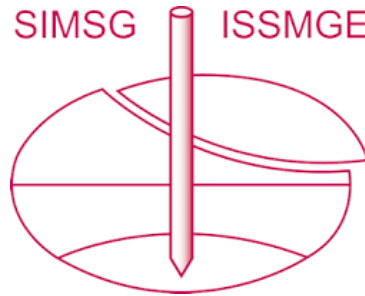


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weight. If a 40,000 lb roller (10,000 lb drawbar pull) is required for the sandy soil, a 36,600 lb one (14,600 lb drawbar pull) will be needed for the clayey soil to secure compaction to a 300 lb per sq in indicated saturated penetration resistance of both soils. That, apparently, is the reason the same roller can be used on almost all types of soils; however, teeth of somewhat (about 50%) larger area will be required for the sandy soil. It is most interesting to note that the 300 lb per sq in indicated saturated penetration resistance "standard" results in the same shear strength by use of the same roller for each of these two extreme types of soils.

CONCLUSIONS

The series of soil tests that have been described originally were made to determine the effect of the use of various methods of laboratory soil compaction; when the relationship between compactive effort (foot pounds per cubic foot) and soil dry weight was determined 4), the work was extended to include shear strengths with the results that have been described. It was also desired to investigate various "modifications" of the originally proposed compaction methods 3), the result of which is that the original methods remain in use, without the addition of any of

the "modifications", with the future objective of the collection of better data regarding the compaction equipment and methods required to produce prescribed shear strengths in proposed dams to enable the design and construction of more economical side slopes, with known factors of safety, than is now possible. A limited amount of data is being presented regarding the relationship between compactive efforts in field and laboratory 5). It is suggested that all those who have sufficient facilities should also investigate this most essential link between theoretical and practical soil mechanics for, in the final analysis, all laboratory and experimental data is just about worthless unless the results secured actually can be applied to the work - a condition that at present is rare.

REFERENCES

- 1) R.R. Proctor, Construction and Operational Details for a Simple Machine to Test Soils in Double Shear. Paper to this Conference.
- 2) Proceedings, Amer.Soc. of Civil Engrs., Vol. 110 (1945) Page 633
- 3) Engineering News-Record, Aug. 31, Sept. 7, 28, 1933.
- 4) See Paper No. IXb 12.
- 5) See Paper No. IXb 14

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IX b 12

RELATIONSHIP BETWEEN FOOT POUNDS PER CUBIC
FOOT OF COMPACTIVE EFFORT TO SOIL DENSITY
AND
SUBSEQUENT CONSOLIDATION UNDER VARIOUS LOADINGS

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SYNOPSIS

There has been a wide variation in the compactive efforts used in laboratory compaction of soils by organizations engaged in the control of soil compaction for dams or highways, and an equally wide variation in the weights of rollers used, while, for the most part, there has been little or no connection between compactive efforts in the laboratory and field. There is presented herewith the results secured by compacting two soils, one very sandy and the other very clayey, over a wide range of laboratory compactive efforts (5,000 to 90,000 ft lb per cu ft), together with a discussion of the relationship between the compactive effort the maximum soil dry weight secured, and the corresponding Indicated Saturated Penetration Resistance. The relationship between the consolidation of about 900 soil test specimens and the indicated saturated penetration resistances of the specimens as compacted is shown, together with the relationship between the compactive effort, compacted soil dry weight, and anticipated settlement (consolidation) under similar loadings of four compacted soils ranging from sandy to clay.

COMPACTIVE EFFORT, DRY WEIGHT, PENETRATION RESISTANCE, AND THE INDICATED SATURATED PENETRATION RESISTANCE

Method of Preparation of Figs. 1 and 2.- The two soils were each compacted by ten different methods varying from a 5-3/4 lb tamper dropped 25 times from a height of 6 inches on each of three soil layers in a 1/20 cu ft container (4312 ft lb per cu ft), to a 10 lb tamper dropped 25 times from a height of 6 feet on each of three soil layers in a 1/20 cu ft

container (90,000 ft lb per cu ft), each tamper having a 2 inch diameter face; a fresh (previously uncompacted) soil sample was used for each compaction curve. While there is an appreciable difference (See Fig. 4) in these test results from the use of the 10 lb tamper, (the 5-3/4 lb is considered "standard" by the author) there is no substantial difference in the conclusions to be presented here because of the use of two tampers of different weights.

The Indicated Saturated Penetration Resistance.- Referring to Fig. 1 it will be noted

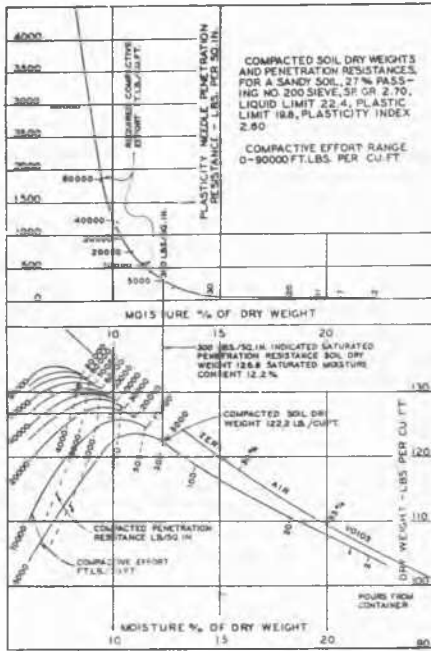


FIG. 1

that the soil dry weight line shown at 126.8 lb per cu ft intersects the zero air voids curve at 12.2% soil moisture content. This is the condition of complete saturation and lowest penetration resistance of this soil at a dry weight of 126.8 lb per cu ft. Many different methods have been proposed for evaluating a soil dry weight such as this, among which is the expression of the dry weight as a percentage of that dry weight secured by some specified tamping method of dropping a tamper from a given height. Two such methods in general use are represented by 12,375 and 56,250 ft lb per cu ft in Fig. 1, which shows a maximum soil dry weight for this soil of 126.2 and 131.2 lb per cu ft respectively. For these methods. The dry weight of 126.8 lb per cu ft would then be expressed as "100.5% density" by the first method and as "96.4% density" by the second. One other similar method that gives still different results, about "98.8% density" in this case, is also in general use. Obviously, there is no common ground for the comparison of results between these methods and all their variations and, to complicate things further, it is customary to use "standards" that are 90% or 95% of each of these three different methods; other percentages have been used in "special" cases.

The Indicated Saturated Penetration Resistance evaluates this, or any other, soil dry weight by a different method, the penetration resistance of the soil when fully saturated, as determined by assuming that the 126.8 lb per cu ft soil specimen (Fig. 1) when saturated at 12.2% moisture content would have the same penetration resistance - 300 lb per sq in., as the 122.2 lb per sq in. compacted specimen that plots on the compacted soil dry weight curve at 12.2% moisture content. The only way to check the correctness of this assumption is to prepare specimens to known dry weights, saturated them, and measure the penetration resistance; this takes considerable time in the case of very clayey specimens. Another method is to measure saturated penetration resistances at the conclusion of percolation-consolidation tests; however, such specimens have been con-

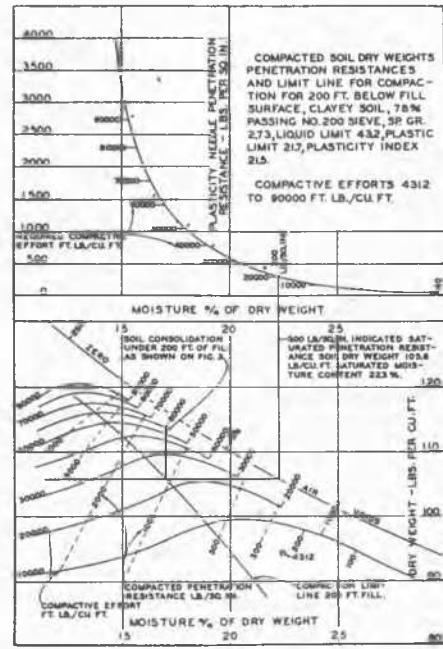


FIG. 2

solidated to a higher than compacted dry weight so these results should not be completely reliable. Considerable effort was made to determine the accuracy of the foregoing assumption of saturated penetration resistance until it was realized that it did not matter whether it was accurate or not as long as the "Indicated Saturated Penetration Resistance" was always determined in the same way, for all of the essential factors regarding compacted soils (shear strength, consolidation under loading, percolation rate, dry weight per cubic foot, and compactive effort per cubic foot) can be expressed in terms of the indicated saturated penetration resistance, which has been used successfully for fourteen years in evaluating the relative density of soils, compacted and natural.

Discussion of Data Shown in Figs. 1, 2, and 4.- Fig. 4 shows the maximum soil dry weights and indicated saturated penetration resistances versus the compactive effort, taken from the same basic data used to prepare Figs. 1 and 2. It will be noted that, at the same compactive effort (foot pounds per cubic foot) the 10 lb tamper secured a somewhat higher soil dry weight and a somewhat higher indicated saturated penetration resistance than did the 5-3/4 lb tamper. This indicates that neither the soil dry weight nor the indicated saturated penetration resistance can be used as a "standard" unless the same weight tamper is used; similar comparisons have indicated that results from 1/30 cu ft and 1/20 cu ft containers are not comparable. It is quite apparent that the "standards" for comparison of soil compaction results should not be changed frequently. The inherent error from using controlled drops of tampers wherein too much compactive energy is used for those points on the soil dry weight curve that plot adjacent to the zero air voids curve 1) has been, for the most part, eliminated from these drawings by stopping the plotting of each foot pound per cubic foot compactive effort curve as shown. Some of the higher compactive effort results plotted about half way between the soil dry weight curve as shown and the zero air voids

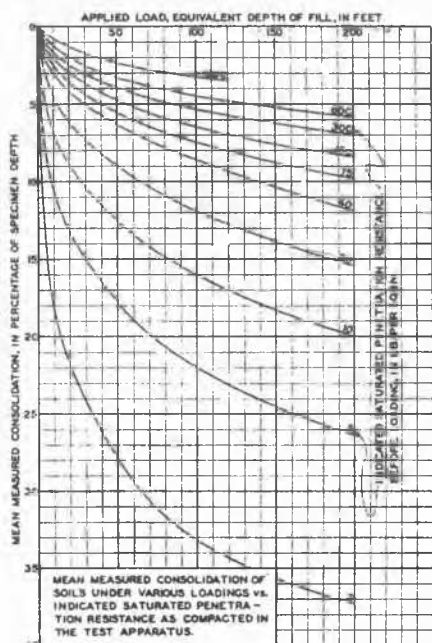


FIG. 3

curve; for instance, at about the right hand end of the 40,000 ft lb per cu ft compactive effort soil dry weight curve (soil dry weight 128.8 lb per cu ft, moisture content 10.1%), the 70,000 and 30,000 ft lb compactive efforts will secure soil densities closer to the zero air voids curve than 40,000 ft lb per cu ft would, but, at the same moisture content, the dry weight will be higher and the penetration resistance lower, indicating some pressure, probably from entrapped air, within the soil. The compactive efforts should be decreased to about the values shown along the zero air voids curve to avoid this error. The penetration resistance curve shown is for the points selected for the end of each dry weight curve as just described; the correct compactive efforts to use are also written along the penetration resistance curves.

The penetration resistances of all the compacted specimens can not be plotted clearly in the usual manner because of their falling too close together for proper identification. Accordingly, the penetration resistances for various compactive efforts have been plotted along with the dry weight curves; for instance referring to Fig. 1, the use of 32,000 ft lb per cu ft and 10.3 per cent moisture content, results in a 128 lb per cu ft compacted specimen that has a penetration resistance of 1000 lb per sq in. And, similarly, the use of 10.0 per cent moisture content and somewhat less than 5000 ft lb per cu ft also results in a compacted specimen with a 1000 lb per sq in. penetration resistance and with a dry weight of 118 lb per cu ft. It is thus seen that the use of the compacted penetration resistance alone to determine compaction is not reliable without also taking the soil dry weight or the indicated saturated penetration resistance of the soil into consideration. A compacted penetration resistance of 2000 lb per sq in. can be found in both Figs. 1 and 2 over a compacted soil dry weight range of 20 lb per cu ft; however, the indicated saturated penetration resistance for the maximum and minimum soil dry weights over this range are 1300 and 60 lb per sq in. for the soil of Fig. 2, and 650

SOIL DRY WEIGHTS AND INDICATED SATURATED PENETRATION RESISTANCES FOR SOILS OF FIG. 1 AND FIG. 2 FOR COMPACTIVE EFFORTS 5000-90000 FT. LBS. PER CU. FT. SECURED BY DROPPING 5 OR 10 LB. TAMPERS ON SOILS IN 1/20 CU. FT. CONTAINERS.

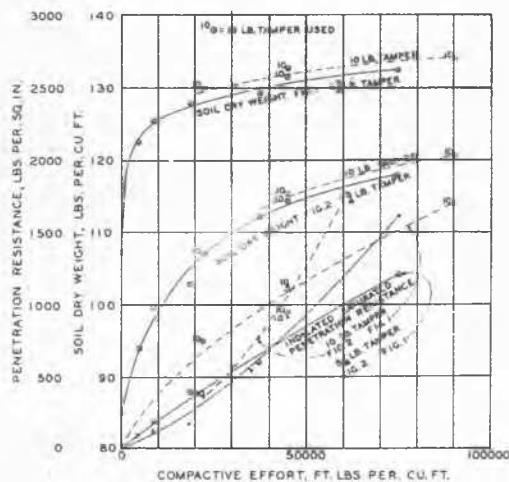


FIG. 4

and 11 lb per sq in. for the soil of Fig. 1. The results shown on Figs. 1 and 2 can be used to study the properties of these soils when compacted under all practical conditions; shear, consolidation, or expansion test results can be superimposed on Figs. 1 and 2 with very interesting results; limit lines for soil compaction to prevent saturation by soil consolidation can also be shown to advantage on such figures, as shown on Fig. 2.

Discussion of Data Shown in Fig. 7.— Fig. 7 shows the soil dry weights and the corresponding indicated saturated penetration resistances secured by compactive efforts from 0 to 75,000 ft lb per cu ft for soils ranging from sand to clay, together with the percentages of the compacted soil dry weights secured by the 56,250 and 12,375 ft lb per cu ft compaction methods. These percentage marks on the soil dry weight curves were located by the soil dry weight corresponding to the percentage of the maximum soil dry weight secured by the method; for instance, the 56,250 ft lb per cu ft method secured a soil dry weight of 131.2 lb per cu ft as shown on the upper or "sandy" soil curve, 95% of this value is 124.6 lb per cu ft, which locates the 95% mark on the upper curve. The energy in ft lb per cu ft required to secure this "95% compaction" can thus be scaled from the drawing; it is 7500 ft lb per cu ft. It is thus determined that the use of 95% compaction, as defined by this method, reduces the compactive effort to 7500 lb per cu ft., which is 13% of the "standard". The 300 lb per sq in. indicated saturated penetration resistance "standard" is also shown. It will be noted that, for all the curves, the gain in soil density is much more rapid to the left (lower compactive effort) of the 300 lb per sq in. Than to the right (higher compactive effort), and that a relatively narrow compactive effort range (15,000 to 22,000 ft lb per cu ft) is required. 2)

SOIL CONSOLIDATION UNDER VARIOUS LOADINGS

Data from Percolation-Consolidation Tests.— As the results of percolation-consolidation

COMPARISON OF INDICATED SATURATED PENETRATION RESISTANCES VS COMPACTIVE EFFORTS FOR FOUR SOILS.

SOIL	% PASSING NO. 200 SIEVE	SP GR.	LIQUID LIMIT	PLASTIC LIMIT
□ SAND	3	2.67	20.1	—
○ SANDY	27	2.70	22.4	19.8
⊗ CLAYEY	78	2.73	43.2	21.7
⊕ CLAY	98	2.72	45.0	28.6

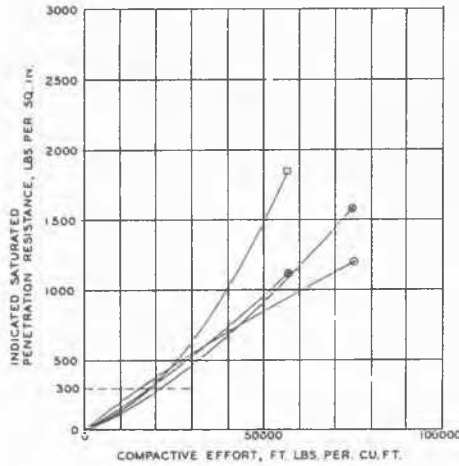


FIG. 5

SOIL DRY WEIGHTS AND INDICATED SATURATED PENETRATION RESISTANCES FOR COMPACTIVE EFFORTS OF 75000 FT. LBS. PER CU. FT. FOR FOUR SOILS.

SOIL	% PASSING NO. 200 SIEVE	SP GR.	LIQUID LIMIT	PLASTIC LIMIT
□ SAND	3	2.67	20.1	—
○ SANDY	27	2.70	22.4	19.8
⊗ CLAYEY	78	2.73	43.2	21.7
⊕ CLAY	98	2.72	45.0	28.6

-AND SHOWING THE REQUIRED COMPACTIVE EFFORTS TO SECURE FROM 90% TO 100% OF THE SOIL DRY WEIGHT SECURED BY COMPACTION METHODS REQUIRING 12,375 AND 50,250 FT. LB. PER CU. FT.

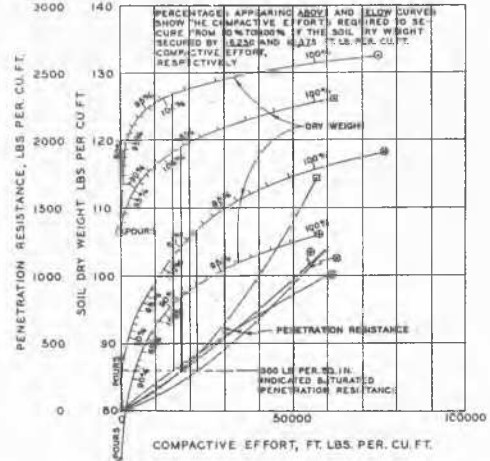


FIG. 7

COMPARISON OF SOIL CONSOLIDATION UNDER 50 LB. PER SQ. IN. LOADING AFTER COMPACTION AT COMPACTIVE EFFORTS FROM 5000 TO 75000 FT. LBS. PER CU. FT. FOR FOUR TYPES OF SOILS.

SOIL	% PASSING NO. 200 SIEVE	SP GR.	LIQUID LIMIT	PLASTIC LIMIT
□ SAND	3	2.67	20.1	—
○ SANDY	27	2.70	22.4	19.8
⊗ CLAYEY	78	2.73	43.2	21.7
⊕ CLAY	98	2.72	45.0	28.6

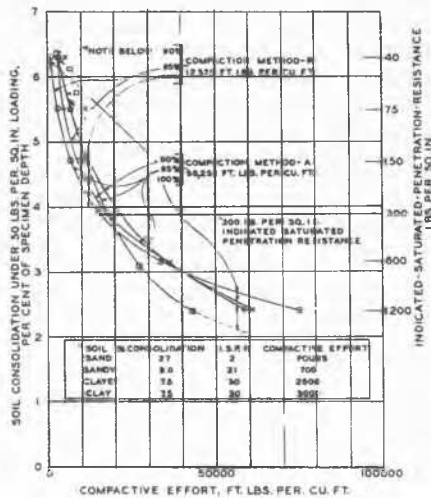


FIG. 6

900 percolation-consolidation tests. The test results from which the figure was prepared vary between the limits of one-half the consolidation shown to twice that shown for the portion of the figure lying above the 75 lb per sq in. indicated saturated penetration resistance line; it is believed that there will be found progressively less variation for points falling below this line. Soils that appear to be similar show the same variations and, accordingly, it is believed that the mean results shown in Fig. 3 are more reliable to use than individual tests of one soil, depending, of course, on how representative the sample may be of the entire volume of soil to which the test results are to apply.

Significance of Test Results Shown by Fig. 3.— The soil consolidation shown in Fig. 3 has several uses. In dam construction it enables controlling the compaction of the soils to dry weights and at moisture contents that prevent the saturation of the soils from consolidation as shown in Fig. 2, where a limit line for a 200 ft depth of fill is shown; if the compacted soil dry weight and moisture content plot on the limit line the consolidation under a 200 ft depth of fill will then increase the soil dry weight so the soil will then plot on the compaction curve. In connection with foundation it enables the prediction of the settlement that should be allowed for and, in the case of pavement subgrades, it explains to a considerable extent the failure of rigid pavements as it is quite obvious that deflections of the order of the soil consolidation results of Fig. 3 are beyond the capabilities of rigid paving slabs in the case of very heavy loads and relatively thin pavements.

Soil Consolidation Expressed in Terms of Compactive Effort.— Fig. 5 shows the indicated saturated penetration resistance of four soils, ranging from sand to clay (3 to 98% passing the No. 200 sieve) versus laboratory compactive efforts. Fig. 6 shows the predicted consolidation of these four soils by use of Figs. 3 and 5, for various compactive efforts; for example, Fig. 5 shows that the sandy soil, when compact-

test began to accumulate (in 1935) it was noted that there was a wide variation in the consolidation under similar loadings of what appeared to be similar soils. The plotting of the soil dry weights as placed in the percolation cylinders and as removed disclosed that this consolidation appeared to be controlled by the soil density. Accordingly, a figure similar to Fig. 3 was prepared and it was found that the soil consolidation could be classified approximately in terms of the indicated saturated penetration resistance.

Soil Consolidation Expressed in Terms of the Indicated Saturated Penetration Resistance Fig. 3 represents the mean results from about

ed by 15,000 ft lb per cu ft, will have an indicated saturated penetration resistance of 300 lb per sq. in., and Fig. 3 shows a consolidation under a 50 lb per sq in. loading of 3.9% for soils having an indicated saturated penetration resistance of 300 lb per sq in.; accordingly, 3.9% consolidation has been plotted on Fig. 6 at 15,000 ft lb per cu ft compaction effort on the sandy soil. The anticipated soil consolidation from the use of "90, 95, and 100% compaction" shown on Fig. 7 has been shown on Fig. 6 for the 12,375 and 56,250 ft lb per cu ft compaction methods.

CONCLUSION

The data from which the foregoing discussion was prepared have been accumulating over

a considerable period of years and have been assembled into the various figures in an effort to learn more of the relationship between compactive effort, soil density, and soil consolidation, and to find reasons why similar results were not always secured from soil compaction where apparently the same methods were used.

REFERENCES

- 1) R.R. Proctor, Laboratory Soil Compaction Methods, Penetration Resistance Measurements, and the Indicated Saturated Penetration Resistance. Paper to this Conference.
- 2) See Paper IXb 14 for further discussion of the relationship between field and laboratory compaction.

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IX b 13

A COMPARISON OF THE PHYSICAL PROPERTIES OF AN ALLUVIAL SILT COMPACTED BY FIELD AND LABORATORY METHODS

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SYNOPSIS

A comparison of the physical properties of a soil compacted by field and laboratory methods is made in this paper. From an investigation of shear, consolidation, and permeability characteristics, it is shown that there is little difference in the physical properties of a field and laboratory compacted alluvial silt.

INTRODUCTION

The present trend in earthwork construction makes the investigation of this problem very desirable, particularly, if the design of projects is to be based on the results of laboratory compaction tests.

The characteristics of the particular soil examined were determined by the unconfined compression, triaxial shear, consolidation, and permeability tests which were performed on soil compacted by field and laboratory methods. All tests were performed at approximately the same moisture content and density. Testing procedures described by Casagrande in "Notes on Soil Testing for Engineering Purposes" were followed. 1)

SELECTION AND CLASSIFICATION OF THE SOIL

A highway embankment constructed of an alluvial silt was chosen as the source of material for the research. Field compaction was accomplished with a double-unit sheepsfoot roller developing a working pressure of three hundred pounds per square inch on the area of each foot. No moisture control was exercised during construction. Final construction was completed on February 8, 1947.

Undisturbed samples were removed from the embankment by the method described by Bertram, in "Soil Tests for Military Construction", applying to "chunk samples". 2) Average dry density and moisture content values for the field compacted soil were 102.0 pounds per cubic foot and 16.2 percent, respectively. Average field compaction of the soil was 93 percent of the Modified AASHTO method and 96 percent of the

Standard Proctor method. The compaction characteristics of this material are shown by the curves in Figure 1.

Soil constants, which were determined by standard testing procedures 3), and the grain-size distribution curve are shown in Figure 2. The soil was classified as an A-4 material using the U. S. Public Roads Classification System 4) or an ML material by the Army Classification System. 5)

SHEAR CHARACTERISTICS IN AN UNCONFINED STATE

A comparison of the shear characteristics for field and laboratory compacted soil in a non-confined state was made. Unconfined compression tests were performed with a Universal Testing Machine so controlled that the average rate of strain for the tests was fifteen-thousandths of an inch per minute and the average time for failure was six minutes. Loads were measured to the nearest 0.25 pound.

A comparison of the unconfined compressive strength for field and laboratory compacted soil is shown in Table 1. Although there is considerable variation in the modulus of elasticity and unit strain at failure for field and laboratory compacted soil, the average values for these two factors are in relatively close agreement.

Despite the fact that slightly greater densities and lower void ratios were obtained for the laboratory compacted soil, the maximum ultimate strength of the field compacted soil was approximately ten percent higher than for the laboratory compacted soil. The greater ultimate strength was attributed to a phenomenon