have been opened than at the time the soil survey is made. The identification of the soil profile indicates roughly the amount of these items to be provided for on plans, but in Michigan's variable glacial deposits final dimensions can best be fixed when the cut is made and the grade exposed for study in detail. During this period the soil engineer serves as consultant on such problems as foundations for structures, peat marsh treatment, slope treatment, erosion control, borrow materials, and density control in embankment construction.

This standard soil survey procedure may be varied to meet special conditions. In connection with flexible pavements one of these special conditions is presented by the so-called betterment program of sealing or surface treating existing gravel roads. Projects of this type are low cost and do not involve the conventional surveys and plans. In this case the soil map with subgrade corrections and other recommendations may serve as plans for the project (Fig. 2).

Michigan soil survey methods lend themselves to application in a wide range of design, construction, and maintenance activities. They are fast, simple, and economical of personnel. The field identification of soil profiles is completed first. Sampling and testing operations follow. The most important function of the field identification survey is to supply soil engineering design information, but in addition to this function it also contributes in a number of ways to the value of laboratory test results. First, it provides area significance to test results. Second, it yields information concerning the extent to which the environment of the sample may be normal at the time of sampling. Third, it indicates changes which may be expected in this environment. Finally, it suggests the influence which these changes will exert on the significance of test results. In this varied manner the soil survey supplies the background for the design of flexible surfaced roads in Michigan where subgrade conditions so quickly express themselves in surface behavior.

DEVELOPMENT OF A PROCEDURE FOR THE DESIGN OF FLEXIBLE BASES

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SYNOPSIS

The design procedure described in this paper is the result of an investigation, still in progress, set up to establish a relationship between field performance of granular bases and bearing values obtained in the laboratory by means of the California bearing test, or modifications thereof.

The field investigation involved condition surveys of bituminous surfaces placed on granular bases, the determination of thickness, density and moisture content, and North Dakota cone bearing value of the subgrades. Samples of the base materials and subgrades were sent to the laboratory for analysis and bearing values. Field moisture and density determinations were also made to determine seasonal and annual fluctuations in bases and subgrades.

The field studies revealed that failures had occurred within practically the entire range of moistures and densities found in the road, which would indicate generally inadequate thickness of base on plastic soil subgrades. There was some relation between moisture content and the plastic limit of the subgrade soils. At more than 95 percent of the test points the subgrade densities were between 90 and 105 percent of AASHO-T99 maximum density and averaged 97.2 percent. It was apparent that under these density conditions the subgrade moisture content was the most important factor in determining whether or not failures occurred at any given thickness. The field data also indicated that during the

period from 1943 to 1945 the average subgrade and base densities remained reasonably constant. The average moisture contents in subgrades and bases were practically the same in the summer of 1945 as in 1943. The average maximum moisture content found in the spring of 1945 exceeded that found in the summer by 0.8 percent in the case of bases and by slightly more than 2.0 percent for the upper six inches of the subgrades.

Laboratory tests were made using the California bearing test procedure on specimens molded as described in the 1938 Proceedings and on specimens compacted to standard AASHO and modified AASHO densities. It was concluded that, for all methods of compaction used, soaking of the specimens from the top resulted in moisture conditions more severe than were found in the field and that some modifications of the soaking procedure was desirable.

On the basis of considerable laboratory data it was decided that the California bearing test offers a practical method for evaluating subgrade soils and granular materials provided that samples are tested at moisture contents and densities such as exist or are anticipated on Minnesota roads. Plastic subgrade soils are compacted to 97 percent of AASHO maximum density and at moisture contents equal to a percentage of saturation determined from the relationship established between plastic limit and percentage of saturation. Bearing tests are made on plastic soils without soaking or using a surcharge on the specimens. For granular materials design bearing values are determined from tests on specimens compacted to AASHO maximum density and subjected to four days soaking from the bottom. A surcharge is used during the soaking and bearing tests.

A curve was developed by plotting the bearing values obtained in the modified California bearing tests described above against the combined thickness of base and mat found at the test point in the field. By use of distinctive symbols representing failure and non-failure, it was found that the curve could be drawn in such a position as to indicate minimum thicknesses above which practically no failures occurred. This curve and the above described test procedure form the basis of design of flexible bases in Minnesota.

Construction of granular bases for bituminous surfaces was begun on an experimental basis in Minnesota in 1934. Beginning in 1936 and continuing up to the present time, granular bases, as a step in stage construction, have constituted a considerable portion of the construction program. As of January 1, 1946 there were 2,338 miles of bituminous surfaces built on this type of base. The experience with this type of road has been such as to justify its continued use.

At the time of our early work with this type of construction there was little precedent to serve as a basis of design. Design of the stabilized mixtures and the depth of base to be used were based on the data obtained in a soil survey of the project. Improvements in the design and in construction methods have been made as a result of experience gained since 1934, but the development of standards for the evaluation of the subgrade soils to serve as a criterion for required depth of base has been, until relatively recently, based on "trial and error." General observations and detailed field condition surveys furnished information which was used in improving the design of later construction. With this background a tentative basis, entirely empirical, was set up in which the thickness of base was dependent upon the textural class of the soils of which the subgrade was to be constructed. The following tabulation shows the base depths commonly used up to 1940, as related to the classes of subgrade soils:

Textural Class	*Base Depths*[a]
Sands, loamy sands and better sandy loams	2 to 4 in.
Poorer sandy loams, loams, clay loams, silty clay loams and some of better clays	6 in.
Heavy clay loams, silty clay loams, loessial silt loams and poor clays	6 to 12 in.

[a] not including bituminous mat.

Some variations were made from the tabulated standards, depending on availability of materials, traffic conditions, height of grade line and other local conditions. Some consideration was given to quality of material used in the base course but the design of the stabilized mixture was largely dependent upon the proportions of the gravel aggregate and the soil binders. The binder soils were frequently heavy and in such instances considerable difficulty was encountered in the mixing operations.

The need for a more scientific basis for determining base thickness had been recognized during the earlier stages of development. Although a number of theories and suggested procedures had been published none had been generally accepted. It was recognized that there was a relationship between the conditions and properties of the subgrade soils and the thickness of base required to carry a given load. The problem was (and still is) to establish a practical measure of this relationship.

Following a few years of service it became apparent from condition surveys that the development of a more reliable yardstick for the determination of base thickness was imperative. An evaluation of our design standards on the basis of field performance was necessary, so a research project having the following broad objectives was set up:

1. To develop a method for determining the required thickness of flexible bases.
2. To establish procedures for improving the construction of subgrades; and
3. To revise our specifications governing the design and construction of soil-stabilized gravel bases.

The investigation was set up to embrace a field study of previously constructed bases and a laboratory study. The latter was an attempt to develop a method for the evaluation of subgrade and base materials as a basis for design.

The field study was begun in 1942 and was continued in 1943, 1944 and 1945. Projects included in the 1942 survey were for the most part selected because of the numerous failures which had occurred on them. In the later surveys other projects were studied to include wider ranges of soil classes, base thicknesses, and types of construction. Projects on which very few or no failures had occurred were also included.

On each project data were obtained regarding the construction history, general surface condition at the time of survey, type and volume of traffic, and general drainage conditions. Several test points were selected on each project. At each point of test the following information was recorded:

- Location by stationing or mileage and distance from center line
- Cut or fill section
- Approximate gradient
- Height of grade above natural ground or ditch bottom
- Description of surface condition and condition of bituminous mat and base
- The height of grade above water level if water was standing adjacent to the road.

The thickness of bituminous mat, base and sub-base was measured. Moisture contents and densities of the base, sub-base and of the upper 6 in. of subgrade were determined. The moisture content at an 18-in. depth in the subgrade was also obtained. The textural classification of the soils in the subgrade to a depth of 2 ft was recorded. North Dakota cone tests were made on the surface of the subgrade. During the 1942 and 1943 surveys samples of the subgrade were taken at most test points, and samples of base were taken from one or two test points on each project. Samples were at least 50 lb to provide sufficient material for the various laboratory tests.

The extent of the surveys was as follows:

Projects	*Test Points*
1942—19[a]	72
1943—40	189
1944—10	60
1945—12	109

[a] partial information on 4 other projects.

The survey in 1945 differed somewhat from the previous ones in that several sets of observations were made during the spring thawing period which started about March 12th. During June and early July tests were repeated at the same points, so that a record of moisture fluctuation during the spring "breakup" season was obtained. Of the 12 projects in the 1945 survey, eight had been studied in 1943 and five in both 1943 and 1944.

In selecting points at which to make the tests, cracking of the bituminous mat in the wheel tracks was considered as failure, regardless of the degree of severity of the cracking and deformation. Tests to determine conditions at failed sections were made only at points where the failures appeared to be progressing in area or severity at the time of survey. At many points of failure which had occurred prior to our surveys, it appeared that conditions had changed so that when the survey was made these areas were carrying traffic with no evidence of further distress.

Figure 1 shows a typical failure caused by excessive yielding of the subgrade.

Figure 1. Typical Failure

TABLE 1
TYPICAL FIELD DATA

Station	Condition	Thickness		Soil Class	Dry Density		Moisture		N.D. Bearing Subgrade
		Mat	Base		Base	Subgrade	Base	Subgrade	
		in.	*in.*						
4006+80	Allig. & Displaced Sealed but slightly porous	1	3	Clay Loam Till	132.3	97.0	5.5	19.36 18.21 at 18 in.	390
4028+10	Allig.—Well sealed	1	6	do.	140.9	97.5	5.2	19.00 21.53 at 18 in.	440
4056+80	Bad rutting & Allig. See picture	1	3	do.	140.5	99.5	4.7	18.80 19.40 at 18 in.	279
4124+30	Cracking & Allig.	$\frac{3}{4}$	4	do.	136.3	98.7	6.0	18.45 20.78 at 18 in.	353
4153+10	Good—Fill section	$\frac{3}{4}$	7	do.	131.2	105.7	5.7	18.52 24.89 at 18 in.	372
4167+30	Bad displacement	$\frac{3}{4}$	4	Bl. C. L. 7–12 in.	138.0	102.9	5.0	20.46 29.61 at 18 in.	344
4230+00	Good	$\frac{3}{4}$	$3\frac{1}{2}$	F. & V.f. S.L.	130.3	94.4	5.7	21.79 20.88 at 18 in.	306
4304+50	Yielding—Well sealed Low fill	$\frac{3}{4}$	5	Clay Loam Till	136.3	107.5	5.2	18.94 22.49 at 18 in.	374

R.S. 4207—MARSHALL-LYND—T.H. NO. 23—7-28-42
Base, 1940—MC-O Prime, $\frac{3}{4}$ in. S.C. Mat, 1940—Light Seal in 1941

A tabulation of typical data obtained from the field surveys is shown in Table 1.

Routine identification tests were made on the subgrade samples taken during the 1943 survey and moisture-density curves were obtained by the method of AASHO T99-38. A comparison of the 1943 field moisture and density data with the soil properties determined from the laboratory tests, appeared to warrant the following conclusions:

1. As shown in Figure 2 some failures had occurred within practically the entire range of moistures and densities found in the roads studied. This would indicate that the base

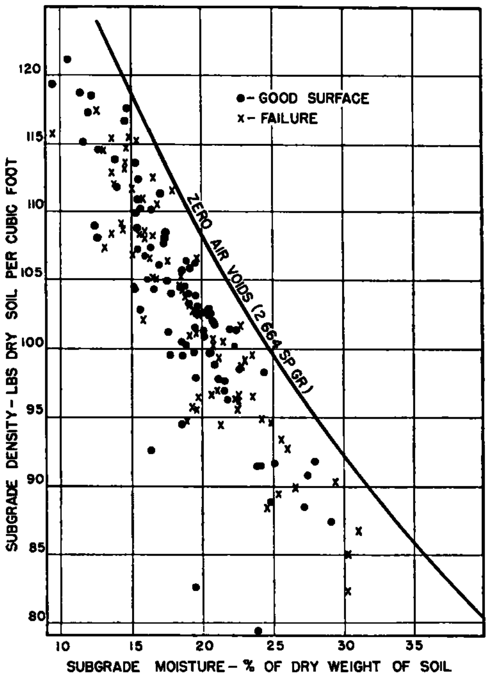

Figure 2. Moisture and Densities in Subgrades 1942–1943 Surveys

thicknesses which had been previously used were inadequate on most subgrades composed of plastic soils.

2. The subgrade moisture contents expressed as percent of dry weight of soil varied with different textural classes of soils and there was some degree of relationship between the moisture content and the plastic limit of the soil as shown in Figure 3.

3. Subgrade densities averaged 97.2 percent of the maximum density determined by the method of AASHO T99-38. The range in densities was not wide, since at more than 95 percent of the tests points the subgrade densities were between 90 and 105 percent of maximum, and at about 60 percent of the test points densities from 95 to 100 percent of maximum were found.

4. In studying the soil classes and properties, thickness of base and mat, and the moisture and density of base and subgrade, all as related to surface conditions at the various test points, it appeared that subgrade moisture content was possibly the most important factor in determining whether or not failures occurred at any given thickness. For instance

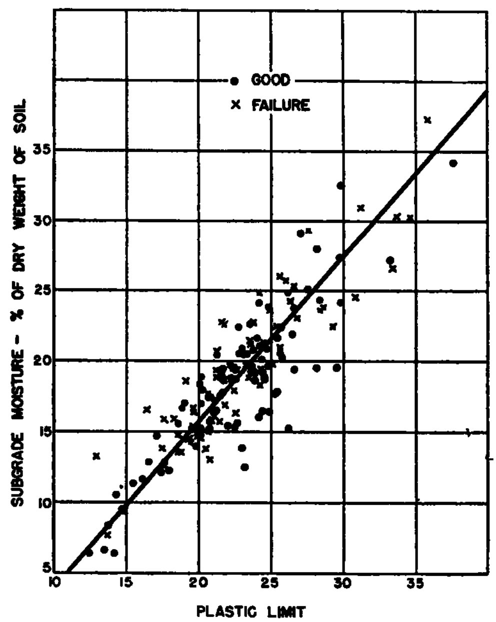

Figure 3. Relation between Subgrade Moisture and Plastic Limit, 1943 Survey

at 20 test points where the soils in the subgrade had moisture contents below 70 percent of their plastic limit, only one failure had occurred where the combined thickness of base and surface was more than 6 in. At 17 test points where the soils in the subgrade had moisture contents from 95 to 105 percent of the plastic limit, only three points were found at which the surface was good where the combined thickness of base and mat was less than 10 in.

5. The conditions found in bases did not appear to be an important factor in causing failures. Exceptions were found at a few test points, where concentrations of binder soil in stabilized bases appeared to be a con-

tributing factor, and at some points where deformation due to traffic consolidation of poorly compacted granular bases appeared to be the principal cause of surface failure. Densities of stabilized gravel bases in general were about at AASHO maximum and moisture contents rarely exceeded 90 percent of optimum moisture.

The preceding conclusions provided a basis for further research. The facts that densities were fairly uniform and moisture contents were related to the soil properties as determined by routine tests, appeared to justify the assumption that subgrade conditions might be predicted with a sufficient degree of accuracy to serve as a basis for design. The next problem was to develop a testing procedure that would evaluate the relative load supporting capacities of various soils within the range of moisture contents and densities which might be anticipated in the roads. It also appeared to be desirable to obtain further data relating to fluctuation in subgrade moisture content and density, both seasonal and over a period of years.

The field studies made in 1944 were started late in April, and data were obtained on seven projects during a period of about eight weeks. When the moisture contents and densities were compared to those obtained on the same projects during the 1943 surveys, it was found that there was no significant difference in average base or subgrade condition. It was believed that these surveys were made too late to determine the maximum spring moisture content.

The 1945 field studies were designed to obtain several sets of moisture determinations, and at least one set of density determinations per project, beginning when the frost was out of not more than the upper foot of the road, and repeating the tests at intervals during the entire thawing period. A survey was made on all projects between June 1st and July 20th to determine summer conditions.

Some data were obtained from 12 projects. On eight projects, at least three sets of tests were made within a period of from one to seven weeks after thawing had commenced. After the test data had been tabulated, the following observations were made:

1. Subgrade densities and base densities as determined in the summer of 1945, each averaged less than 0.5 lb per cu ft greater than the densities determined during the spring thawing period. Summer densities were higher at 28 of 50 test points where direct comparisons could be made.

2. The densities found in the spring of 1945 averaged somewhat higher than those at the same points tested in the summer of 1943. Successive density values obtained by tests from 1943 to 1945, indicate that there had been a slight increase in density of the base and in the upper 6 in. of subgrade during that period. Our limited data did not indicate that bases and subgrades lose density in measurable amounts upon thawing in the spring.

3. The average maximum moisture content found in bases in the spring of 1945 exceeded that found in the summer by 0.8 percent.

4. The average moisture content of bases in the summer of 1945 was practically the same as that in the summer of 1943 as shown in Figure 4.

5. The average maximum moisture content found in the upper 6 in. of subgrades during the spring of 1945 exceeded that found in the summer by slightly more than 2.0 percent.

6. The average moisture content of the subgrade in the summer of 1945 was practically the same as in the summer of 1943 as shown in Figure 5.

7. Moisture contents at 18-in. depth in the subgrade usually exceeded those in the upper 6 in. of the subgrade by from 2.0 to 3.0 percent both in spring and summer.

8. The maximum moisture contents found in bases and subgrades did not occur at any specific stage of thawing. In bases, 51 percent of the test points had maximum moisture contents at some time within 2 weeks after thawing started, and 42 percent of the test points had maximum moisture contents from 3 to 6 weeks after thawing period. In subgrades, at 55 percent of the test points the maximum moisture content was found before the frost was entirely out, and at the remaining test points the maximum moisture content was found after the subgrade was free from frost. The various projects studied required a period of 4 to 6 weeks for complete thawing of the subgrade.

In summarizing the information obtained from all of the field studies for the purpose of determining the subgrade conditions for which

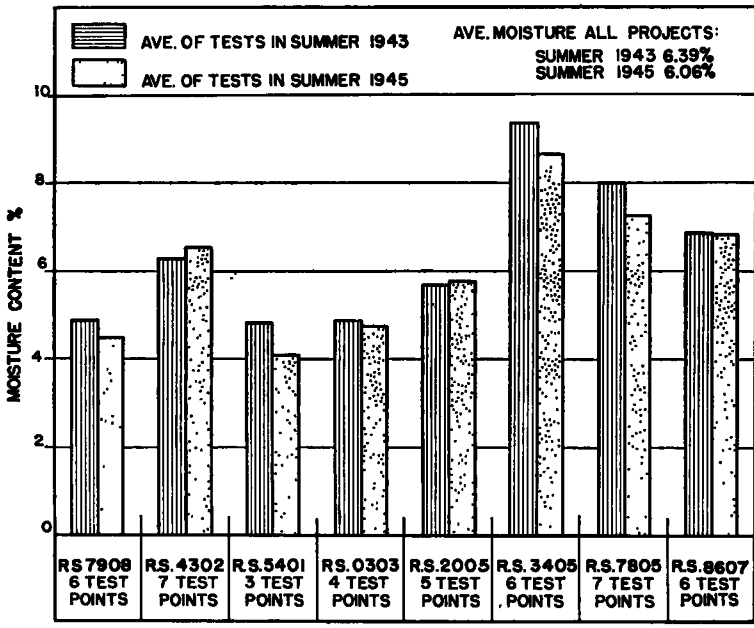

Figure 4. Moisture Content in Bases

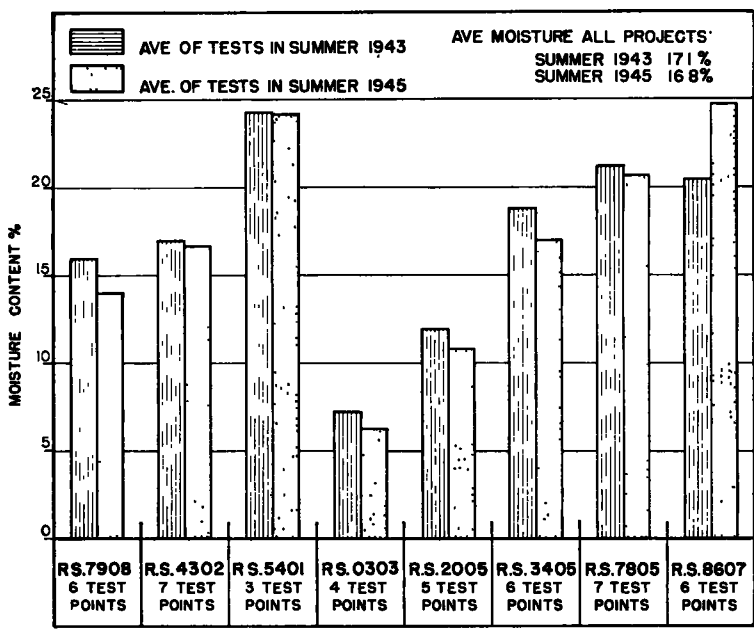

Figure 5. Moisture Content in Upper 6 in. of Subgrade

base designs should provide, moisture contents of subgrade soils were expressed as percentages of optimum moisture, plastic limit, and saturation. The average moisture content found in subgrades tested in the 1943 survey was 104.1 percent of the average optimum moisture. The relation between field moisture content and optimum moisture does not appear to be related to the textural class of the soil.

The average subgrade moisture content in the summer of 1943 was 82.6 percent of the average plastic limit. During the spring of 1945, the moisture contents at many points approached or exceeded the plastic limit. The relation between maximum moisture contents and the plastic limit appeared to depend to some extent upon the textural class of soil. Moisture contents above the plastic limit were found more frequently in clays and other heavy textured soils than in the light sandy loams.

Saturation is defined as the moisture content required to completely fill the voids in a soil. The percentage of water required for saturation is a variable depending on the density of the soil. The average percentage of saturation found in subgrades in 1943 was 81. Maximum percentages of saturation found in the spring of 1945 varied, and apparently had some relation to the textural class of soil. Heavy textured soils having plastic limits of above 20 reached 90 to 95 percent of saturation. Sandy loams with plastic limits of 15 or less were not found at above 85 percent saturation.

These subgrade moisture data from Minnesota appear to agree in general with data from other Mississippi Valley States as summarized by Miles S. Kersten in *Proceedings* of the Highway Research Board, Vol. 24 (1944).

It is recognized that the field studies were made on projects on which base and surfacing had been in place for several years. No data were available regarding subgrade moisture and density at the time that the bases were placed. However, it is believed desirable to use as a basis for design the conditions which exist in roads after a period of service rather than those which exist at the time the road is constructed.

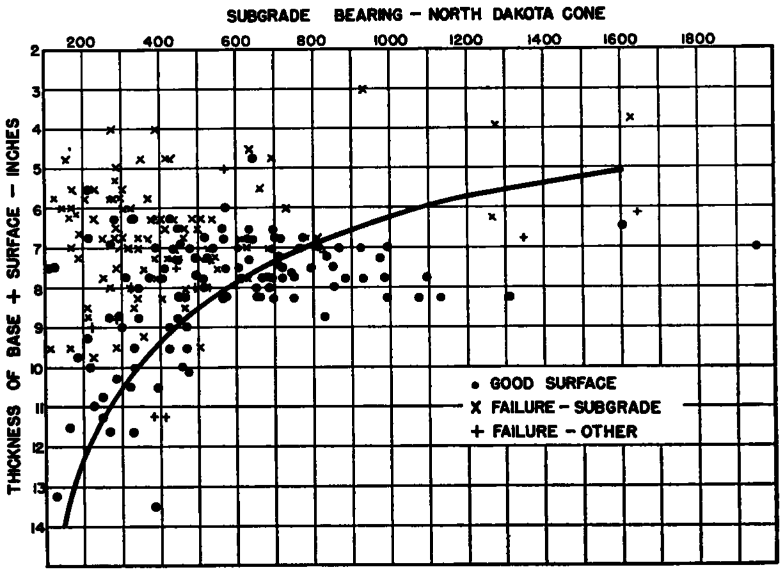

Figure 6. Tentative Design Curve—N. Dakota Cone Test

NORTH DAKOTA CONE BEARING TESTS

Bearing tests were made on the subgrade using the North Dakota cone method. This method was selected because of its simplicity and because the North Dakota Highway Department had used a correlation between adequate base depths determined by field observations and the bearing values obtained by the cone test as a basis for design with apparently satisfactory results.

The subgrade bearing values obtained at both failed and good areas when plotted against the combined thickness of base and bituminous surface as shown in Figure 6, indicated a relation between bearing value and required depth. From the curve it was evident that total thicknesses of from 6 to about 15 inches would be required on subgrades composed of plastic soils found in Minnesota. The data shown in Figure 6 were obtained from the 1942 and 1943 field studies. Each bearing value plotted is the average of at least two tests made within an area of subgrade of about one square foot. It was found that values obtained by repeated tests usually varied by less than 20 percent. However, it was observed that the presence of small pebbles within the volume of soil affected by the cone penetration apparently caused erratic results. The test did not appear to be reliable for use on coarser granular materials, and its accuracy for testing the pebbly, glacial tills found in many areas of Minnesota is somewhat questionable. However, it was believed that the average values obtained on the subgrade of most projects provided a means for evaluating that subgrade at the time of testing.

Some experimenting was done with the North Dakota cone test on laboratory compacted specimens. Tests were made on the soil samples taken during the field survey. These were compacted by the AASHO Method T99-38 at moisture contents comparable to those found in the subgrades. Values obtained from the laboratory tests and from the field tests were not in sufficiently close agreement to establish a relationship although the average values obtained in the field exceeded those obtained from the Laboratory test.

The use of the North Dakota cone test was discontinued in field studies subsequent to 1943.

LABORATORY STUDY

Standard Laboratory Tests

Samples of the subgrade soils taken during the 1942 field study were tested by standard laboratory procedure to determine the gradation, textural class, PRA group, liquid limit, plastic limit, field moisture and centrifuge moisture equivalents, shrinkage limit, shrinkage ratio, and volumetric change. There appeared to be no consistent relationship between these tests values and the performance of the base courses placed on soil subgrades. Laboratory tests which were made on samples taken during the 1943 and later field studies consisted of only the sieve and hydrometer analysis, liquid and plastic limit tests, determinations of specific gravity, and the moisture-density relationship by the method of AASHO T99-38.

California Bearing Tests

It was hoped that a relatively simple test could be used in the laboratory to evaluate the bearing capacities of soils and that bearing values obtained from such a test could be correlated with data obtained from the field studies to furnish a basis for future design. It appeared that the California bearing test was well adapted to this purpose in view of its long and apparently satisfactory use by the California Division of Highways and its general use by the U. S. Engineer Department. The necessary equipment was obtained and 26 subgrade samples were tested, following the standard procedure described by O. J. Porter of the California Division of Highways in *Proceedings* of the Highway Research Board, Vol. 18, (1938). Included in these tests were soils classified texturally as sandy loam, fine sandy loam, loam, silt loam, clay loam, silty clay loam, silty clay and clay, all of which were obtained during the 1942 field surveys.

The CBR (California bearing ratio) values obtained on soaked specimens of these soils, with only three exceptions, were less than three. Bearing values of this magnitude, according to the design curves in Porter's paper in *Proceedings*, Highway Research Board, Vol. 22 (1942), would require combined base and surfacing thicknesses of more than 18 in. Field observations did not seem to justify such base depths, as very few failures under our traffic conditions had been observed where thicknesses were more than 10 in.

An analysis of these data obtained from the California bearing tests led to the following observations:

1. Densities obtained by the California compaction procedure were considerably higher than those found in the field. The maximum densities obtained by the California method exceeded the densities found in the field by an average of 24 percent.

2. The soil specimens swelled from 2 to 17 percent upon soaking, and the moisture content in the top inch at the time of testing was considerably greater than that contained by these soils when taken from the subgrade.

Because of the wide difference between the moistures and densities of test specimens and the conditions which actually existed in the subgrades, modification of the California procedure appeared to be desirable.

Compaction tests were made on samples of the same soils used in our original California tests, using the method of AASHO T99-38 and in some cases the modified AASHO method that was used by the U. S. Engineers. The relation between moisture-density curves obtained by the three methods of compaction of a typcial plastic soil is shown in Figure 7. Specimens of these soils were compacted by static load to the AASHO and modified AASHO maximum densities and, after a four day soaking period, bearing tests were made. Samples in this series of tests had, in general somewhat higher CBR values than those prepared by the California method of compaction, but a relatively narrow range of values was obtained on soils of various textural classes. Moisture contents in the upper inch were, on the average, lower than those in specimens compacted to the California maximum density, but in most cases they exceeded the moisture contents found in the same soils in the road.

It was concluded that for all methods of compaction which were used, soaking of the specimens from the top resulted in moisture conditions more severe than were found in the field, and that some modification of the soaking procedure was necessary.

It was found that by using a perforated base plate under the specimens, and allowing them to take up water from the bottom only, the resulting moisture contents approached more closely the maximum moisture contents found in the field. Surcharge weights of from 0.5 to 0.7 lb per sq in. were used on the specimens during the soaking period. The water level in the tank was maintained $\frac{1}{4}$ in. above the base plate. CBR values of specimens soaked in this manner were generally higher than those of specimens of the same soil compacted and soaked in accordance with the California method. It was found that the time required to reach constant weight in specimens soaked from the bottom varied from one week to as much as six weeks. The length of time involved was an objectionable feature of this method of soaking.

Other bearing tests were made in which specimens were compacted by static load to the same densities and at the same moisture contents as had been found in samples after capillary soaking as described above. These specimens, when tested immediately after molding, were found to have bearing values agreeing in general with those obtained on specimens subjected to the capillary soaking.

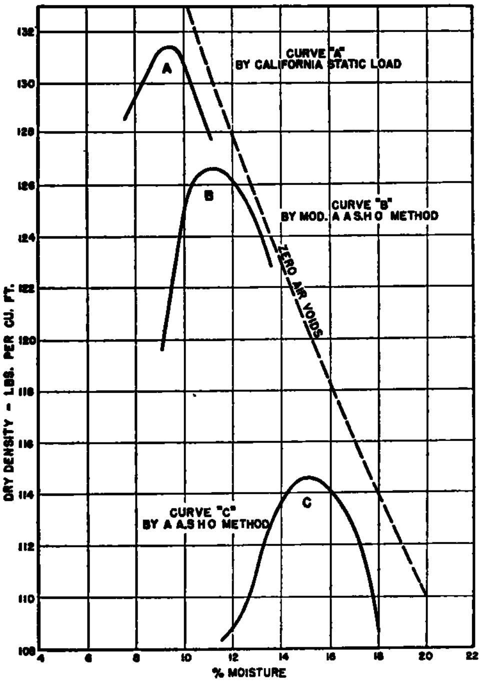

Figure 7. Moisture-Density Curves

Tests made on samples of stabilized base by the standard California method gave CBR values of from 11 to 94. It was found that for non-plastic or slightly plastic granular materials the difference in maximum densities obtained by the various compaction methods was much less than for plastic soils. It was also found that soaking from the bottom for a four day period was long enough for these materials to reach a maximum moisture content. In making the bearing tests on non-plastic granular materials, it was noticed that shearing failure and uplifting of the surface of the specimen between the plunger and side of mold often occurred at relatively low loads. By using a surcharge ring on the surface of the specimen the upward movement was reduced and higher bearing values were obtained.

To determine how closely moisture and densities would have to be reproduced in test specimens to obtain a check on bearing values,

TABLE 2

EFFECT OF VARIATIONS IN MOISTURE AND DENSITY UPON BEARING VALUES

Specimens tested at approximately equal moisture contents and variable densities

Sample No.	Soil Class	Moisture	Density	Bearing Value
		%	lb per cu ft	
S.S. 44564[a]	Clay	23.8	95 8	153
"	"	24.3	93.1	130
"	"	23.9	91.2	137
S.S. 44563[b]	Fine Sandy Loam	13.3	118.3	213
"	"	13.1	115.0	257
"	"	13.2	111.9	213

Specimens tested at equal densities and variable moisture contents

Sample No.	Soil Class	Moisture	Density	Bearing Value
		%	lb per cu ft	
S.S. 44564[a]	Clay	23.9	91.2	137
"	"	25.2	91.4	113
"	"	28.2	91.3	78
"	"	32.6	91.3	45
S.S. 44563[b]	Fine Sandy Loam	13.2	111.9	213
"	"	14.5	112.4	130
"	"	16.4	112 0	60
"	"	17.2	112.1	48

[a] S.S. 44564 has optimum moisture of 24.0 percent and maximum density of 93.6 lb per cu ft.

[b] S.S. 44563 has optimum moisture of 13.2 percent and maximum density of 115 2 lb per cu ft

a series of tests was made, using a clay and a fine sandy loam soil. In one set of tests each soil was compacted to variable densities at the same moisture content. In the other set of tests the moisture content was varied and the specimens were compacted to equal density. The results of these tests are shown in Table 2. The bearing value shown in this table is the unit load in lb per sq in. which results in a 0.2-in. penetration. It appeared that for plastic soils minor differences in density did not greatly affect the bearing values, but small variations in moisture content changed the bearing values considerably. Non-plastic or slightly plastic granular materials differed in this respect from the plastic soils. Crushed rock and some of the stabilized gravels when tested at 97 percent of AASHO maximum density had bearing values of only 50 to 80 percent of the values obtained from tests on the same materials compacted to maximum density.

On the basis of the work described above and considerable other data developed in the laboratory, it was decided that the California bearing test was a suitable and practicable method for evaluating relatively the subgrade soils and granular material for use as base or sub-base, provided that samples were tested at moisture contents and densities such as existed or were anticipated in Minnesota roads. Following is a brief description of the method of preparing specimens for testing:

In the test of subgrade soils the samples are air dried and pulverized and pebbles retained on a No. 4 sieve are removed. In the case of granular materials all material passing a ¾-in. or 1-in. sieve is used. Preliminary to molding the specimens the moisture content and the density at which the specimens are to be tested are determined. The amount of water required to bring a 10-lb sample to the required moisture content is computed, added and thoroughly mixed. A pressure spray gun is used for adding the water. The sample is then placed in a mixing bowl and stored in a moist air cabinet for a period of 4 to 20 hr. After computing the weight of the moistened material required for a compacted specimen 4 in. in height in a 6-in. diameter mold, that amount is weighed out and rodded lightly in the mold. Compacting is done in a compression machine using whatever total load is necessary to obtain a specimen of 4-in. height. Preliminary compaction is accomplished by using plungers in both ends of the mold, using a removable split ring to support the mold until a total load of 600 lb has been applied. After removing the supporting ring, loading is resumed. The testing head is moved at the rate of 0.05 in. per min. By means of an Ames dial, the operator can determine when the specimen has been compacted to slightly more than 4 in. The load is then released, the assembly is taken from the machine, the bottom plunger removed, and a base plate attached to the mold. The mold is again placed in the compression machine and by means of a plunger the specimen is forced down to the bottom of the mold, and compaction completed to the 4-in. height. The load required to obtain the required density has been found to vary for different materials from 100 psi to 2000 psi. In compacting, some allowance must be made for rebound after removing the load. The amount of re-

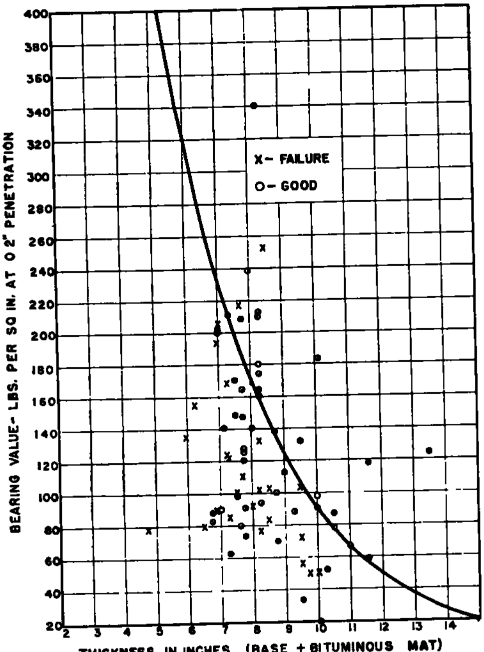

Figure 8. Thickness in Inches (Base + Bituminous Mat)

bound will vary with different materials and at different moisture contents. After some experience, an operator is able to judge quite closely the amount of rebound and will consistently produce specimens within 0.02 in. of the desired height.

The method of making the bearing test is identical with the standard California method. However, instead of expressing the bearing value as a ratio, we express it as the load in lb per sq in. which results in a 0.2-in. penetration of the plunger into the specimen.

Development of Design Curve

California bearing tests were made on samples of subgrade soils which had been taken during the 1943 survey. To obtain a relative evaluation of the conditions which were found in the field, bearing tests were made in which each specimen was compacted to the same density and at the same moisture content found in the road. Each bearing value was plotted in relation to the combined thickness of base and mat at the corresponding test point. By use of distinctive symbols representing failure and non-failure, it was found that a curve could be drawn in such a position as to indicate minimum thicknesses above which practically no failures occurred.

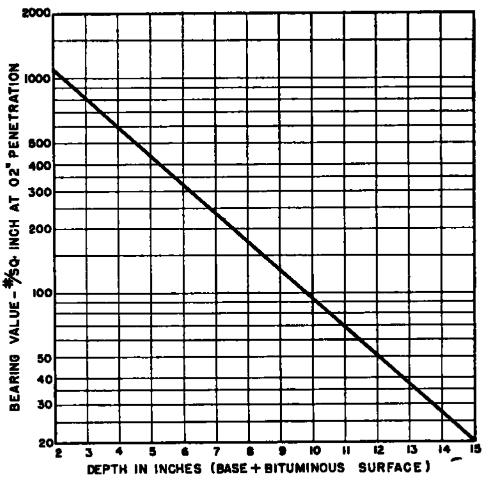

Figure 9. Tentative Design Curve

Figure 8 shows the relation between bearing values and total thickness.

The desirability of having more test points to fix the position of such a curve is recognized, but due to the limited number of projects which had been constructed with more than 9-in. base thickness, the opportunity for obtaining additional data was limited. However, it was believed that the curve as developed was based on sufficient data to justify its use as a tentative design curve. By projecting the curve shown in Figure 8 on a semi-log scale, as has been done in Figure 9, the tentative design curve was obtained. The total thickness of reinforcing layers required above a material having any given bearing value may be readily determined from this curve.

For the upper base layer a modification of the requirements of the design curve is permitted. From the curve, it is indicated that base materials having bearing values of 1100 are required immediately beneath a 2-in. bituminous surface. From many tests it has been found that only crushed rock and exceptionally well-graded gravels and soil stabilized gravels have bearing values of 1000 or more when tested after capillary soaking. On a basis of experience to date a minimum bearing value of 750 has been established as permissible for upper base materials.

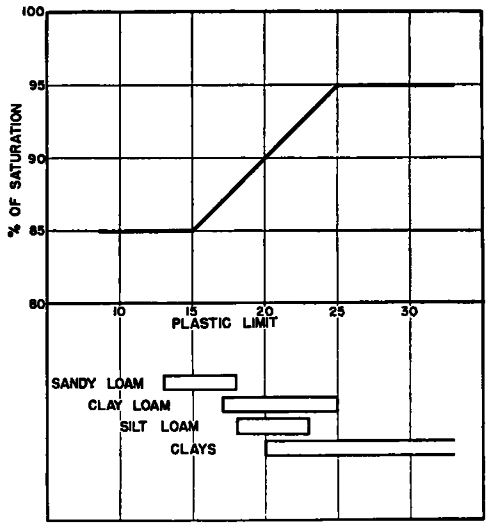

Figure 10. Moisture Content for Design Bearing Tests

Design Criteria

Inasmuch as the bearing values of soils, base, and sub-base materials vary, depending largely upon moisture and density conditions, it was necessary to determine what subgrade and base conditions should be provided for in design. Stated briefly, our policy has been to design for average compaction, and for the probable maximum moisture contents which will occur at those densities.

For plastic soils bearing tests to determine the design bearing values are made on specimens compacted to 97 percent of AASHO maximum density, and at moisture contents equal to the percent of saturation determined from the relation between plastic limit and percent saturation shown in Figure 10. This curve was developed from data obtained from the field studies, and it is believed that in Minnesota the percentages of saturation indicated will rarely be exceeded. Bearing tests on plastic soils are made without using a surcharge on the specimens, as it was found that the use or non-use of surcharge weights had little effect on bearing values.

For granular materials design bearing values are determined from tests made on specimens compacted to AASHO maximum density and subjected to 4 days soaking from the bottom. For base materials, a surcharge weight of about 0.2 psi is used during the soaking period and the bearing test. For sub-base or subgrade materials, a surcharge weight of about 0.5 psi is used during the soaking period and the bearing tests. These surcharge weights are used to simulate the confining effect of base and bituminous mat on these materials as placed on the road.

Design Procedure

In Minnesota preliminary soil surveys are usually made after the location survey has been completed and prior to preparation of grading plans. Samples of the typical soils available within the roadway limits or from borrow pits are submitted to the laboratory for testing. The results of the bearing tests are used, to some extent, to determine which soils should be placed in the upper portion of the subgrade, and to determine the necessary total base thickness. Knowing the bearing characteristics of the soils available on a project, provision can be made in the plans for the most effective use of these soils in the grading operations.

Samples of sand, gravel, and binder soil which may be used for base and sub-base are submitted to the laboratory prior to preparation of plans for the base. Bearing tests are made on the samples of sand and gravel and on soil stabilized mixtures containing various percentages of binder soil. From these tests a determination is made of the thicknesses of the component layers of sub-base and base; the necessity for stabilization; and the most desirable percentage of binder soil to use in the stablized mixture.

As an example of the application of our design method, a subgrade soil having a bearing value of 50 would, from the tentative design curve, require a total thickness of 12 in. of sub-base, base and bituminous surface.

If sand having a bearing value of 300 is available on the project, it may be used as sub-base to within 6 in. of the road surface. If a 2-in. bituminous surface is to be placed, a 4-in. layer of base composed of gravel, stabilized gravel or crushed rock having a bearing value of more than 750 would complete the design.

CONCLUSIONS

1. The subgrade moisture and density conditions found in the field should be used as a basis for design. The moisture and density conditions selected as design criteria are related to certain soil properties. It is believed that the moisture contents in sub-grades in Minnesota will rarely exceed those used for design.

2. Modification of the California method of compaction and soaking is necessary to evaluate subgrade soils at the moisture and density conditions selected for design.

3. The penetration test of the California method is suitable for evaluating, in the laboratory, the relative load supporting capacity of subgrade and base materials.

4. The method of design is empirical and is based on conditions in Minnesota.

5. Using this basis of design, some failures may still occur but it is believed that the repair of a few broken areas will be more economical than the construction of base thickness sufficient to eliminate all failures.

6. It is recognized that the tentative design method does not as yet provide adequately for variations in density and nature of traffic. The test procedure and the design method are such that changes can be made as future investigation may indicate desirable. On such basis this report should be considered as a report of progress to date only.

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