane tires were used in the earlier tests. Although the size and geometric proportions of the tire appear to have some effect on the load-reaction curve, the effect is a minor one, at least for the range of tires used, and was not considered in the analysis.

Granular paving materials are blended and mixed in a pug mill mixer, placed in lifts of about 4-in. compacted thickness, and compacted by vibratory methods. Densities are comparable to those obtained in the field by rolling. A single material is usually used for the entire pavement depth, but some composite sections have been constructed.

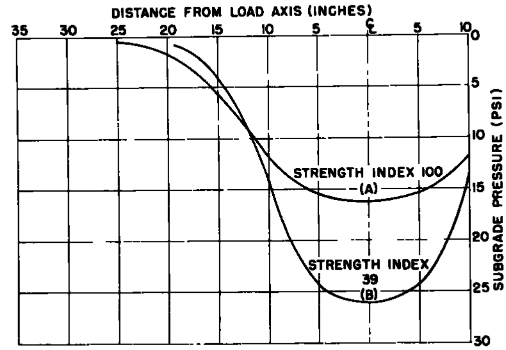

Figure 3. Cross-sectional views of pressure distribution.

The asphaltic hot-mix used to date has been obtained from commercial plants supplying material for highway and street work. Vibratory compaction of the asphaltic concrete has been supplemented by hand and pneumatic tamping.

Granular materials have included gravel, clay-gravel, sand, crushed limestone, and crushed slag. The materials were selected to provide wide ranges of grading, roughness, particle shape, and plasticity. They are not necessarily representative of

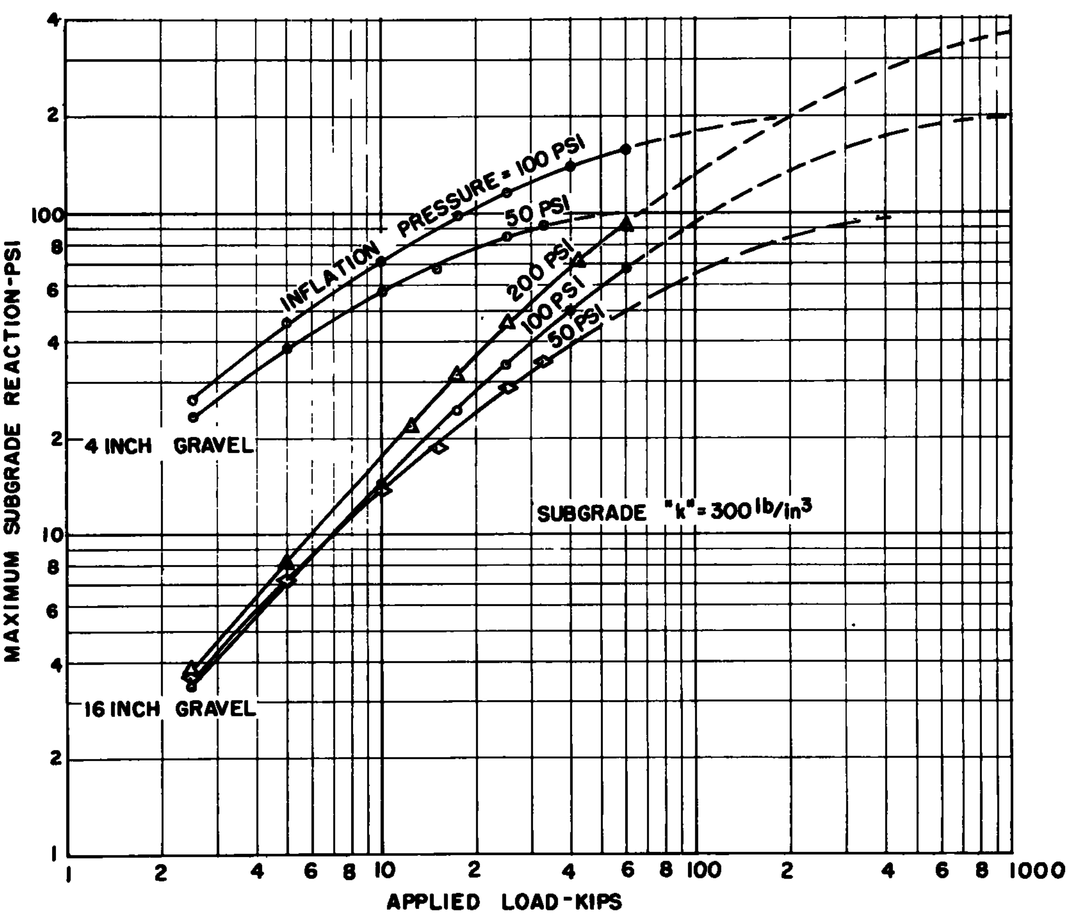

Figure 4. Typical load-reaction data.

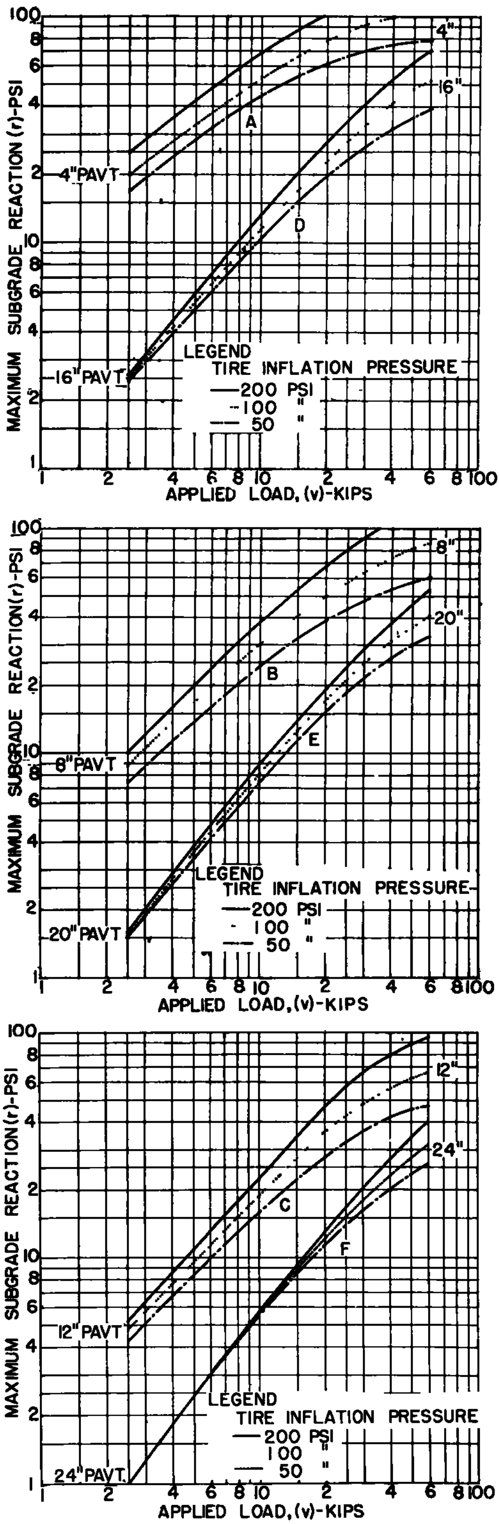

Figure 5. Generalized curves for standard gravel and weak subgrade.

the best or the average of the general types of material used. Typical samples are shown in Figure 2.

A portion of the paving mixture is set aside for construction of at least three triaxial specimens. These are designed to be of the same density, moisture content, and state of curing as the corresponding pavement section. When unplanned variations in these variables occur, the triaxial results are adjusted accordingly on the basis of judgment and experience.

There is some evidence that the lateral pressure for the triaxial test should vary, depending on the degree of confinement which the material will have in the pavement layer where used. The relationship and procedure now in use are defined later in the paper.

Inasmuch as the load transmission test itself is a static test, it follows that the triaxial tests should be run at a loading rate low enough to eliminate any dynamic effect on the indicated strength of material. This would involve loading at a strain rate of about 0.01 percent per minute, and would require several hours to run one test. In order to achieve a reasonable production rate the granular materials and mixtures, all of which are affected to a similar degree by rate of loading, have been tested at a strain rate of 0.5 percent. The asphaltic concrete specimens, much more sensitive to this effect, were loaded at a strain rate of 0.02 percent, which gave comparative results. The indicated strengths under triaxial test are not absolute values but are used only in comparing each material with the standard.

DISCUSSION OF TEST DATA

The pressure pattern on the subgrade may be expressed conveniently in the form of pressure "contours." When loading with single tires, however, with the maximum value always occurring under the center of load, the pressure distribution may be shown more simply by use of cross-sectional views on the principal axes of the pattern. This has been done in Figure 3.

Although the entire distribution pattern is required for some purposes, such as studies of multiple loading, it often is possible to use the maximum value of the subgrade reaction as a convenient measure of comparative pavement performance. For example, pavement A of Figure 3 has done

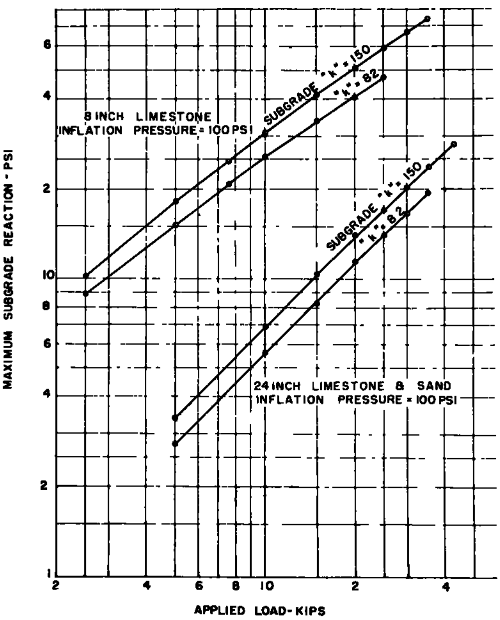

Figure 6. Effect of subgrade modulus.

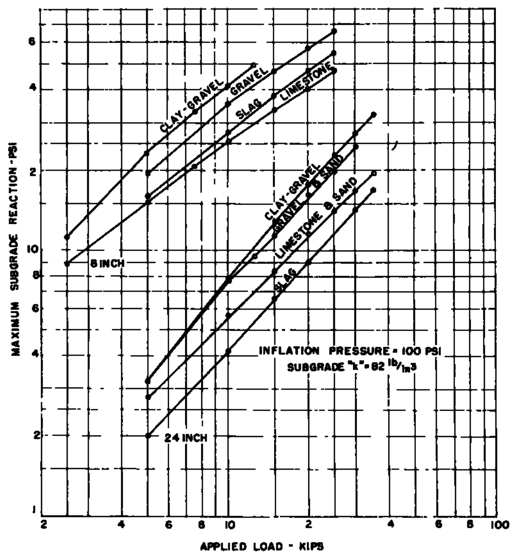

Figure 7. Effect of pavement strength.

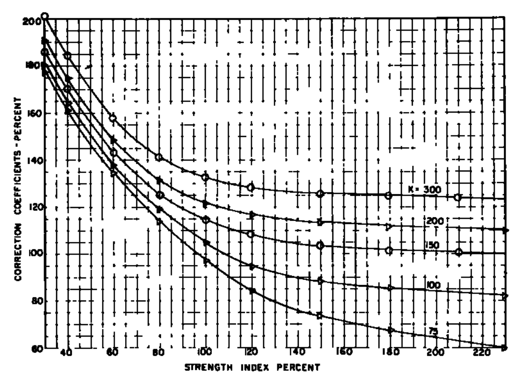

Figure 8. Correction coefficients.

a better job than pavement B in distributing load over the subgrade and this fact may be expressed by a numerical comparison of maximum subgrade reactions. This is the criterion used to measure pavement effectiveness in this report.

Figure 4 presents typical load-reaction curves plotted from actual test data. When plotted on log-log scales the bottom portions of the curves are nearly straight. The spacing and slope of the curves vary widely with pavement thickness. As the loads are increased the curves tend to flatten, reflecting the effect of increased contact area. If contact pressures on the pavement surface were uniform, and were equal to the initial tire inflation pressure, the maximum subgrade reaction would tend to approach this value as a limit when the applied load and corresponding contact area became infinitely large.

Lawton (9) showed that the contact pressure under a tire is far from uniform and may reach a maximum considerably above the nominal inflation pressure, even under moderate loads. The dotted portions of the curves in Figure 4 indicate that extrapolation of the curves to a value of twice nominal inflation pressure would not be unreasonable.

After compilation and analysis of all available data it was possible to construct the generalized curves of Figure 5 which by simple interpolation will give the relationship of maximum subgrade reaction to applied load for any combination of pavement thickness and inflation pressure within the limits indicated. These curves apply directly to only the standard gravel base course material and weak subgrade (k = 82). They are similar to those presented in CAA Technical Development Report No. 282 (8), but have been revised slightly for better over-all agreement with all the test data now available.

In order to generalize the curves for all conditions it is necessary to provide corrections for the effects of subgrade stiffness and the strength (or stiffness) of the paving material. Changes in either of these variables tend to move the loading curves parallel to themselves as shown in Figures 6 and 7. On a log-log graph this means that ordinates from one curve are related to those of another curve by a constant ratio. Values of maximum subgrade reaction taken from Figure 5 can be corrected for other subgrade and pavement strengths by simply applying correction coefficients taken from Figure 8.

Subgrade stiffness is indicated by use of the familiar modulus of subgrade reaction (k) used in Westergaard's theoretical analysis of rigid pavements. Use of this "heavy liquid" concept of subgrade support is particularly appropriate to the mechanical subgrade used in the load transmission tests.

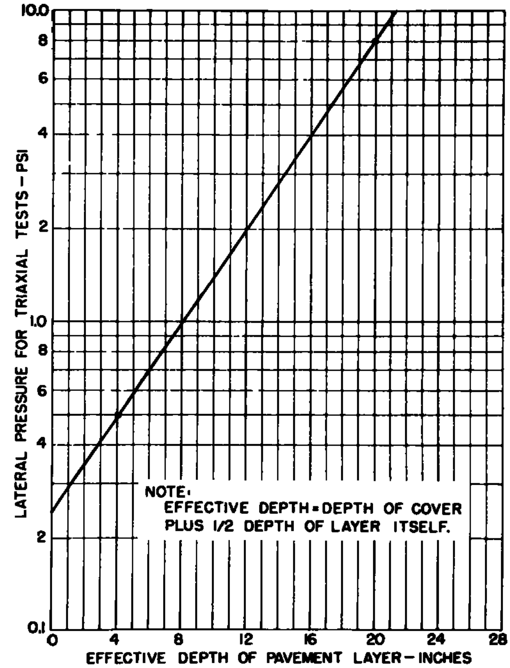

Figure 9. Determination of lateral pressure for triaxial tests.

The strength of the pavement section is expressed as a "strength index." This is the percentage of the strength of the gravel base course material used as a standard in preparing the curves in Figure 5. The strength index of a pavement section may be determined from triaxial tests in the following manner:

1. Divide the proposed pavement section into layers if necessary, each not more than eight inches thick, and each composed of only one type and quality of material.
2. Perform triaxial tests on specimens representing each layer of material, using a lateral pressure which is determined by the average depth of the layer in the pavement section. See Figure 9 for the lateral pressure to be used.
3. Divide the vertical pressure at failure, determined in Step 2, by the corresponding value for the standard gravel at the same lateral pressure. Values for the standard gravel are given in Figure 10, which also shows average curves for some of the other materials which have been tested.
4. If the pavement consists of more than one layer, take a weighted average of the ratios obtained for the various layers in Step 3. This is the strength index for the entire pavement section.

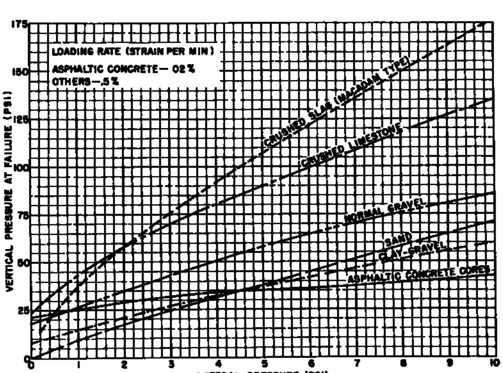

Figure 10. Triaxial test data--relationship of principal stresses.

It may appear that a modulus of deformation representing stiffness rather than ultimate strength should be a better criterion for comparing paving materials. This has not proved true in the analysis thus far, but is being studied further.

Values of subgrade reaction computed from triaxial test data by use of Figures 5 and 8 have been compared with the corresponding values actually measured in the load transmission tests. Deviations of measured values from computed values were plotted on probability paper and are in Figure 11. The plotted points approach a curve of normal distribution, indicated by a straight line on the graph. The standard deviation is 11 percent.

Of the 804 readings involved in the comparison, 93 percent fall within 20 percent of the computed values. Deviations greater than 20 percent occurred mostly in small readings where differences of one pound per square inch or less appear large when expressed percentagewise. Any closer correlation between computed and measured values apparently can be achieved only by use of a more complicated process, and does not appear justified from a practical point of view.

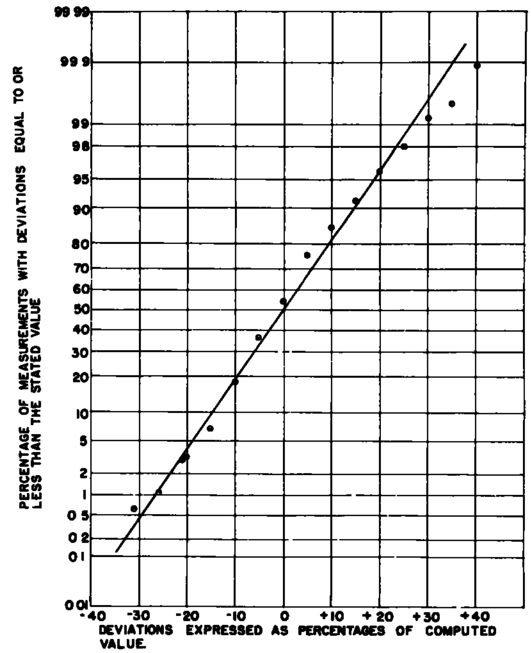

Figure 11. Deviation of measured vs computed values.

APPLICATION TO DESIGN PROBLEMS

From a qualitative standpoint the load transmission data add nothing new in the field of flexible paving design. Stated in general terms, the effects of pavement thickness, tire inflation pressure, pavement stiffness, and subgrade stiffness have been known for a long time, either through experience or through theoretical studies. What the load transmission project has done is to express these general relationships in specific figures which can be used in the design and evaluation of pavements.

It must be recognized, of course, that a pavement may fail from any one of three major causes, as follows:

1. Deterioration from weather or other environmental conditions.
2. Shearing failure or plastic flow within the pavement structure itself.
3. Subgrade distortion or displacement caused by a lack of load distribution in the overlying pavement. The third type of failure is very common and is the only one related directly to the load transmission studies.

Stress values predicted from the load transmission data may be used in checking theoretical thickness design formulas, in checking the shape and spacing of families of design curves, and in extending empirical design methods to areas not covered adequately by service experience. They also may be used directly in a method of thickness design based on a limiting stress or deflection in the subgrade. For a specific design problem it will be necessary to determine or assume the critical load, tire inflation pressure, and subgrade modulus, and the strength indexes of the materials under consideration for the various pavement layers.

The limiting subgrade deflection for a single load application may vary widely (say from 0.025 to 0.25 in.) for a given design problem, depending primarily upon the expected frequency of load application and the design life of the pavement. Deflection measurements from the WASHO and AASHO test roads, from military traffic tests, and from many universities and highway departments should prove valuable in setting the limit for a specific design condition.

It has been suggested that shear deformation or radius of surface curvature might be a better criterion of impending failure than would vertical subgrade stress or deformation. These suggestions are sound but tend to ignore the practical difficulties of measuring or computing the critical values involved. There certainly is ample evidence from both the field and the laboratory of a relationship between vertical deflection and failure. Evidence of an increasing interest in this relationship is given by the emphasis on deflection measurements of one type or another in the WASHO and AASHO road tests.

Although the triaxial test is the only strength test used extensively for comparing different materials in this CAA program, it is entirely possible that some other test could be used for this purpose. It would be necessary to know (a) that the test could handle the various materials in their normal field condition of moisture and density, (b) that it would simulate to a reasonable degree the field conditions of loading or stress development, and (c) that the measured quality or characteristic would be directly related to the stress resistance or strength of the whole structure.

One point of particular importance in pavement design is the time rate of loading. The critical pavement areas on airports are the aprons and taxi-ways upon which the loads are either static or moving slowly. The situation is somewhat different on highways except in urban areas, and particularly at intersections. All of this simply suggests that the time rate of loading in the basic strength test should be consistent with field loading conditions.

The load transmission test is a static test, corresponding to the most severe condition of airport paving design. The related triaxial tests were run at low rates of loading in order to minimize dynamic effects and provide a fair basis of comparison. Limited tests at other loading rates indicated that the asphaltic concrete was much more sensitive to this variable than were the granular materials. This implies better comparative performance under conditions of short-duration loading, and is consistent with the WASHO traffic tests. It is hoped that this effect can be studied further in subsequent research programs.

FUTURE TEST PROGRAMS

The load transmission testing equipment is now being used in a study of the effects of multiple-wheel loading. This is the only activity scheduled and will terminate the program unless a need is shown for further work of this type.

Although the testing program has been geared specifically to needs of the airport rather than the highway, it appears that the results may be, to some extent, applicable to both. The current AASHO road tests should provide a convenient opportunity to check this assumption.

CONCLUSIONS

1. Data from 804 test loadings have been generalized into curves from which the maximum subgrade reaction can be predicted for a wide range of flexible pavement sections and loading conditions.
2. The generalized data may be used directly in a pavement thickness design method based on a limiting subgrade deflection, or they may be used to supplement or extend other design methods.
3. Although further refinements are possible, particularly in the correlation between load test data and strength tests of materials, the relationships given in this paper are considered accurate enough for practical design use.

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Discussion

W. H. CAMPEN, Manager, Omaha Testing Laboratories, Omaha, Nebraska — Two questions are raised by this paper. First, in addition to reducing pressure on the subgrade, bases must resist consolidation and displacement. In other words, the bases must not displace at all and the consolidation should be neglible. In evaluating the distributive power of the bases in this research, was the deformation in the base courses measured and if so can they be included in the paper?

Secondly, the tests made with the transmission device show that bases composed of different aggregates reduce the pressure on the subgrades at different rates. Did the triaxial tests on the same mixtures show the same relative results? This is brought up because it was suggested that the quality of a base may be measured by the triaxial test.

It should be emphasized that the research conducted on the transmission device is of utmost importance. The research was undertaken at a great expense, to obtain basic information on (a) the distributive power of flexible bases, on subgrades of different strengths, by both tires and rigid steel plates; (b) the effect of quality of base; (c) the effect of composition of base; and (d) the effect of thickness of base and other points.

Although a number of reports have been made on several phases of the research, it is felt that the results have not been fully analyzed and summarized. It is suggested that the final analysis be made by a sub-committee of the Flexible Design Committee of the Highway Research Board.

D. W. LEWIS, Chief Engineer, National Slag Association, Washington, D. C. —This discussion is prompted by the lack of adequate explanation of the aggregate characteristics in the tests which form the basis for the author's summary of the CAA test program results. It is believed that the reader may not be aware of the differences involved, which affect the basis on which valid comparisons could be made.

For example, it is stated in the Synopsis that "the triaxial test is used to compare strengths of the various materials (gravel, clay-gravel, sand, limestone, slag, and asphaltic concrete) used in the pavement sections." Figure 7 shows comparative curves labeled only with the aggregate type—slag, limestone, etc. Inasmuch as slag and limestone are normally furnished in comparable gradings, this would lead the reader to assume that type of aggregate is the major variable involved.

In the section, "Apparatus, Materials, and Procedures," the statement is made that the materials covered "wide ranges of grading, roughness, particle shape, and plasticity: and in Figure 10 the curve for slag bears the label "Macadam Type." However no information is given which would permit the reader to evaluate the actual differences involved. Because this same difficulty is experienced to some extent in previous papers in this series, a review of the characteristics of these materials would appear to be in order.

CAA Technical Development Report No. 144 (author's ref. 2) reports the results of triaxial tests on the various materials used. Figure 1 in this report shows the gradation curves, and indicates that the slag and stone had essentially similar gradings, although the slag contained the lesser amount of fines from the No. 8 sieve down, and had about 1.5 percent of minus No. 200 material compared to 12 percent or more for the stone.

The triaxial results, shown in Tables I-IV and Figures 1-4 in Report No. 144, indicate considerably higher strengths for the slag at all lateral pressures tested. These results led the authors to state in Conclusion No. 7 of the report:

"In load transmission tests of base courses the crushed slag should be the best of the four materials tested triaxially and the sand should be the poorest. This tentative conclusion is subject to verification when load transmission tests are completed on all four materials. This conclusion applies to the particular materials tested, and should not be construed to include all other materials of the same general class."

Because no tests were run with the slag below 5-psi lateral pressure, it is not reasonable to extrapolate the data reported to cross the curve for stone, as is shown in Figure 10 of the current paper.

Reports of the load transmission tests are contained in CAA Technical Development Report No. 269 (author's ref. 6), but using a radically different grading for the slag than had been used in the triaxial tests. Macadam-type construction was used, with 1- to 1½-in. material placed first, followed by fines (all passing the No. 4) vibrated into place. It was described as "a gap-graded material practically devoid of fines passing the No. 200." However, the limestone used was a dense, well-graded crushed aggregate from 1½ in. to 0 with about 10 percent passing the No. 200 sieve, as in the triaxial tests. Thus the variable of grading—well-graded crushed aggregate vs a "macadam grading"—was added to the normal variations in particle shape, surface texture, angle of internal friction, etc., that originally existed between the slag and limestone. However, many of the results are reported or shown graphically in such a manner that the casual reader might well interpret them as showing differences between types of aggregate alone.

Triaxial curves shown in Figure 4 of Report No. 269 are identical to those in Figure 10 of the current paper, with the inference that they are based on data appearing in previous reports. The curves shown for "normal gravel" and "sand" match the average curves in Report No. 144, except that the one for sand has been extended—or extrapolated—to a zero value. The curve shown for limestone correlates closely with the maximum strength values shown in Report No. 144, but the curve for slag appears to be totally different from that previously shown.

The present paper does not resolve this question regarding the basis for the curves shown in Figure 10. If actual triaxial tests with slag in the "macadam grading" have been made, comparison of the results with those on the continuously-graded crushed slag reported previously would provide interesting information on the effects of grading on strength in triaxial compression tests.

With respect to the data as currently presented, however, the writer wishes to emphasize two points as follows:

1. Comparable test results for the two crushed aggregates used—slag and limestone—are available from the CAA studies only in Technical Development Report No. 144, where triaxial test results on similar gradations are reported.

2. Subsequent reports, including this latest summary, contain data based on tests involving the major variable of gradation—in fact, different types of construction—in addition to the variable of aggregate type.

It is unfortunate that these two major variables have been included in this manner. As a result, neither comparisons of slag with limestone (effect of particle shape, etc.), nor of graded crushed aggregate bases with macadam-type bases, can be made with any confidence in their validity.

CLOSURE, Raymond C. Herner--Mr. Campen's kind remarks concerning the load transmission testing program are appreciated and some clarification and elaboration of the specific points raised in his discussion are offered.

In some of the plate loading tests the deflections of both the surface and subgrade were measured. The internal deformation of the base course under load was then determined as the difference between these two deflections. For subgrade deflections in the range from 0.1 to 0.3 in. the ratio of subgrade deflection to surface deflection ranged generally from 65 to 90 percent for 8-in. pavements and from 25 to 50 percent for 24-in. pavements. Corresponding ratios from field test data available from other sources (such as the WASHO test road and the Hybla Valley test track) are of the same general order of magnitude. Surface deflections were not measured in the load transmission tests in which tires were used as the loading medium.

The effect of pavement quality is particularly significant if the pavement rests on a weak subgrade. In such instances the subgrade deflection under a pavement of poor quality may be as much as three times that found under a pavement of high quality and equal thickness. If the pavement is supported on a strong subgrade the effect of pavement quality is less. These comparative effects are shown graphically in Figure 8 of the current paper.

If reasonable allowances are made for accidental and experimental errors, the triaxial test procedure outlined will rate the materials in the same order of performance found in the load transmission tests. Although some unexplained differences have been found, and possible refinement of the correlation process is still being studied, the present procedure is considered to be sufficiently accurate for design purposes.

Up to the present the treatment of load transmission test data by the CAA has consisted primarily of organizing and summarizing the results of the loading tests and the correlation of these results with results from triaxial tests of the paving materials. Although general suggestions have been made for application of the test data to paving design problems, no attempt was made to set up a detailed procedure. If any responsible organization wishes to carry the work further, the CAA certainly will cooperate to the fullest extent possible.

Mr. Lewis indicates that he is interested primarily in a direct comparison of base course materials rather than the over-all objective of the load transmission testing program. He points out that the crushed slag used in the later tests was of somewhat different gradation that that described in T.D. Report No. 144, and infers that this change has tended to show slag to disadvantage in comparison with competing materials. A simple comparison of the reported data is sufficient to disprove this assumption.

Figure 10 of the current paper gives a strength of 107 psi for slag when tested at a lateral pressure of 5 psi, and 177 psi when tested at 10 psi. The corresponding values from Figure 3 of Appendix II of T.D. Report No. 144 are 96 and 139 psi. It appears, therefore, that the change in grading actually has increased the triaxial test values by 10 to 27 percent in the range of lateral pressures for which direct comparisons are available.

This illustrates the inherent danger in making blanket comparisons between competing materials. The CAA tests have shown that the effectiveness of a material for a particular use is governed by its gradation, moisture content, and state of consolidation, as well as by its mineralogical composition. The best material or mixture for one purpose is not necessarily the best for another, and the designer must consider all factors before making his decisions. The load transmission project is concerned only with finding the methods by which the pertinent facts may be measured and evaluated.

Except for the "standard gravel" curve, which is used as a basis of comparison for other materials, the triaxial curves given in the various references are intended only to show the range of values obtainable from materials of widely different physical characteristics. Each pertains only to the specific material tested, and readers have been warned repeatedly against unwarranted generalization of these specific test data. Although a comprehensive triaxial study of materials might well be justified, it is beyond the scope of the current project.

Mr. Lewis is incorrect in assuming that the slag and sand curves were extrapolated to the lower ranges of lateral pressure without benefit of test data. The records show that 46 specimens of the "macadam-type" slag mixture were tested at lateral pressures of less than 5 psi, and these form the basis for the later curves. Because of the voluminous test data from the load transmission project, involving literally millions of individual measurements, the results have been condensed somewhat for publication. The original data are available for inspection by anyone who wishes to avail himself of the opportunity.

Frankly, the author is somewhat mystified by the apparent concern of Mr. Lewis and his associates regarding the tests of their material. All tests to date have shown that slag is an excellent material for base course construction. All reports published thus far—including both T. D. Report No. 144 and the current paper—are entirely consistent on this point.