wearing courses have given satisfactory service. This is believed due in part to the fact that hotmix wearing courses were used extensively.

From the results of the evaluation and pavement behavior studies it is considered that the CBR method is reasonably satisfactory for both evaluation and design. The thickness requirements indicated by the design curves are satisfactory. The method of preparing the sample to meet the condition which is expected to ultimately obtain under the pavement is not entirely satisfactory. The indications are that it may be slightly on the conservative side even in conditions of heavy rainfall and high water table. As these conditions improve the conservativeness increases. In areas of low rainfall with excellent drainage and low water table the method is definitely conservative without the provision to reduce pavement thickness 20 per cent for these conditions.

As previously stated, steps are being taken to evaluate these conditions. The highway departments of several of the states have worked out numerical indices which certainly have merit and are worthy of consideration. The studies of moisture conditions under pavements in areas of different rainfall, conditions of ground water, and drainage conditions are improving our knowledge of flexible pavements and will lead to improved design. The general procedures employed by the Corps of Engineers have demonstrated they give good results. More data are being collected daily and as they are analyzed and correlated a more scientific method of design and evaluation may be developed.

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THE USE OF PLATE BEARING TESTS IN THE EVALUATION OF SUBGRADES FOR HIGHWAYS

VIII b 9

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INTRODUCTION

The use of load tests to test the strength of soil foundations has been made for many decades, as it was necessary for the builder to know if the foundation was strong enough to support the building or structure he proposed to construct. At first, the tests were rather crude and often performed without proper knowledge of the behavior of soils as foundation materials, with the result that in many instances the load carrying capacity of the foundation was exceeded and the structure suffered collapse or excessive settlement. As time went on, engineers learned more and more about the behavior of soils as foundations and more how to test them, until testing technique has now been developed to the point where engineers are able to measure quite accurately the load carrying capacity of soil foundations and their settlement characteristics.

Soil foundations for structures in most cases are several feet below the surface of the ground where they are protected from the action of the elements, such as moisture and frost action. In highway work the pavement foundation or subgrade is near the ground surface where fluctuations in moisture content and the effects of frost action are to be expected. This presents a problem to the pavement designing engineer who must taken into consideration the effects of these conditions. The extent of the fluctuations in moisture must be known and the effect they have on the bearing capacity of the particular soils determined. The depth to which frost penetrates and its effect must also be determined. This means that the engineer responsible for the determination of the correct bearing value of the subgrade must either conduct his loading test on the soils at the conditions anticipated or be able to intelligently adjust the values obtained at a certain condition to the condition anticipated.

When field loading tests are made on subgrade soils, they must be made at the conditions of moisture and density that exist at that time. It is on rare occasions that the existing conditions coincide with the conditions desired for the test and it is quite difficult to produce these conditions in the field if they do not exist. Some engineers adjust the bearing value obtained under the existing conditions to other conditions by the use of supplementary shear tests. A shear test is first made on a sample of the soil, either undisturbed or disturbed, having the same density and moisture content as the soil tested in the field loading test; and another shear test is made of the soil at the density and moisture content desired. These two shear test values are assumed to bear the same relationship with one another as the two bearing values.

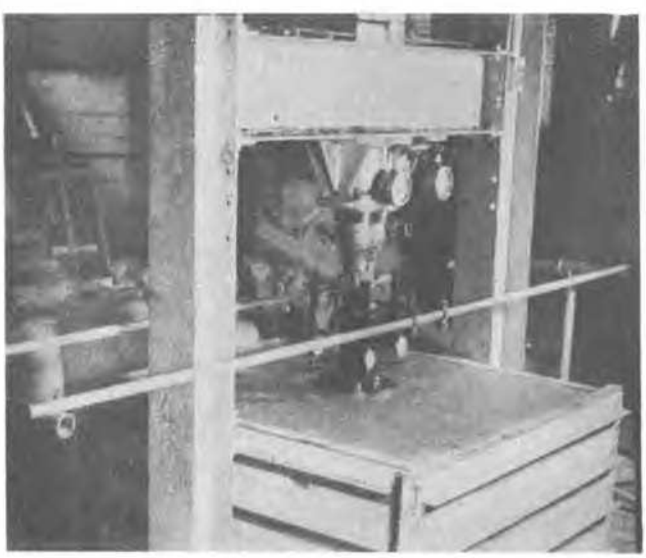
Another method of obtaining bearing values to suit the desired conditions is the Laboratory controlled load test. This test may be conducted full-scale for highway work without the use of very heavy equipment, since the equivalent diameter of the largest contact area of vehicles using highways is about 12 inches. This method is used by the Soils Laboratory of the North Carolina State Highway and Public Works Commission in their work on the evaluation of highway subgrades and bases under the direct supervision of the author.

THE LOAD TEST

The soil to be tested is mixed with sufficient water in a concrete mixer to raise the moisture content to the percent desired, and then it is placed in layers in a box, 42 inches square and 24 inches deep. Each layer is tamped with a pneumatic tamper to the density desired. The thickness of the soil layers and the amount of tamping governs the density obtained and these factors vary with the soil. The magnitude of these factors is determined experimentally. The compacted soil is covered with water-proof paper or canvas to prevent evaporation and the mass allowed to "season" from 24 hours to 36 hours. This seasoning period allows a more uniform distribution of moisture. This cover material is also used over the area of the soil not covered by the bearing plate during the loading test.

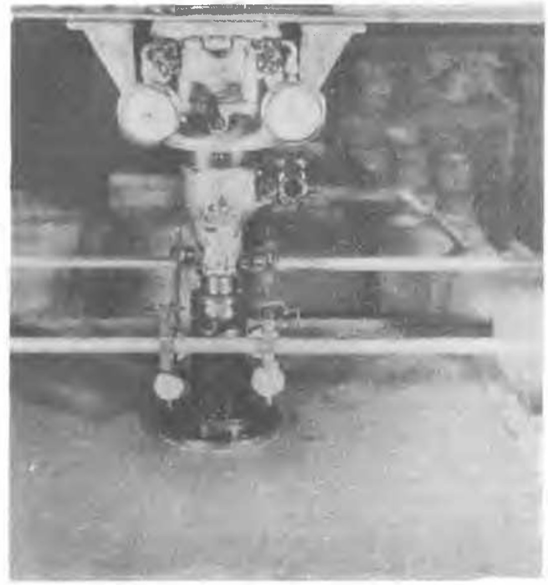
After the soil has been properly seasoned, the bearing plate is carefully seated and levelled on the surface of the soil in the exact center of the box. When placed in the exact center of the box, the plate is in proper position to receive the head of the 25-ton Black and Decker Loadometer which is attached to the cross-beam of an "H" frame.

The loadomater is equipped with two pressure dials which indicate pressures applied in pounds. One of the dials has a capacity of 5,000 pounds, registering in 25-pound divisions, and the other has a capacity of 20,000 pounds, registering in 100-pound divisions. The pressure dials are attached to the Loadometer with a "T" connection equipped with two-valves for shutting off the pressure from either dial when not in use. Figures 1, 2, and 3 are illustrations of the load testing equipment in operation.



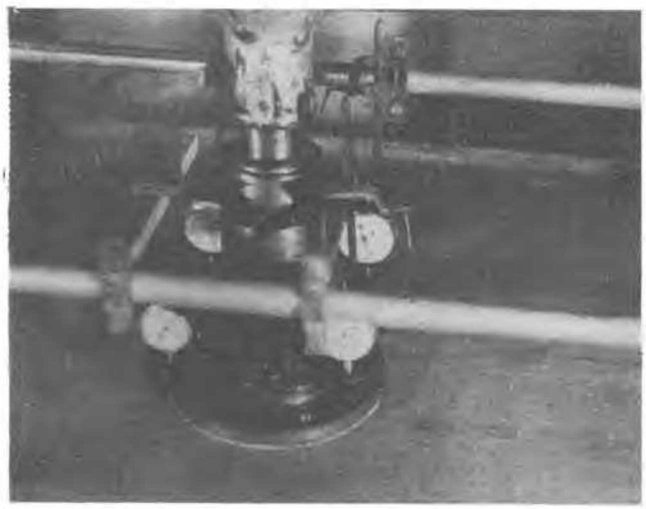
Laboratory load test apparatus in operation

FIG. 1



Close-up of loadometer and dials

FIG. 2



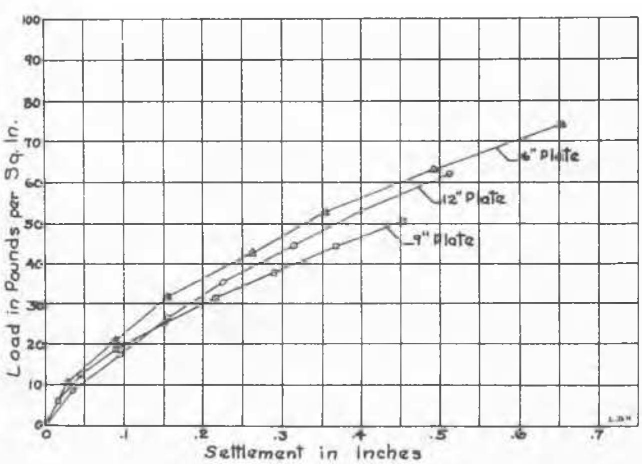
Close-up of micrometer dials showing their arrangement

FIG. 3

Four micrometer dials capable of measuring to .001", with a range of 1", are placed equidistantly around the circumference of the plate for measurement of settlement. They are supported by suitable rods connected to rigid reference points situated outside of any zone of influence.

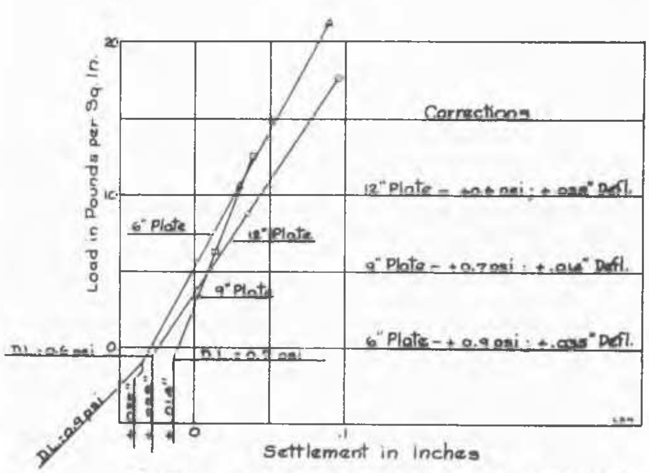
Load tests are made with 3 round, steel plates, 1" thick, and having diameters of 12", 9", and 6". The use of three plates of different diameters permits establishment of a load-area relationship and determination of stress reactions and soil coefficients essential in measuring the bearing capacity limit of the soil. This technique was developed by Professor W.S. Housel and reported by him at the International Association for Bridge and Structural Engineering in 1936.

The static type of load test is used by the North Carolina Laboratory which consists of applying loads in increments to the plates and measuring the settlements caused by the loads. Each load increment is held for one-hour or until movement of the plate has ceased for a period of 15 minutes, whichever occurs first. The micrometer dials are read and the readings recorded at 5, 20, 35, 50, and 60 minutes after the load application. In this manner the amount and rate of settlement are determined. If all plate movement ceases within the 60-minute interval, the total load is not causing failure, but when there is indication from the 50-minute reading that all settlement will not cease at the end of the hour, the total load on the plate is causing failure. The total load to be used in the test is divided into seven or eight equal increments and each increment applied cumulatively. It is desirable that the increments be of such magnitude that at least three or four can be applied before failure of the soil is indicated. At the conclusion of the loading, the total load is removed from the plate and, when all movement ceases, the micrometer dials read and the readings recorded for measurement of recovery. Load test data are used to construct load-settlement diagrams as shown in Figures 4, 5, and 6.



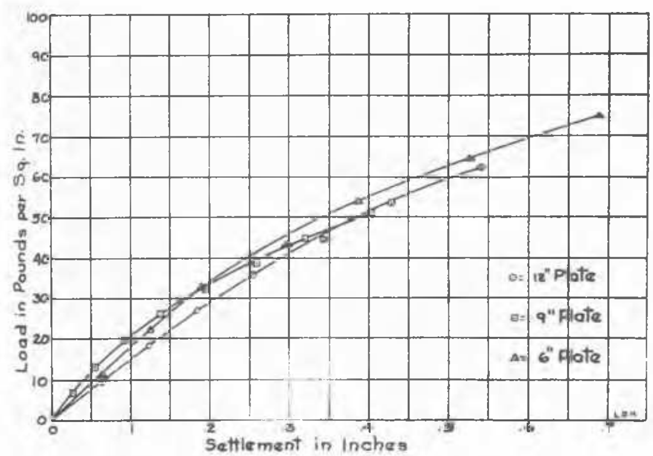
UNCORRECTED LOAD-SETTLEMENT DIAGRAMS

FIG. 4



CORRECTIONS FOR LOAD-SETTLEMENT DIAGRAMS

FIG. 5



CORRECTED LOAD-SETTLEMENT DIAGRAM

FIG. 6

DETERMINATION OF BEARING CAPACITY

The bearing capacity limit of a soil is the maximum load it will carry without failure. When a soil mass is loaded, settlement occurs, which may be attributed to consolidation, a permanent deformation, to elastic deflection, a temporary deformation recoverable upon removal of the load, and, if the load is of sufficient magnitude, to plastic flow, a permanent deformation. Loads that procude plastic flow are in excess of the bearing capacity limit of the soil.

According to Housel, referred to elsewhere in this paper, the supporting power of soil is dependent upon two stress reactions, perimeter shear and developed pressure, which he designates as "m" and "n", respectively. A load, W, having a perimeter, P, and an area, A, resting on a soil is supported by a reaction consisting of the perimeter, P, times the perimeter shear, m, and a reaction consisting of the area, A, times the developed pressure, n. This expressed algebraically is

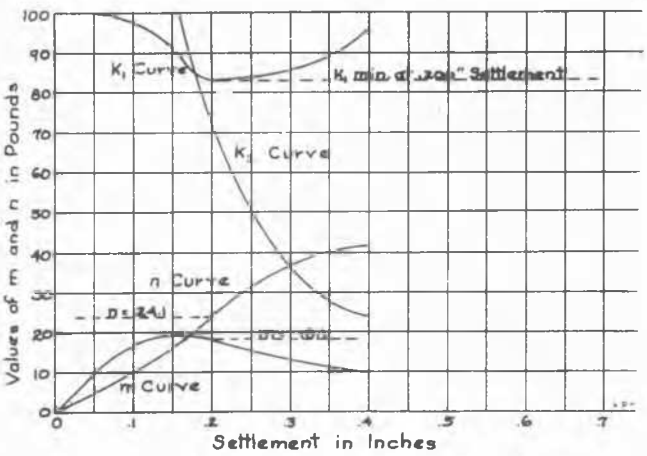
$$W = Pm + An$$

which may be reduced in terms of unit pressure by dividing through by the contact area, A,

$$\frac{W}{A} = \frac{Pm}{A} + \frac{An}{A} \quad \text{or } p = \frac{P}{A}m + n,$$

the equation for bearing capacity.

The load- settlement curve and the size of the bearing plate give all values in the equation except m and n which necessitates data obtained with two or more plates for determination. Values of unit load, p, necessary to apply to two plates of different diameters to secure the same amount of settlement may be substituted in the above equation for bearing capacity to give two equation which can be solved as simultaneous equations for values of m and n. By continuing this procedure for different values of p found in the load test to produce the same settlements of the plates and plotting the values of m and n thus obtained against their corresponding settlements, curves as shown in Figure No 7 may be drawn, from which values of m and n may be determined for any settlement. Load test data from only two plates of different diameters are sufficient, but accuracy practically demands a minimum of three. The use of three plates permits three combinations from which three values of m and n are



STRESS REACTIONS AND SOIL COEFFICIENTS

FIG. 7

obtained for any settlement. The average of each of these three values is used to construct the m and n curves.

The m and n curves do not indicate the bearing capacity limit of the soil, but their relationship and the relationship of values of n to settlement do give coefficients that do indicate the "critical settlement" whose corresponding values of m and n, when substituted in the formula for bearing capacity, determine this value. The coefficients are K_1, the ratio of settlement and developed pressure (d/n) and K_2, the ratio of m and n (m/n). The values of these coefficients are plotted against their corresponding settlements, as shown in Figure 7, and the "critical deflection" occurs at the minimum value of K_1, or the maximum value of K_2, whichever has the smallest settlement.

The data used to construct the diagrams and curves shown in Figures 4, 5, 6, and 7 were obtained from an actual load test made in the North Carolina Soils Laboratory. According to the analysis of the dataas shown in Figure 7, the "critical settlement" occurred at .200", at which settlement the value of m is found to be 18.1 pounds per lineal inch and the value of n to be 24.1 pounds per square inch. Substituting these values in the bearing capacity formula, p = (P/A x m) + n, we have the following values of the bearing capacity limit for the 12"-, 9", and 6" - diameter plates;

p (12" plate) = (1/3 x 18.1) + 24.1 = 30.1 psi.
p (9" plate) = (4/9 x 18.1) + 24.1 = 32.1 psi.
p (6" plate) = (2/3 x 18.1) + 24.1 = 36.2 psi.

In the design of flexible pavements for highways, the value for the 12-inch diameter plate is used, as this diameter is approximately equal to the equivalent diameter of the largest contact area covered by the wheels of the largest highway vehicles.

The bearing values as determined above are the maximum for the soil in that condition of density and moisture content, and when the load is of such magnitude as to exert unit pressures over the areas of contact, a settlement of .200" is to be expected. If the pavement to be placed over this subgrade has a "critical deflection" of only .015", the value of the bearing capacity limit as determined above for a 12-inch plate cannot be utilized without pavement failure. A lower bearing value which will cause only .015" settlement must be used in the design. This value may be calculated by substituting the values of m and n for .015" settlement in the bearing capacity formula. From Figure No. 7 it may be observed that the values of m and n for .015" settlement are 19.3 and 16.1, respectively. Substituting these values in the bearing capacity formula, p = (P/A x m) + n, we have

p (12" plate) = (1/3 x 19.3) + 16.1 = 22.5 psi.

One of the distinct advantages of this method of making a load test is that not only is the bearing capacity limit and the "critical settlement" determined for the soil, but the analysis discloses the values of the reactionary stresses m and n for smaller settlements than the "critical", which permits calculation of corresponding bearing values to suit any predetermined deflection or settlement. Since the test is conducted with three or more plates, the resulting data gives good average values for the soil, a feature to be appreciated in soils engineering work. As stated before, the testing technique and the method of analysis of the load test data was developed by Professor W.S. Housel of the University of Michigan and used in his practice as consultant on many foundation problems. For more details concerning the technique of the load test and the analysis of the data, the reader is referred to Professor Housel's article presented at the International Association for Bridge and Structural Engineering in 1936 under the title "Research in Foundations and Soil Mechanics."

DETERMINATION OF FIELD CONDITIONS

As stated before, the moisture content and density of the soil at the time of load testing is of vital importance. The proper determination of these important factors should be made by careful investigations of soils in service in the particular locality under consideration. One such investigation has been made in North Carolina and another is almost completed in which moisture contents of soil type bases and subgrades in service under the highways in all parts of the State have been observed during every month in the year. In place density tests were also made and samples taken for other tests, such as Mechanical Analysis, Atterberg tests, Compaction tests, and Specific Gravity. The pedological types of the subgrade soils were also determined for the purpose of future correlation of the results of the investigations with the pedological system of classification, if found possible.

Although the field work of these investigations has been completed, a few laboratory tests are to be completed before the data can be recapitulated and thoroughly studied.

The results obtained to date indicate that subgrade densities found in the field will average slightly under those obtained by the Standard compaction test (American Association of State Highway Officials Designation: T 99-38). Seldom were densities found to be less than 90% of this value and many were found to exceed this value slightly. It is therefore indicated, at the present, that the density of the soil should be at approximately that obtained by the Standard compaction test when load tested. This is the density required in the load tests made up to the present time.

The moisture content of a soil expressed as a percent of the weight of the dry soil has little meaning unless the type of soil is known and the influence various moisture contents has upon that type. A well graded sandy soil compacted to Standard density will be saturated with a moisture content of about 12% by weight while a heavy clay soil compacted to Standard density will require nearly three times this percentage for saturation. The subgrade soils encountered in the two investigations were found to belong to the A2 non plastic and plastic, A4, A7-5, and A7 Subgrade Groups, as classified by the Public Roads Administration,and the moisture percentages were found to vary more with the type of subgrade than with the seasons of the year. A preliminary examination of the data obtained to date indicates that, in general, the moisture contents of subgrade soils belonging to the A2 and A4 groups stay below the point of saturation the year around, and in the majority of cases do not exceed the optimum moisture for Standard Compaction, which is the moisture contents used in the soils that have been tested for bearing capacity by load tests. The moisture contents of the subgrade soils belonging to the A7-5 and A7 groups ,however,were found to approach the saturation point, which exceeded the optimum moisture for Standard Compaction. In some cases this excess was quite appreciable, which will in all probability necessitate corrections to be made to the load test values obtained on these type of soils. Future load tests made on soils of these types will be conducted at higher moisture contents than in the past. Just how much higher moisture contents will be used and their relation to the saturation point of the compacted soil, the optimum moisture for Standard compaction, the Plastic Limit, or any other test value is yet to be determined by a careful study of the data obtained from the two investigations. It is not expected that this change will materially affect the values used in present design practices in this State as they are somewhat conservative due to the lack of exact information concerning moisture conditions at the time the values were tentatively adopted.

CONCLUSIONS

The evaluation of highway subgrades can be accurately done by the use if plate bearing tests if the proper testing technique is followed and the results correctly analysed. The testing technique described and the analysis of the data obtained in which stress reactions and soil coefficients are used to calculate bearing capacity seem to the writer to be sound, and while the work required seems to be considerable, when compared with that required by some other methods, the results achieved are more reliable and useful in bearing capacity determinations.

Conditions of moisture to be encountered is a most important factor in placing the correct evaluation on a subgrade, since this factor has much influence on bearing capacity.Assumptions not based on factual data obtained from thorough investigations may lead to errors of some magnitude.

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FLEXIBLE PAVEMENT DESIGN CRITERIA FOR VERY HEAVY MULTIPLE WHEEL LOAD ASSEMBLIES

VIII b 10

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The present trend in landing gear assemblies for the very heavy airplanes is toward multiple wheels..It is expected for the near future that these planes will have their weight carried by two principal wheel assemblies,each composed of a twin-tandem arrangment of wheels with the tires inflated to as high as 200 psi with 300-psi pressures a possibility. This paper will present the method used by the Corps of Engineers to develop flexible pavement design criteria considered satisfactory to support this type of wheel load. It is recognized that complete design criteria will include requirements as to the type and quality of the several component parts of the pavement structure, and compaction requirements to prevent detrimental settlement. However, this discussion will be limited to the development of total thickness requirements of base and pavement to prevent shear failure in the underlying subgrade soil.

To date, the Corps of Engineers has no factual data relative to requirements for high pressure tires and for twin-tandem assemblies. Single wheel design curves for wheel loads up to 200,000 lb have been developed and are believed reasonable for tire pressures of about 100 psi. These curves are presented in Part XII of the Engineering Manual published by the Office, Chief of Engineers, and their development has been the subject of numerous papers. 1), 2). Data are available and an analysis has been made for twin wheels as a result of a special study to determine the flexible pavement requirements for the B-29 Superfortress.3) A method of design for any multiple wheel assembly and for tires inflated to 100 psi has also been presented. 4) Therefore, although the method of design which will be presented must be considered as tentative and will require validation, it is not entirely theoretical since it does have some foundation of ac-