ily it would be uneconomical to prevent this process from taking place because, to do so, blanketing of the layers to prevent evaporation would be required. This is attested to by the fact that some engineers are skeptical of the economy of retaining the compaction moisture content in swelling clays as is proposed in the report. It is unfortunate that the dry curing process has been overlooked to date in most laboratory investigations of granular soils and flexible base materials, because so many of these test results appear to have been affected more greatly by compaction moisture than by absorbed moisture.

Mr. Campen's discussion has done much to point out various phases of this report which need further clarification.

COMPACTION AND STRENGTH CHARACTERISTICS OF SOIL[1] AGGREGATE MIXTURES

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SYNOPSIS

This paper reports one of the researches conducted by the Highwaz Research laboratories of Purdue University co-operating with the State Highway Commission of Indiana. A series of compaction and strength tests were performed on four soil-aggregate mixtures to determine their compaction and wet strength characteristics under varying soil contents.

On the basis of the test data, it was indicated that, for a given gradation of an aggregate, there is an optimum soil content at which maximum densities are attained. The optimum soil content where strengths are concerned is somewhat less than that indicated by the compaction tests. Maximum densities do not necessarily mean maximum strengths whenever soil-aggregate mixtures containing varying percentages of soil near the optimum are compared. The tests on mixtures of soil and crushed stone resulted in the highest density and strength values of the materials, with the soil-gravel, soil-sand, and soil-dune sand mixtures resulting in the next highest values in the order given.

It was concluded that insofar as densities and strengths are concerned, a small quantity of soil mixed with granular materials is desirable, but that larger quantities are detrimental.

In recent years performance surveys of various types of pavements have been made to determine the causes of numerous failures observed each spring in both rigid and flexible pavements. It has been observed that, in most cases, there is a distinct difference between the performance of pavements located on plastic, silty-clay soils with no base courses and those constructed on granular or semi-granular materials. The importance and need for increased use of granular base courses has been shown in connection with rutting of flexible pavements and traffic-bound roads. Likewise, rigid pavements constructed directly on plastic soils have been found to pump badly, particularly under conditions of heavy traffic.

One of the primary problems, wherever granular and semi-granular materials are used, concerns the amount of fine material that should be permitted in an aggregate, and the effect of the fine material on the compaction and wet-strength characteristics of soil-aggregate mixtures. Fine-grained soils have low unit weights, good supporting power when dry, have high capillarity, have poor drainage characteristics, and have very low supporting power when they contain excessive water. On the other hand, granular materials have high unit weights, are not

[1] The word soil as used in this text refers to material that will pass a No. 200 mesh sieve.

affected greatly by moisture, have excellent drainage properties, and have excellent mechanical stability when in a wet condition. Since these two materials have such widely varying physical properties, it is apparent that the physical properties of soil-aggregate mixtures depend upon the relative quantities of the various materials that make up the mixtures.

Mechanical stabilization is the increase in strength resulting from the increase in density that is possible whenever small amounts of fine-grained soils are mixed with an aggregate. The addition of small amounts of soil to a clean aggregate fills the voids and decreases the permeability; however, the density attained with a mixture of the two materials is much higher than that of either of the materials alone.

Performance surveys have been used to advantage in correlating pavement performance with subgrade soil textures. An extensive study of the performance of flexible pavements during the 1943 spring breakup (*1*)[2] indicated a wide range in thickness requirements for base-pavement combinations. Pavements located on well-drained granular soils were performing satisfactorily, even when the combined base-pavement thickness was only 4 to 6 in. Likewise, the performance of rigid pavements has been correlated with soil textures. On heavily traveled roads, pavement pumping has been severe when no base course was used and when slabs were placed directly on plastic soils (*2*) (*3*).

Porter (*4*) reported a method for determining the thickness requirements of base courses for flexible pavements which was used extensively by the War Department, Corps of Engineers, during the war for airport pavements (*5*). However, the published data are limited in regard to the effect of gradation and soil content on the strength and compaction characteristics of base course materials. The effect of mixing soil with graded aggregates was explored by Carpenter and Willis (*6*). In 1939, DeKlotz (*7*) reported on the effect of the quantity and quality of soil. Willis (*8*) reported a study on the effect of variations in plastic index on the stability of granular base course materials having the same gradation.

[2] Italicized numbers in parenthesis refer to list of references at the end of the paper.

It is significant that in both the field performance survey data and in results of various laboratory programs, the detrimental effect of high soil content has been well established. However, the effect on strength and compaction characteristics of adding increasing quantities of material passing a No. 200 mesh sieve to a graded aggregate has not been thoroughly studied.

It was the purpose of this study to determine the effect of the soil content on the strength and compaction characteristics of soil-aggregate mixtures and if possible, to determine an optimum soil content for such aggregates as bank-run gravel, crusher-run limestone, graded sand, and dune sand. The scope of the study is limited to the wet strength and compaction characteristics of the mixtures and does not cover such factors as the effect of the fine material on frost action. The investigation supplements in part the current work of Henderson and Spencer (*9*) on the use of stabilized materials as base courses to minimize pavement pumping. However, the study has not been concerned with the drainage properties of soil-aggregate mixtures and is in contrast to the work of Sweet and Woods (*10*), in which the need for well-drained subgrades and base courses is indicated from the standpoint of concrete durability. The work is concerned with the strength characteristics of various materials commonly employed for use in base courses which are to be used as an integral part of the pavement-base structure, and is a continuation of the study initiated in the Joint Highway Research Project laboratories at Purdue University during the fall of 1945 (*11*).

MATERIALS TESTED

In this investigation four granular materials were tested. They were; a clean glacial-terrace gravel, a clean coarse sand, a crushed limestone, and a dune sand. Varying percentages of a silty clay were added to each of these materials so that the effect of the material finer than the No. 200 mesh sieve could be studied. The silty clay was the soil overburden material for the gravel and coarse sand used in the test series. The limits of consistency for the soil portion of the mixes (material finer than the No. 200 mesh sieve) were, liquid limit 27.2 and plastic limit 22.1. The grain size distribution curves for the various mixes are shown in Figures 1 to 4.

The first series of tests was performed on soil-gravel mixtures, the amount of material finer than the No. 200 mesh sieve being varied from 0.4 to 21.0 percent. The raw materials that made up the mixtures were a 40-60-percent combination of the sand and gravel, with the soil portion varied by the addition of different amounts of the silty

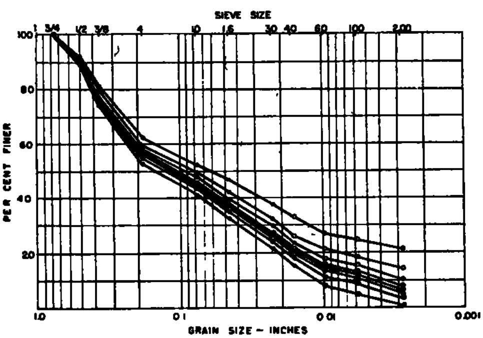

Figure 1. Grain Size Distribution Curves—Soil-Gravel Mixtures

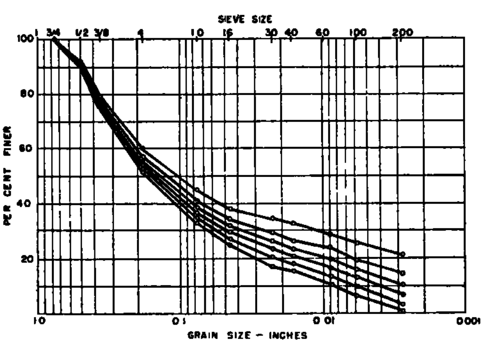

Figure 2. Grain Size Distribution Curves—Soil-Crushed Stone Mixtures

clay. All the material retained on the $\frac{3}{4}$-in. sieve was eliminated from the gravel before the start of the tests.

Since the soil that was added to the gravel contained some fine sand, the gradation of the material retained on the No. 200 mesh sieve varied as the soil content was varied. It was considered desirable to keep the gradation of the material retained on the No. 200 mesh sieve as nearly constant as possible for all the mixtures, thereby leaving as the only variable the amount of material finer than the No. 200 mesh sieve. To accomplish this, a small amount of fine sand, with a gradation the same as the sand in the silty clay, was added to all the mixes except the 21 percent mix.

The gradation of the 21 percent mix was changed the greatest amount by the addition of the silty clay; therefore, the design of this mix was used as a basis for all of the mix designs In the 21 percent mix, the proportion of materials required to bring the

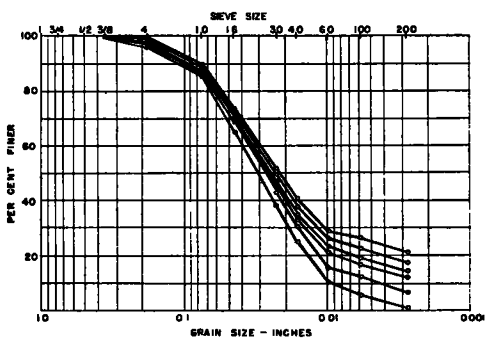

Figure 3. Grain Size Distribution Curves—Soil-Coarse Stone Mixtures

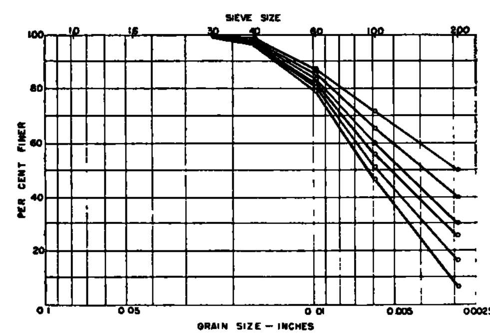

Figure 4. Grain Size Distribution Curves—Soil-Dune Sand Mixtures

total percent finer than the No. 200 mesh sieve to a value of 21 percent was first calculated. The gradation of the material retained on the No. 200 mesh sieve in the mix was then calculated. This gradation was used as the standard for all the mixtures, after the various amounts of material finer than the No. 200 mesh sieve had been deducted and the new gradation curves had been computed. The addition of the fine sand to the mixtures maintained the gradation of the aggregate at a constant value; however, it caused the lean mixes, in particular the 0.4 percent mix, to contain a large amount of fine sand in comparison to the larger-sized aggregate.

For the second series of tests, the soil was mixed with crushed limestone. This material was used so that the effect of angularity of grains could be studied. These mixtures were proportioned in the same manner as were the gravel mixtures, with similar amounts of material finer than the No. 200 mesh sieve used; however, the leanest mix contained approximately one percent finer than the No. 200 mesh sieve, rather than 0.4 percent (due to the presence of limestone dust).

The third series of tests was performed on mixtures of coarse sand and soil. These mixes were proportioned in exactly the same manner as were the soil-gravel mixes. The quantity of soil was again varied from 0.4 to 21.0 percent; however, the gradations of the intermediate mixes were changed somewhat, due to the trend in the test results.

The fourth series of tests was performed on dune sand, to which was added varying percentages of soil ranging in amount from 6.9 percent to 50.0 percent. The dune sand was a uniform fine-grained material which contained a small amount of silt.

DESCRIPTION OF TESTING EQUIPMENT

The equipment used was similar to that used for the standard California bearing ratio test. The specimens were compacted by means of an impact hammer 3 in. in diameter, which weighed 10.4 lb, and was dropped from a height of 12 in. It was found that the compactive effort produced by this device was approximately equal to that of the standard Proctor device. Figure 5 shows compaction data obtained with this device compared to those obtained by the standard Proctor machine, for two materials.

The mixtures were compacted in cylindrical molds 6 in. in diameter and 4⅝ in. in height. The molds had an over-all height of 8 in.; however, a spacer 3⅝ in. in height fitted inside the cylinder and the mixtures were compacted on top of this spacer, making the height of the specimen 4⅝ in.

Before the specimens were tested for penetration resistance, they were placed in a tank and allowed to soak from both the top and bottom for a period of four days. The strength tests were performed by penetrating the specimens with a piston having an end area of 3 sq in. The load was applied at a constant rate of 0.05 in. per min. Before the test was started a load of 10 lb was applied to the piston and the load and penetration dials set at zero. The load at each 0.1-in. penetration was recorded.

A surcharge device 5¾ in. in diameter and weighing 12¼ lb was used in all the tests. The penetration piston passed through a hole in the center tapered from a diameter at the top of 2⅜ in. to a diameter at the bottom of 2 in.

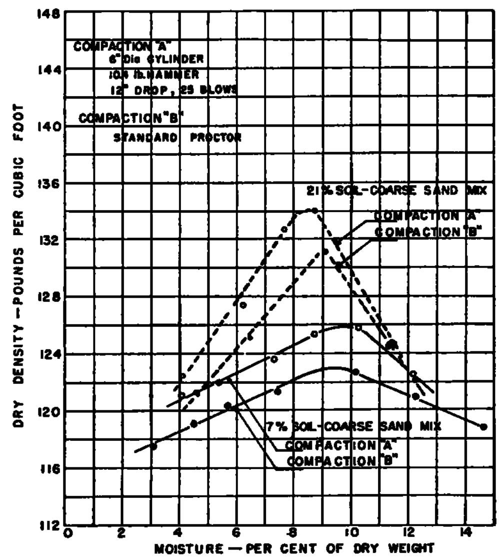

Figure 5. Comparison of Compaction Data Obtained from Compaction Device with Standard Proctor

The method of test was varied from the standard in that the soaked specimens were tested while in a small metal tank which contained water coincident with the top of the specimen. However, since the portion of the specimen being penetrated was several inches below the top of the cylinder, the water did not have access to the specimen, except through the bottom. The cylinders were placed in this box with water in an effort to minimize the draining of the specimen while the test was in progress.

RESULTS

Compaction Tests. To determine the compaction characteristics of the soil-gravel mixtures six compaction curves were developed for each mix with 5, 15, 25, 35, 55, and 100 blows, respectively. The results

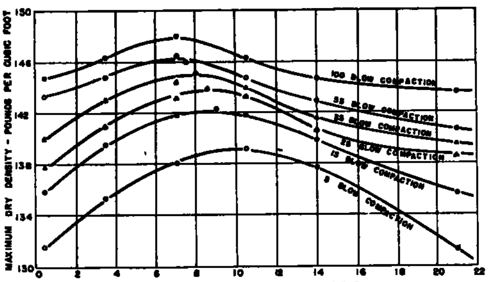

Figure 6. Variation of Maximum Density with Soil Content—Soil-Gravel Mixtures

of these compaction tests are shown in Figure 6. The density values shown are the maximum dry densities in lb per cu ft, and represent the peaks of the compaction curves. It can be seen that there is a definite soil content (optimum) at which the density of the mixes was at a maximum. As the amount of silt and clay was increased from 0.4 percent to approximately 10 percent, the voids between the aggregate grains were gradually filled with the soil material; likewise, the density was gradually increased to a maximum value. The use of additional soil caused the density to decrease.

The group of curves showing the variation of density with quantity of soil for the six compactive efforts indicate that the optimum decreased a small amount as the compactive effort was increased. The largest optimum soil content obtained was 10 percent (for the 5-blow compaction). The smallest optimum soil content obtained was 7 percent (for the 100-blow compaction). However, to determine the effect of breakage of the aggregate on gradation, compaction tests were performed on mixtures that contained an amount of soil equal to that indicated by the peaks of the curves for the respective compactive efforts. Sieve analyses were made on each of these materials after the tests were completed for one compaction curve. The results of these sieve analyses are shown in Table 1. Here it is indicated that there is a definite gradation of mix at which maximum densities are attained. It is significant that the amount of breakage was sufficient to increase the percentage of material finer than the No. 200 mesh sieve from 0.1 percent for the 5-blow test to 3.0 percent for the 100-blow test. A large portion of the breakage occurred when the specimens were compacted at the lower moisture contents.

Shelburne (*12*) found that the degradation of aggregates under conditions of rolling and mixing approached a Fuller's maximum density curve (*13*) as an ultimate. The percentage of material finer than a No. 200 mesh sieve given by Fuller's maximum density curve is 6.2. This is somewhat smaller than that determined by this investigation. The amount of material finer than the No. 200 mesh sieve at which maximum densities are attained depends on the volume of voids in the aggregate. If the aggregate is well graded and the volume of voids is

TABLE 1

GRADATION OF THE SOIL-GRAVEL MIXES CONTAINING OPTIMUM AMOUNTS OF SOIL—AFTER COMPACTION

Sieve Size	10.5% Mix 5 Blows	9.0% Mix 15 Blows	8.5% Mix 25 Blows	8.0% Mix 35 Blows	7.5% Mix 55 Blows	7.0% Mix 100 Blows	10.5% Mix 0 Blows	Fuller's Max. Density[a]
	% Finer	*% Finer*	*% Finer*	*% Finer*	*% Finer*	*% Finer*	*% Finer*	*% Finer*
¾ in.	100	100	100	100	100	100	100	100
½ in.	86.2	93.2	89.5	92.2	92.1	92.5	90.3	81.7
⅜ in.	74.2	82.0	87.8	80.2	80.5	80.0	77.0	70.7
No. 4	54.6	57.8	57.6	58.3	57.4	59.1	57.5	50.0
No. 10	45.5	46.9	45.7	45.9	45.9	47.1	47.1	32.4
No. 16	39.1	39.3	38.1	38.6	38.8	39.8	40.0	25.0
No. 30	29.6	29.1	27.9	28.7	29.3	29.8	29.3	17.6
No. 40	24.7	23.7	23.1	23.6	24.0	24.8	24.1	14.8
No. 60	18.6	18.6	17.7	18.2	18.4	18.9	17.7	11.4
No. 100	14.7	15.6	14.5	15.1	15.3	15.6	15.1	8.9
No. 200	10.6	10.7	10.0	10.5	10.4	10.0	10.5	6.2

[a] Percentage finer than given sieve $= 100 \sqrt{\dfrac{\text{size sieve opening (in.)}}{\text{maximum size aggregate (in.)}}}$

small, the amount of fine material required to fill the voids is small.

Figure 7 shows the variation of density with number of blows for the mixes tested. As the number of blows was increased from 5 blows to 100 blows, the largest percent increase in density was shown by the 0.4 percent mix (increased 9.96 percent). This large increase in density can probably be attributed to a large extent to breakage of the aggregate grains. The 21 percent mix

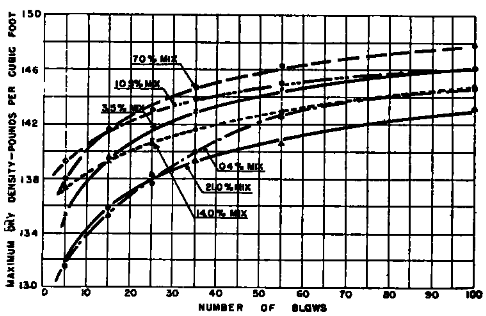

Figure 7. Variation of Maximum Density with Number of Blows—Soil-Gravel Mixtures

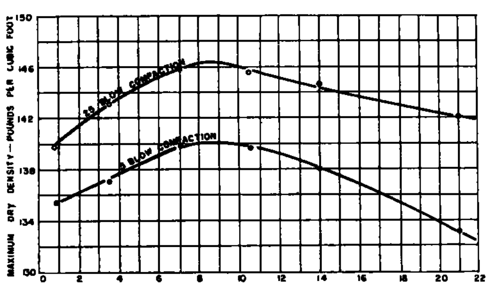

Figure 8. Variation of Maximum Density with Soil Content—Soil-Crushed Stone Mixtures

increased 9.2 percent in dry density as the number of blows was increased from 5 to 100 blows. Here the large increase in density was due to the compaction of the silt and clay that more than filled the voids between the aggregate particles. The smallest increase in density was shown by the 10.5 percent mix (increased 5.02%). This mixture consists of a near-optimum gradation and the amount of breakage was negligible.

The curves also show that as the number of blows was increased, the densities approached a maximum beyond which the increase in density was negligible for additional blows. For example, the 7.0 percent mix (top curve, Fig. 7) showed an increase in density of 5.5 lb per cu ft as the number of blows was increased from 5 to 25 blows, 2.0 lb per cu ft from 25 to 45 blows, 1.0 lb per cu ft from 45 to 65 blows, and 1.0 lb per cu ft from 65 to 85 blows.

In the case of the soil-crushed limestone mixtures (Fig. 8), maximum densities were indicated for approximately the same quantity of soil as for the gravel mixtures. No tests were made to check the amount of breakage; however, since the gradations of the two materials were nearly alike, it is reasonable to assume that breakage effected the test results of the crushed stone in a manner similar to those of the gravel. Grain

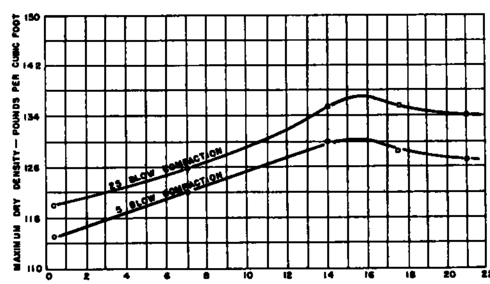

Figure 9. Variation of Maximum Density with Soil Content—Soil-Coarse Sand Mixtures

shape had no apparent effect on the compaction test results. The unit weights of the crushed stone mixes were somewhat higher than the gravel mixes; however, the specific gravities were 2.70 for the gravel and 2.79 for the crushed limestone.

The results of the compaction tests performed on the soil-sand mixtures are shown in Figures 9 and 10. The optimum soil contents were 16 percent for the coarse sand and 40 percent for the dune sand; these values are in contrast to the 10 percent soil for the soil-gravel mixes. In the latter mix, 42.0 percent by weight is retained on the No. 4 sieve. If this percentage of material is deducted from the mix and a new percentage finer than the No. 200 sieve is calculated, a value of 17.2 percent is obtained $\left(\frac{10.0}{58.0} \times 100\right)$. This value agrees closely with the value of 16 percent determined by tests on the course sand mixes. Also in the 16 percent soil-course sand mix approximately 62 percent is retained on the No. 40 sieve. If this material is deducted and a new percentage is calculated, a value of 42 percent is obtained, which is in close agreement with the 40 percent value obtained for the dune sand mixes.

When the percentage finer than a given sieve is used as the criterion for maximum density, the ratio of the weight of this portion of the mix to the total weight is actually used as a measure of the volume of voids between the aggregate particles. This necessarily means that the optimum as determined by this series of tests holds strictly true only for aggregates with gradations similar to those used in this investigation.

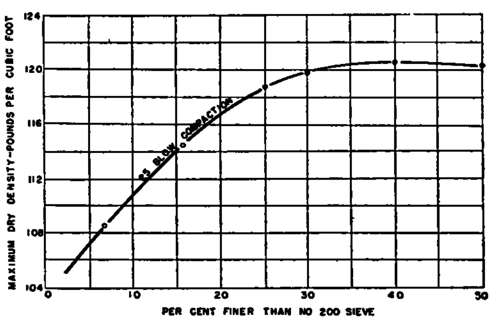

Figure 10. Variation of Maximum Density with Soil Content—Soil-Dune Sand Mixtures

Figure 11 shows a comparison of the optimum gradation curves determined in this investigation, with Fuller's maximum density curves (shown as broken lines). The gradation of the aggregate in the coarse sand and gravel deviated the largest amount from that given by the ideal curves, likewise the difference between the optimum soil contents and that given by Fuller's curve was the largest for these materials. In the case of the dune sand mixtures, the 40 percent mix was nearly ideally graded from maximum size down to the No. 200 mesh sieve and the optimum of 40 percent soil checked close with the 41.9 percent given by Fuller's curve. If the aggregate in the gravel, crushed stone, and coarse sand had been better graded the optimum soil contents would have been, no doubt, much less.

Penetration Tests. To investigate the strength characteristics of the various materials, a penetration test similar to the California bearing ratio test was used *(4)* *(5)*. The test was varied inasmuch as the specimens were kept as nearly saturated as possible during the penetration tests. This was accomplished by placing them in a box so that water had access to the specimen through the bottom. This probably did not have a great effect on the more dense mixtures; however, the tests performed on the lean mixes were, no doubt, affected by the method of test.

In the standard California bearing ratio test, the penetration curves are expressed as a percentage of a standard curve, with

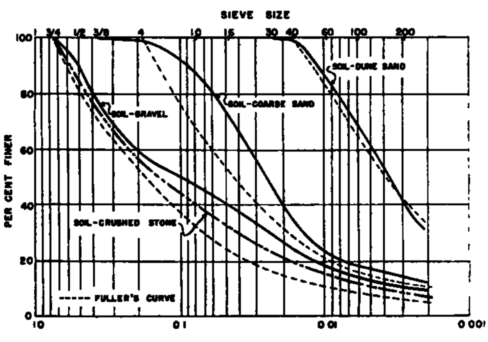

Figure 11. Comparison of Optimum Gradation Curves with Fuller's Maximum Density Curves

the ultimate load taken as that value at 0.5 in. penetration. The unit loads for the standard specimens are as follows:

Penetration *in.*	Unit Load *lb per sq in.*
0.1	1,000
0.2	1,500
0.3	1,900
0.4	2,300
0.5	2,600

Several types of load-penetration curves were obtained from this series of tests. Three typical curves are shown in Figure 12. In one curve the unit load did not increase appreciably beyond 0.1-in. penetration. Another type of curve developed a concave upward portion for low penetrations. Whenever such curves were encountered, they were corrected by drawing a new curve parallel to the steepest portion to the curve, but through the origin (5).

The concave type of curve may have been caused by one or both of two factors. In the first place, it was noticed during compaction that some of the material was jarred loose and thrown to the edge of the cylinder. Then as the hammer fell on the specimen a large portion of the impact was taken by the material near the edge, thus causing a soft spot to develop in the center (where the penetration piston came in contact with the specimen). Secondly, it is possible that

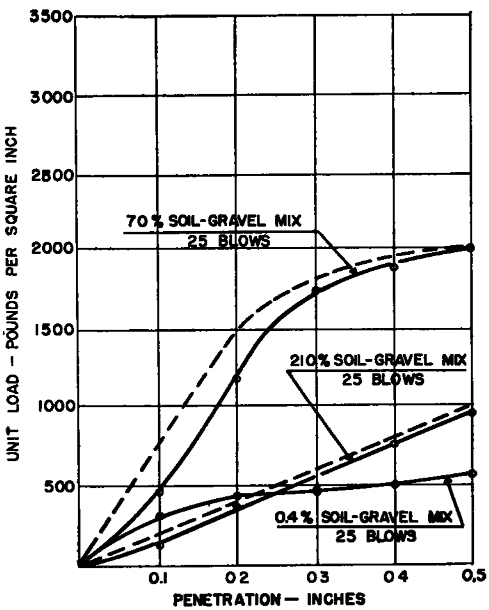

Figure 12. Typical Load-Penetration Curves

the piston was not always firmly seated at the start of the penetration test.

The penetration curves were compared on the basis of the average of the ratios of the unit loads for each increment of penetration to the corresponding standard values (7). This procedure appeared logical inasmuch as the individual values varied somewhat, due to the size of aggregate. Also, since the shapes of the individual curves varied for the different mixes (see Fig. 11) it seemed desirable that the entire penetration curve should be used in analyzing the data.

The dry densities of some of the specimens tested for bearing strength were somewhat less than those indicated by the compaction curves. This was particularly true for the lean soil-gravel mixtures. The average of the densities of the 7.0 percent mixes (25-blow compaction) was 140.0 lb per cu ft, while the maximum dry density as indicated on the compaction curve was 142.8. This was no doubt due to breakage of the aggregate during compaction. In contrast, in the 10.5 percent mixture the densities of the specimens were the same as those indicated by the compaction tests.

Figure 13 shows the effect of the percentage of material finer than the No. 200 mesh sieve on the bearing ratios of the soil-gravel mixtures. Maximum bearing values were obtained with 7 percent soil, which is less than the optimum (10%) as determined by the compaction tests. This may have been

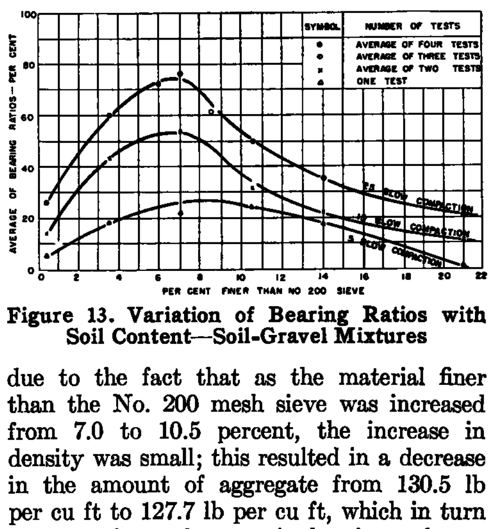

Figure 13. Variation of Bearing Ratios with Soil Content—Soil-Gravel Mixtures

due to the fact that as the material finer than the No. 200 mesh sieve was increased from 7.0 to 10.5 percent, the increase in density was small; this resulted in a decrease in the amount of aggregate from 130.5 lb per cu ft to 127.7 lb per cu ft, which in turn accounts for a decrease in bearing value.

Figures 14 to 16 show the results of the tests performed on the soil-crushed stone and the soil-sand mixtures. The same trend is shown in that maximum bearing values resulted when the quantity of soil was somewhat less than that indicated as the optimum by the compaction tests.

Figure 16 shows the variation of bearing ratios with density for all the mixes tested. Each bearing ratio is plotted against the average of the corresponding densities of the mixes that were tested for bearing strength. In cases where the bearing ratio was an average of several tests, the corresponding density values also represent the average of the same number of tests. Each point represents one mix at a given compactive effort. The continuous lines connect the points that represent the mixes containing a quantity of soil less than optimum, and the broken lines connect those for mixes containing a quantity of soil greater than optimum.

The set of curves indicate that strength is not necessarily a function of density unless the materials are compared on the basis of the relative amounts of soil contained in

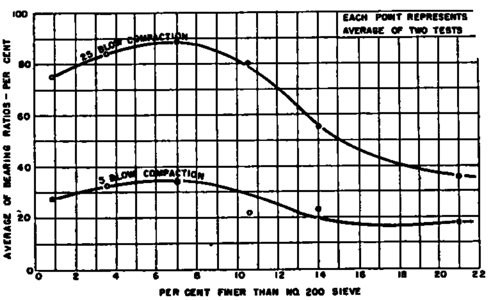

Figure 14. Variation of Bearing Ratios with Soil Content—Soil-Crushed Stone Mixtures

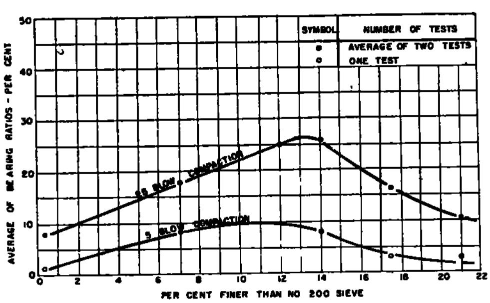

Figure 15. Variation of Bearing Ratios with Soil Content—Soil-Coarse Sand Mixtures

the mixes. In some cases higher densities resulted in lower bearing values due to the excess soil in the mixes.

CONCLUSIONS

The following statements of results and conclusions are based on the results of laboratory tests reported in this paper and cover only the compaction and strength characteristics of certain soil-aggregate mixes. Such factors as permeability and frost action were not included in the scope of the study. The conditions of test were nearly ideal, inasmuch as exceptionally high densities were obtained. In addition, the specimens tested for bearing values were saturated with water to a relatively high degree.

1. For a given aggregate there is an optimum soil content at which maximum densities are attained. The soil content for maximum strength is less than the optimum as determined by compaction tests. For the soil

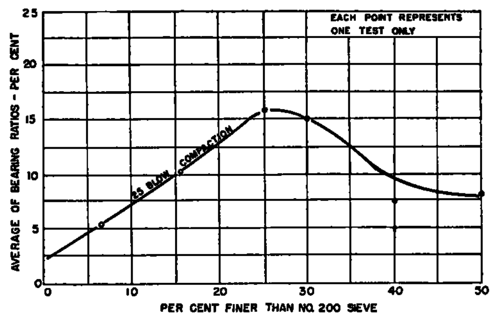

Figure 16. Variation of Bearing Ratios with Soil Content—Soil-Dune Sand Mixtures

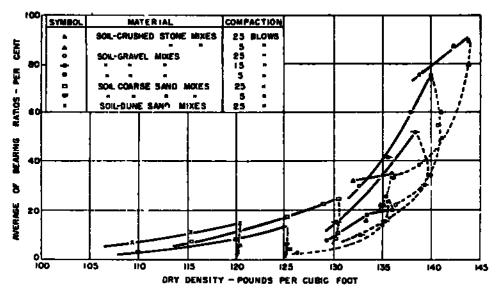

FIG 16 VARIATION OF BEARING RATIOS WITH DENSITY

Figure 17. Variation of Bearing Ratios with Density

and aggregates used in this investigation the soil contents were as follows:

	Max. Density	Max. Strength
	Percent soil	
Soil-gravel.................	10	7
Soil-crushed stone..........	9	7
Soil-coarse sand..	16	13
Soil-dune sand...	40	25

2. The results of the compaction tests indicated that the optimum soil content decreased as the compactive effort increased. However, gradation tests indicated that within the limits of gradation employed, aggregate breakage was sufficient to cause

the gradation to change, and approach a near-constant optimum gradation similar to Fuller's maximum density curve.

3. A relation exists between density and strength of soil-aggregate mixtures if the quantity of soil is taken into account. When the soil content of the mixtures is greater than optimum the strengths are lower, for comparable densities, than those of the mixtures containing a quantity of soil less than optimum.

4. From the standpoint of density and strength a small amount of soil is a desirable addition to base-course aggregates.

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