Iowa State Compaction Apparatus for Measurement of Small Soil Samples

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A method has been developed for preparing specimens either for use in evaluating additives in soil stabilization studies or for controlling density in field construction. This method, in use at Iowa State University for several years, employs specimens 2 in. in diameter by 2 in. (approximately) high and requires only about one-tenth the material and one-third the time needed for making the standard AASHO-ASTM (or Proctor) specimens.

The density results obtained with this apparatus very closely correlate with the results obtained with the standard method. The results obtained with 17 raw soils and 10 soil-cement mixtures are presented. In addition, the effects of applied compactive energy on the densities of the different types of specimens are given.

• IN 1933, Proctor (1) described one of the first scientific approaches towards the study of soil compaction. He showed that there is a definite relationship between the maximum density to which a soil may be compacted, the amount of energy applied in the compaction process and the moisture content of the soil during compaction. Thus, for a given soil there is a moisture content which, with a given compactive effort, will give a maximum density.

Proctor devised a laboratory test for obtaining the optimum moisture content and maximum density. The compactive energy used in this test was equivalent to that produced by field compaction equipment. Standardized laboratory procedures, equipment, and ways for reporting results were developed. The ASTM Committee E-10 on Standards (2) gave it tentative standard status and the present designation is D 698 - 58 T. The American Association of State Highway Officials (3) accepted this test in 1938 and have listed it in their standards.

The development of heavier compaction equipment, particularly during and after World War II resulted in the creation of a modified laboratory test procedure by the Corps of Engineers. This modified test—commonly referred to as the modified Proctor or modified AASHO moisture-density test—is also standardized by both AASHO and ASTM. Their present designations are AASHO Designation: T 180 - 57, and ASTM Designation: D 1557 - 58 T, respectively.

These standard methods are well known to soil and highway engineers. They are now among the most widely used methods in control and design of highway and airport construction.

Recent expansion in soil stabilization research has increased the demand for soil moisture-density and strength studies. This increased activity has again pointed out drawbacks in these standard tests. Investigations involving these tests require large volumes of soil and relatively long periods of time in which to prepare specimens. Thus, any reliable moisture-density test that would reduce sample and performance

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time requirements would greatly aid soil stabilization research and would also be helpful in construction control. This problem has been studied by many investigators.

OTHER MOISTURE-DENSITY TESTS

In the late 1940's, British engineers studied the Dietert test (4) which was in use in foundry-sand testing. This was adapted to become a laboratory compaction technique (5). The Dietert apparatus consists of a 2-in. diameter mold supported on a metal base by two vertical pegs. About 150 g of soil material passing a ⅛-in. sieve are put into the mold and compacted by dropping an 18-lb weight through 2 in. onto a steel plate covering the soil. Each end of the soil in the mold is compacted with 10 blows. The Dietert apparatus, though more convenient than the AASHO-ASTM tests, has certain disadvantages. The apparatus is rather cumbersome, the specimens for all soils are not the same size and, generally, have higher densities than those obtained with the standard AASHO-ASTM apparatus. No attempt has been made to correlate this apparatus with the modified AASHO-ASTM apparatus.

The Harvard test (6), developed in 1950, employs a miniature compaction apparatus which consists of a cylindrical mold 1.3125 in. in diameter and 2.816 in. long. Soil passing the No. 4 sieve is compacted in this mold by means of a ½-in. diameter steel rod to which a prestressed spring is attached. Soil is added to the mold in five equal increments. The rod is forced into each layer of the soil until the tension on the spring is just released; then the rod is raised, and the cycle is repeated the desired number of times.

This apparatus has certain advantages in that small quantities of soil and little compactive energy are required to prepare each specimen. It is claimed that this apparatus gives moisture-density curves more closely duplicating field compaction curves than those from either the laboratory-dynamic or static methods of compaction. Its main disadvantage is that no single compactive effort or procedure adequately duplicates either field compaction or laboratory density for all types of soils. Thus, before any investigation, a correlation study has to be made. Furthermore, many investigators feel that the reproducibility results obtained with the Harvard apparatus have to be more firmly established.

Two other fairly popular moisture-density test methods have been developed in California. The older method, the California static load test (14), employs about 4,000 g of soil statically compressed in a mold 6 in. in diameter and 8 in. high. A newer method, the California impact apparatus test (2), uses a 2-in. diameter by 36-in. long hinged mold in which the added soil is compacted by the impact of a 10-lb, 2-in. diameter hammer falling through a distance of 18 in. About 2,300 g of air-dry sample are needed for each molding operation. However, both of these methods use as much or more sample than the standard methods—and take as much time or more to perform.

All the preceding procedures have some good features, as well as some bad ones. None of them has all the requirements of an "ideal" compaction apparatus and procedure; that is, an apparatus easily constructed, soil needed in small amounts, little time required to prepare the specimen, and results with good reproducibility.

Accelerated research in soil stabilization led to an attempt to develop such an ideal apparatus by personnel at the Iowa State University Engineering Experiment Station. An apparatus to mold specimens 2 in. in diameter by 2 in. high was first conceived by Davidson and Chu (7) to give densities equivalent to those obtained by means of the standard Proctor technique.* Because preliminary studies (7, 8) showed this apparatus to be feasible, a more complete investigation was carried out to obtain more definite data regarding the use of this apparatus and method.

IOWA STATE COMPACTION TEST

Apparatus

The significant features of the Iowa State compaction apparatus are shown in Figure 1.

Mold.—A cylindrical metal mold having an internal diameter of 2.0 ± 0.001 in. and

*Editor's note: A similar device developed by PCA is described in HRB Proc., 20:824 (1940).

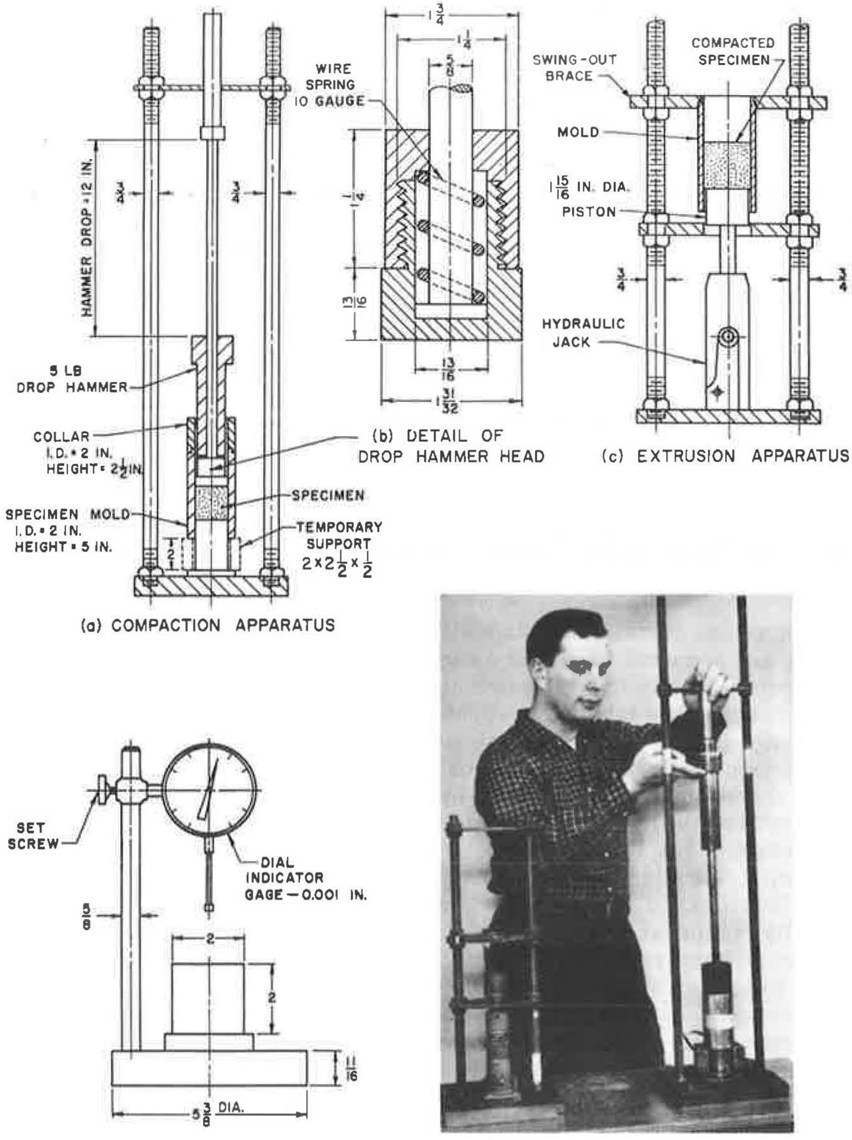

Figure 1. Iowa State compaction apparatus.

and a height of 5.0 in. is used. The mold is provided with a detachable collar that is approximately 2 in. high.

Base.—The cylindrical base has a diameter of $1^{15}/_{16}$ in. and a height of 3.0 in.

Temporary Supports.—The temporary supports are approximately 2 in. in height and are used to hold the mold above the bottom of the base until after the first blow with the hammer.

Frame.—In the frame are two steel rods, a base plate, and a cross-member having a semicircular notch which guides the downward movement of the hammer during compaction.

Hammer.—A 5-lb metal hammer that will drop 12 in. during compaction is used. The entire hammer assembly weighs approximately 10 lb 7 oz.

Extrusion Apparatus.—A hydraulic jack, with a $1^{15}/_{16}$-in. diameter piston, capable of extruding the compacted specimen from the mold without damaging the specimen is used.

Height-Measuring Apparatus.—A dial apparatus capable of measuring the heights of the extruded specimens to the nearest 0.001 in. is used.

Test Procedure

Step 1.—A predetermined amount of air-dry soil or soil-additive mixture is weighed, placed in a mixing bowl, and dry-mixed for 1 min, using a mechanical mixer set at low speed. A Hobart Model C-100, $1/4$-hp mixer has proved satisfactory for the mixing procedure. After dry mixing, the required amount of moisture is added and wet-mixed for 2 min, then the side of the bowl is scraped, the contents briefly hand-mixed and machine-mixed for another 1 min. With some heavy clays it is necessary to hand-mix entirely.

Step 2.—From this mixture, a predetermined amount of soil is taken sufficient to yield a compacted specimen 2.00 ± 0.05 in. high. This is easily determined by trial and error and is generally in the region of 190 g.

Step 3.—The temporary supports are placed about the cylindrical shaft on the compaction apparatus. The 2-in. diameter mold is set on top of these supports and the detachable collar affixed.

Step 4.—The soil is compacted by dropping the 5-lb hammer through a distance of 12 in. for the required number of times. The temporary supports should be removed after the first blow. For example, if a total of seven blows is required, the following procedure should be followed: one blow is added, the temporary supports removed, three more blows added, the detachable collar removed and the mold inverted, the three remaining blows are then added.

Step 5.—The specimen is extruded, its height is measured to the nearest 0.001 in., and weighed to the nearest 0.05 g. Where the height does not meet the 2 ± 0.05-in. criterion, the specimen should be discarded and another one compacted.

Standard Proctor Density Correlation Study

The standard Proctor[1] density correlation study was divided into two phases:

Phase 1.—The aim of phase 1 was to determine if there was a "true" correlation between the results obtained with the two methods of test. In an effort to minimize as many variables as possible, the following procedures were carried out.

Soils.—Five soils (a sand, a silty loam, a gravelly clay loam and two clays) were used in this study. Their properties are given in Table 1. The soils were chosen to cover a broad spectrum of soil types usable with the Iowa State compaction apparatus.

After each soil was transported to the laboratory, it was air-dried and thoroughly mixed. After being crushed with a rubber hammer, the soil was sieved to remove all particles retained on the No. 4 sieve. The soil was then remixed, after which, by repeated quartering it was divided into 20- to 30-lb batches; each batch then was stored in $2^1/_2$-gal containers. Inasmuch as this study was expected to extend over a period of months, this method of storing would reduce to a minimum any differential changes in soil-moisture conditions and gradation effects (9).

Cement.—To determine if the Iowa State apparatus would give the same correlation with soil-cement mixtures compacted to standard Proctor densities as with raw soils, two different cement contents were added to each soil. A new batch of cement, sufficient for the entire study, was obtained and kept in a sealed container when not in use. The cement used was Type I. This type of cement is commonly used in soil-cement construction.

Apparatus.—The Iowa State apparatus, scales, etc., were used throughout the study. The Proctor apparatus and method of compaction used conformed to that specified by Method A of ASTM D 698 - 58 T. The same apparatus, mold, etc., were used throughout.

[1] As used here and in the remainder of the text, the term "Proctor" refers to the test described by ASTM Designation: D 698 - 58 T.

TABLE 1

DESCRIPTION OF NATURAL SOILS

Property	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
Source	Harrison Co., Iowa	Story Co., Iowa (Cook's Quarry)	Durham Co., N. C.	Benton Co., Iowa	Livingston Co., Ill.
Textural composition (% by weight):					
Gravel (4.76 - 2 mm)	0	28	0	0	0
Sand (2 - 0.074 mm)	1	17	13	94	10
Silt (0.074 - 0.005 mm)	80	33	22	2	38
Clay (<0.005 mm)	19	22	65	4	52
Organic matter (%)	0.18	0.14	0.27	0.07	0.73
Cation exchange capacity, (minus No. 40 sieve fraction)(meq/100 g):	15.97	9.43	36.2	9.73	15.29
pH	8.51	8.61	5.56	7.50	8.74
Atterberg limits:					
Liquid limit (%)	34	24	74	19	36
Plastic limit (%)	27	13	26	NP	18
Plastic index	7	11	48	NP	18
Predominant clay minerals (X-ray diffraction)[a]	Mo	—	K, H	Mo, I	I
Classification:					
HRB or AASHO	A-4(8)	A-4(5)	A-7-6(20)	A-3(0)	A-6(11)
Unified	ML	CL-SC	CH	SP	CL
Textural	Silty loam	Gravelly clay loam	Clay	Sand	Clay

[a]Mo = montmorillonite; K = kaolinite; h = halloysite; I = illite.

Operator.—Because work done by more than one operator may give varying results, care was taken that all compaction was carried out by one operator (10). In addition, a system of operator controls was devised to evaluate the efficiency uniformity of the operator throughout the investigation.

Mixing and Molding.—After placing a predetermined amount of air-dry soil (and cement, when used) sufficient for three Iowa State specimens and one Proctor specimen in a bowl, it was mixed as specified earlier. While the specimens were being compacted, a damp cloth was placed over the mixing bowl to maintain constancy of moisture content.

Iowa specimens were compacted by means of 3, 6, 8, 10, 12, and 14 blows per side. At least five moisture contents were used to establish a moisture-density curve for each compactive effort. Each optimum moisture content-maximum density curve for the Proctor specimens utilized at least 30 specimens, and each Iowa curve, at a given compactive energy or number of blows, was obtained from at least 18 specimens.

Operator Controls.—After the preparation of each tenth batch a special batch was prepared and was used as a control batch. Each of these control batches contained exactly the same amount of one soil, cement, and water. The purpose of these controls was to measure operator efficiency. They also gave an indication of which was the more reproducible, the Proctor or the Iowa State specimen.

Test Results for Densities.—Figure 2 shows the maximum densities obtained with the Iowa specimens vs the number of blows per side necessary to obtain these densities. These graphs indicate very clearly the effect of increasing the compactive effort on the maximum densities. As the compactive energy is increased, the maximum densities, each obtained from a typical moisture-density curve for a particular number of blows, also increase. In addition for all soils within the range of compactive energies studied the rate of density increase appears to be constant for a given soil. Again, the rate of density increase is greatest with the fine-grained soils, and it lessens progressively with the coarser-grained soils.

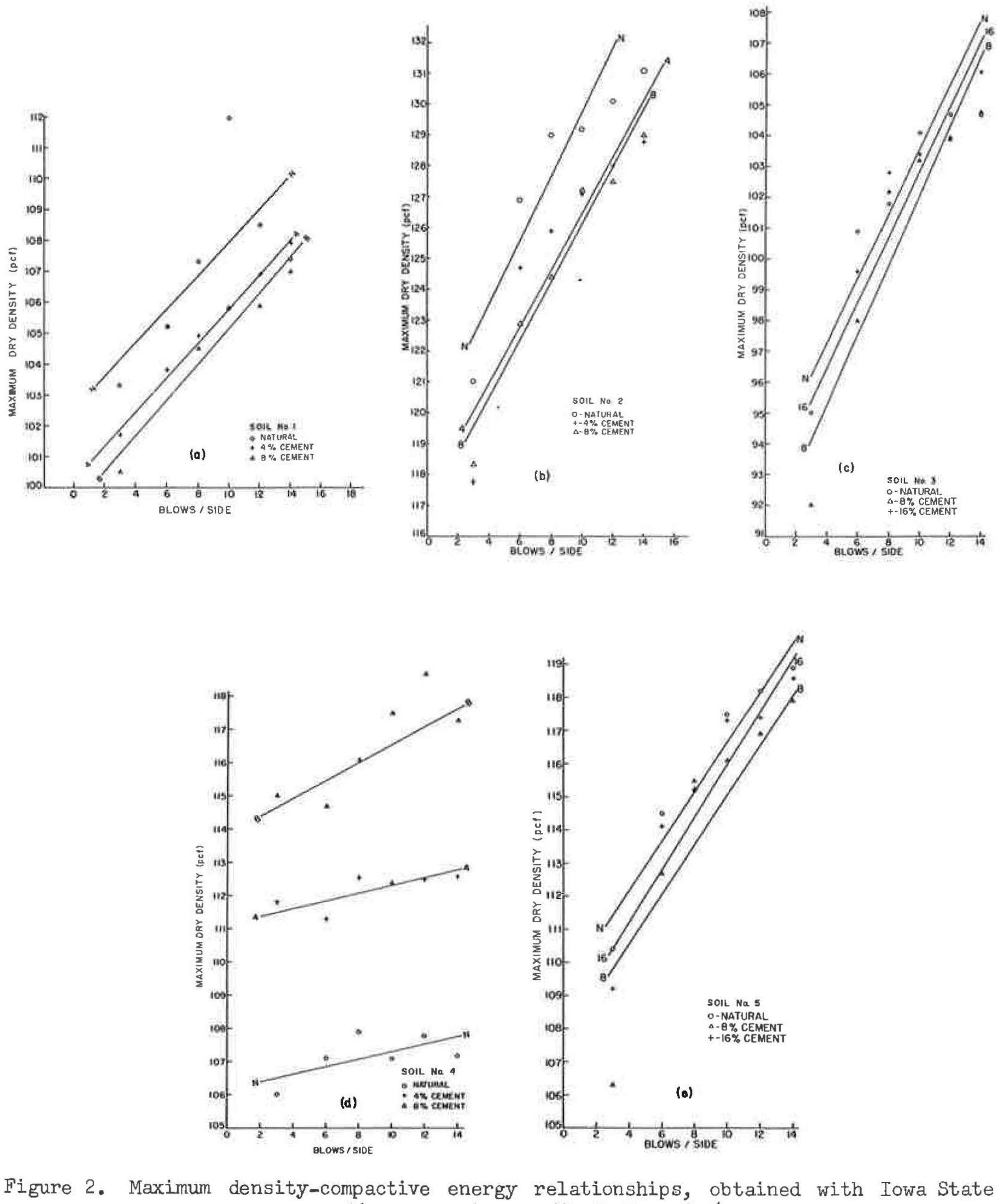

Figure 2. Maximum density-compactive energy relationships, obtained with Iowa State compaction apparatus, soils 1 through 5.

The lines indicated in these graphs were obtained by means of a "least squares" fit; their coefficients of correlation are given in Table 2.

The maximum densities obtained from the Proctor curves are given in Table 3. The number of blows of the Iowa State drop-hammer needed to attain each density is also shown. A problem is how valid is each Proctor maximum density. Davidson (11) has reported that the standard Proctor laboratory test can be performed with an accuracy of ± 4 pcf at least 99.7 percent of the time. A Wisconsin glacial till was used for his accuracy study. This observation would seem to be borne out by the results shown in Figure 3.

TABLE 2

COEFFICIENTS OF CORRELATION INDICATING DEGREE OF RELATIONSHIP BETWEEN MAXIMUM DRY DENSITIES AND COMPACTIVE ENERGIES

Soil No.	Cement Content	Coefficient of Correlation
	0	0.738
1	4[a]	0.997
	8[b]	0.980
	0[c]	0.946
2	4	0.936
	8	0.969
	0	0.958
3	8	0.941
	16	0.963
	0	0.704
4	4	0.841
	8[d]	0.863
	0	0.964
5	8	0.948
	16[e]	0.968

[a]Six blows per side eliminated.
[b]Ten blows per side eliminated.
[c]Fourteen blows per side eliminated.
[d]Twelve blows per side eliminated.
[e]Ten blows per side eliminated.

As mentioned before, control batches were prepared after each tenth regular batch. Each control batch contained exactly 2760 g of Iowa gravelly clay loam, 240 g of Type I cement, and 300 g of distilled water. From each mixture were molded three Iowa test specimens (each compacted with 10 blows per side) and one standard Proctor specimen. Figure 3 is, therefore, a plot of the control number vs dry density for both Iowa State and Proctor specimens. It is clear from these plots that the Iowa State apparatus gives more reproducible results than the Proctor apparatus. All 40 batches gave densities within a spread of 2.7 pcf with the Iowa State apparatus, but the 40 Proctor values enclosed a spread of 7.5 pcf—only 32 of them were within a spread of 3 pcf.

The question arises as to whether this direct comparison is a "fair" one inasmuch as one compactive effort gives densities of about 125 pcf, and the other 113 pcf—and it might be expected the higher density reproducibility results should be better. However, examination and comparison on the basis of the trends exhibited in Figure 3 again indicate that the Iowa State method gives the more consistent results.

To make some allowance for these possible variabilities, the number of blows necessary to attain each Proctor maximum density ± 1½ pcf are also given in the Table.

Test Results for Optimum Moisture Contents.—The optimum moisture contents for maximum Proctor densities are given in Table 3. In a manner similar to that described

TABLE 3

SUMMARY OF CORRELATION TEST RESULTS, PHASE 1

Soil No.	Cement Content	Proctor Test: O.M.C. (%)	Proctor Test: Max. Density (%)	Iowa State Test: Total No. of Blows[a]	Iowa State Test: Equiv. Moist. Content[b] (%)	Proctor Test: Max. Density (pcf)	Iowa State Test: Total No. of Blows[a] Max.	Iowa State Test: Total No. of Blows[a] Min.	Soil Classification: AASHO	Soil Classification: Textural
1	0	18.6	105.8	12	19.2	105.8 ± 1.5	17	7	A-4(8)	Silty
	4	20.3	102.4	8	19.5	102.4 ± 1.5	13	3		loam
	8	19.3	101.8	8	19.9	101.8 ± 1.5	13	3		
2	0	12.2	122.3	6	12.8	122.3 ± 1.5	9	3	A-4(5)	Gravelly
	4	12.9	118.3	2	13.2	118.3 ± 1.5	6	1		clay
	8	14.0	117.4	2	14.1	117.4 ± 1.5	5	1		loam
3	0	24.8	92.5	1	25.0	92.5 ± 1.5	2	1	A-7-6(20)	Clay
	8	10.8	97.5	12	23.6	97.5 ± 1.5	14	9		
	16	9.2	102.3	19	22.3	102.3 ± 1.5	22	16		
4	0	12.9	108.7	42	12.0	108.7 ± 1.5	74	20	A-3(20)	Sand
	4	11.8	113.1	33	12.1	113.1 ± 1.5	62	8		
	8	10.8	115.8	15	11.9	115.8 ± 1.5	26	4		
5	0	16.1	110.6	3	19.1	110.6 ± 1.5	7	1	A-6(11)	Clay
	8	20.2	106.5	1	18.5	106.5 ± 1.5	2	1		
	16	19.4	108.6	3	19.4	108.6 ± 1.5	7	1		

[a]To achieve same density as with Proctor test.
[b]Optimum moisture content to give maximum density with given number of blows.

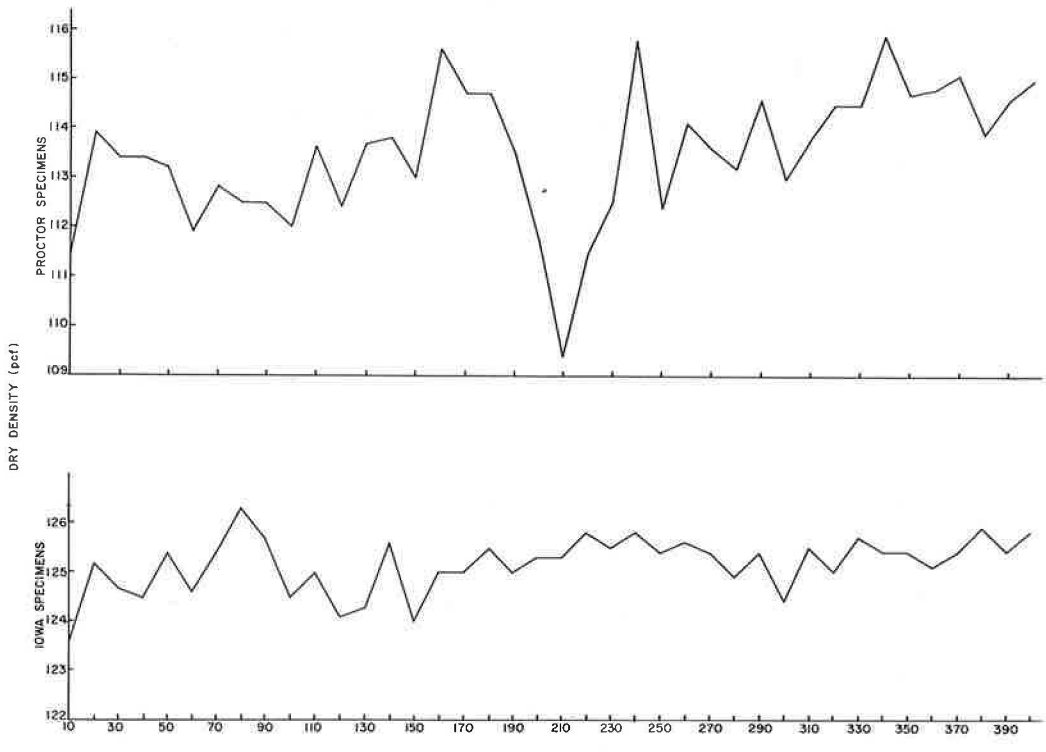

Figure 3. Density-control number relationships for Iowa State and standard Proctor tests.

for densities, the equivalent moisture contents obtained with the Iowa State apparatus were determined and are also shown in the Table.

Summary of Phase 1.—The results in Table 3 indicate quite clearly that the Iowa State compaction apparatus can be used to obtain maximum densities and optimum moisture contents which correspond with those obtained with the Proctor apparatus. However, unlike the Proctor apparatus, the compactive energy (as expressed by the number of blows) may vary from soil to soil.

Phase 2.—The aim of phase 2 was to corroborate the results obtained in phase 1, and at the same time to extend them. Because under normal working conditions, moisture-density relations would not be conducted under strict conditions (that is, by the one operator, batching, etc.), this phase was carried out under what might be considered more usual conditions (12).

Soils.—Eight natural soils (five clays, a gravelly clay loam, a silty loam and a sand) were used. Their properties are given in Table 4. These soils were chosen again so as to cover a broad spectrum of soil types and geographic locations. Soils 1a, 2a and 4a were used in phase 1 also. Soil 10 was originally believed to be sampled from the same source as soil 3, but on analysis its physical properties turned out to be different; therefore, it is treated as a separate soil.

In addition to these natural soils, four artificial soils were produced by means of controlled blending of the natural soils. The properties of these mixtures (a sand, a sandy loam, a gravelly sand, and a gravelly sandy loam) are also given in Table 4.

Preparation of these soils/mixtures was similar to that described for phase 1, except that after final mixing the materials were stored in 200-lb steel containers.

Only raw soils were used here. No cement was added to any mixture.

Apparatus.—Two Iowa State compaction apparatus were used. At different intervals, a different apparatus, scale, etc., were used. The Proctor apparatus and compaction

TABLE 4

DESCRIPTION OF NATURAL SOILS

Soil No.	Natural soil[a]					Combined Soil			
	6	7	8	9	10	12	13	14	15
Source	Harris Co., Texas	Monroe Co., Mich.	Orange Co., Va.	Ringold Co., Iowa	Durham Co., N. C.	—	—	—	—
Textural composition (% by weight):									
Gravel (4.76-2 mm)	0	0	0	0	0	0	0	21.7	35
Sand (2-0.0.74 mm)	3	7	21	21	45	85	54.5	66.7	35.4
Silt (0.074-0.005 mm)	36	36	37	41	18	5	36.9	3.9	24.0
Clay (0.005 mm)	61	57	42	38	37	10	8.6	7.7	5.6
Colloids (<0.001 mm)	37	—	—	—	—	—	—	—	—
Organic matter (%)	0.6	0.6	2.6	0.06	0.1	—	—	—	—
Atterberg limits:									
Liquid limit (%)	65	44	44	41	51	19	19	19	15
Plastic limit (%)	18	21	27	17	26	NP	NP	14	NP
Plasticity index	47	23	17	24	25	NP	NP	5	NP
Specific gravity	2.67	2.68	2.65	—	—	2.65	2.65	2.68	2.68
Predominant clay mineral (X-ray diffraction)[b]	Mo	I, Ch	H	Mo	Mi, K	—	—	—	—
Cation exchange capacity (minus No. 40 sieve fraction)(meq/100 g)	33.1	13.4	12.4	17.5	8.4	—	—	—	—
Classification:									
HRB or AASHO	A-7-6(20)	A-7-6(14)	A-7-6(12)	A-7-6(14)	A-7-6(11)	A-2-4	A-4(2)	A-1-b(0)	A-2-4(0)
Unified	CH	CL	ML-CL	CL	CH-NH, NL-CL	SC-SP	SM	SP-SC or SW-SC	SM-SC
Textural	Clay	Clay	Clay	Clay	Clay	Sand	Sandy loam	Gravelly sand	Gravelly sandy loam

[a]Soils 1a, 2a, and 4a same as soils 1, 2, and 4, respectively, described in Table 1.
[b]Mo = montmorillonite; I = illite; C = chlorite; H = halloysite; Mi = mica; K = kaolinite.

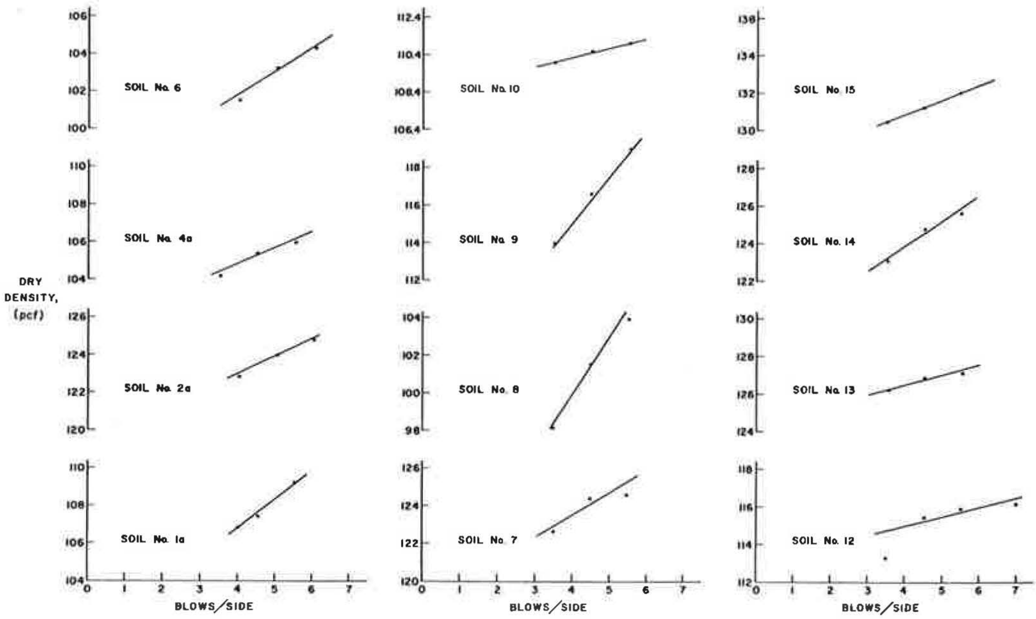

Figure 4. Maximum density-compactive energy relationships, obtained with Iowa State compaction apparatus, soils 6, 7, 8, 9, 10, 1a, 2a, 4a, 12, 13, 14, 15.

method conform to that specified by Method A of ASTM D 698 - 58 T. Three different sets of apparatus were used in this phase of the study.

Operator.—Four different operators were used to compact specimens at varying intervals.

Mixing and Molding.—The mixing and molding procedures were similar to those given earlier in this paper, with the following exceptions.

Proctor specimens were prepared separately from the Iowa State specimens. Each optimum moisture content-maximum density curve for the Proctor specimens used at least five specimens (one specimen giving one point on the curve), whereas each Iowa State curve, at a given compactive energy, was obtained from at least 15 specimens—each point being the average of three values.

Test Results for Densities.—Figure 4 shows the maximum densities from the Iowa State curves vs the number of blows per side necessary to obtain these densities.

These plots again show the effect on maximum densities of increasing the compactive effort. Again, within the range of compactive efforts studied, the rate of maximum density increase appears to be constant within a given soil. Also, the rate of change is greatest with the fine-grained soils and least with the coarse-grained ones. The lines in these graphs are subject to an "eye-fit." Due to the relative paucity of data, a more rigid statistical procedure was not justified.

The maximum densities obtained from the Proctor curves are given in Table 5, as are also the number of blows of the Iowa State compaction hammer needed to attain each density. The number of blows with the Iowa State apparatus needed to attain maximum Proctor densities $\pm 1\frac{1}{2}$ lb are also given in the Table.

Test Results for Optimum Moisture Contents.—The optimum moisture contents for maximum Proctor densities are given in Table 5. In a manner similar to that described before, the equivalent moisture contents obtained with the Iowa State apparatus were determined and are also given in the Table.

Summary of Phase 2.—The results shown in Table 5 also indicate that the Iowa State compaction apparatus can be used to obtain optimum moisture contents and maximum densities that correspond closely to those obtained with the standard Proctor apparatus and procedure. Again, it is clear that, unlike the Proctor test, the applied compactive energy may vary from soil to soil.

TABLE 5

SUMMARY OF CORRELATION TEST RESULTS, PHASE 2

Soil No.	Proctor Test O.M.C. (%)	Proctor Test Max. Density (pcf)	Iowa State Test Total No. of Blows[a]	Iowa State Test Equiv. Moist. Content[b] (%)	Proctor Test Max. Density (pcf)	Iowa State Test Total No. of Blows[a] Max.	Iowa State Test Total No. of Blows[a] Min.	Soil Classification AASHO	Soil Classification Textural
6	19.8	102.4	9	22.7	102.4 ± 1.5	11	7	A-7-6(20)	Clay
7	13.8	119.1	2	12.7	119.1 ± 1.5	4	1	A-7-6(14)	Clay
8	21.0	98.5	7	23.4	98.5 ± 1.5	8	6	A-7-6(12)	Clay
9	14.6	114.7	7	14.7	114.7 ± 1.5	9	6	A-7-6(14)	Clay
10	15.6	109.5	5	18.4	109.5 ± 1.5	11	1	A-7-6(11)	Clay
2a	11.8	121.3	4	14.6	121.3 ± 1.5	7	1	A-4(5)	Gravelly clay loam
1a	16.4	104.7	5	17.4	104.7 ± 1.5	7	3	A-4(8)	Silty loam
4a	12.9	111.1	22	12.0	111.1 ± 1.5	25	19	A-3(0)	Sand
12	11.0	116.8	16	10.0	116.8 ± 1.5	21	9	A-2-4	Sand
13	9.7	125.7	5	11.0	125.7 ± 1.5	10	1	A-4(2)	Sandy loam
14	8.9	127.1	13	9.4	127.1 ± 1.5	15	10	A-1-b(0)	Gravelly sand
15	7.8	132.5	12	7.6	132.5 ± 1.5	15	8	A-2-4(0)	Gravelly sandy loam

[a]To achieve same density as with Proctor test.
[b]Optimum moisture content to give maximum density with given number of blows.

Combination of Phases 1 and 2.—In combining phases 1 and 2, it must be kept in mind that phase 1 was a very carefully controlled experiment, and phase 2 was what might be considered a routine experiment. Also, three of the soils evaluated were used in both experimental phases.

Energy Recommendations.—If the Iowa State test is to be used to simulate the standard Proctor test, it can only do so if the compactive energy (as reflected by the number of blows) is varied. The amounts of variation depend on the characteristics of the soils being tested. The questions then arise as to how the compactive energy should be varied and what the soil characteristics are that cause these changes.

Examination of the more obvious chemical characteristics indicates no relationships. Most of the more common clay minerals are represented, but they appear to have little effect on compactive energies. Also, within the range studied, the amount of organic matter appears to have no influence.

There seems to be little doubt that the physical characteristics of the soil have the most influence. The question is therefore what the simplest breakdown of these characteristics is that justifies compactive energy changes. One of the most widely used soil classification systems is the AASHO system. Although this system has certain debatable features, it has the advantages of being easy to use and of having such wide acceptance that most soil and highway laboratories use it as an aid towards classifying their soil materials as a matter of routine.

Based on this system the following recommendations are given (Table 6) regarding the number of blows of the Iowa State drop-hammer to use with the various soil types.

Where an even number of blows is recommended for a particular soil, this means that one-half the number of blows should be applied to one end of the specimen and the other half should be applied to the other end after the mold is inverted.

TABLE 6

IOWA STATE COMPACTION TEST ENERGIES TO USE WITH VARIOUS SOIL TYPES

Total No. of Blows[a]	Soil Type[b]
6	A7, A6
7	A4
14	A3, A2, A1

[a]Drop-hammer weighs 5 lb and falls through height of 12 in.
[b]Based on AASHO system; soil classified after being passed through No. 4 sieve.

TABLE 7

SUMMARY OF CORRELATION TEST RESULTS

Soil No.	Cement Content (%)	Proctor Test O.M.C. (%)	Proctor Test Max. Density (pcf)	Iowa State Test Recommended No. of Blows[a]	Iowa State Test Equiv. Density[b] (pcf)	Iowa State Test Equiv. Moist. Content[c] (%)	Density Differences (pcf)	Moisture Content Differences (%)	Soil Classification, AASHO
3	0	24.8	92.5	6	96.2	24.4	3.7	-0.4	A-7-6(20)
	8	10.8	97.5	6	94.2	25.2	-3.3	14.4	
	16	9.2	102.3	6	95.4	24.7	-6.9	15.5	
5	0	16.1	110.6	6	111.4	18.5	0.8	2.4	A-6(11)
	8	20.2	106.5	6	109.8	17.9	3.3	-2.3	
	16	19.4	108.6	6	110.3	18.9	1.7	-0.5	
6	0	19.8	102.4	6	100.3	23.6	0.9	3.8	A-7-6(20)
7	0	13.8	119.1	6	122.0	12.8	2.9	-1.0	A-7-6(14)
8	0	21.0	98.5	6	97.0	23.0	-1.5	2.0	A-7-6(12)
9	0	14.6	114.7	6	112.8	14.9	-1.9	0.3	A-7-6(14)
10	0	15.6	109.5	6	109.8	18.0	0.3	2.4	A-7-6(11)
1	0	18.6	105.8	7	104.5	20.0	-1.3	1.4	A-4(8)
	4	20.3	102.4	7	102.2	19.0	-0.2	-1.3	
	8	19.3	101.8	7	101.3	20.0	-0.5	0.7	
2	0	12.2	122.3	7	123.0	12.7	0.7	0.5	A-4(5)
	4	12.9	118.3	7	120.5	12.8	2.2	-0.1	
	8	14.0	117.4	7	119.9	13.6	2.5	-0.4	
1a	0	16.4	104.7	7	106.1	17.2	1.4	0.8	A-4(8)
2a	0	11.8	121.3	7	122.5	13.1	1.2	1.3	A-4(5)
13	0	9.7	125.7	7	126.3	10.9	0.6	1.2	A-4(2)
4	0	12.9	108.7	14	107.5	14.5	-1.6	1.6	A-3(0)
	4	11.8	113.1	14	111.9	14.0	-1.2	2.2	
	8	10.8	115.8	14	115.7	12.0	-0.1	1.2	
4a	0	12.9	111.1	14	107.5	13.2	-3.6	0.3	A-3(0)
12	0	11.0	116.8	14	116.4	10.5	-0.4	-0.5	A-2-4
15	0	7.8	132.5	14	133.3	6.8	0.8	-1.0	A-2-4(0)
14	0	8.9	127.1	14	127.9	9.5	0.8	0.6	A-1-b(0)

[a]To achieve near maximum Proctor density.
[b]Maximum density attained at given number of blows.
[c]Optimum moisture content to attain maximum density with given number of blows.

Where an odd number of blows is recommended, the larger "half" of these blows should first be applied, then the mold inverted and the remaining blows applied.

The temporary supports (as specified under "apparatus") should always be removed after the very first blow is applied.

Analysis.—A summary of the data obtained when the recommended compactive energies are applied to the investigated soils is given in Table 7.

Close correlation between the densities obtained with the Iowa State and the Proctor procedures is found with most mixtures, excepting those containing soil 3. This soil was originally believed to have come from the same source as soil 10 which shows good correlation; however, the physical characteristics of the two soils show them to be quite apart. These differences are strongly reflected in the soil 3, cement mixtures; why the density and moisture differences should be so great is not known at this time.

Omitting the mixtures containing soil 3, 46 percent of the densities achieved with the Iowa State test are within 0.9 pcf, 75 percent are within 1.7 pcf, and 87.5 percent are within 2.5 pcf of those maximum densities achieved with the standard Proctor method of test. Similarly, 46 percent of the optimum moisture contents obtained with the Iowa State apparatus are within 1 percentage point, 75 percent are within 1.5 percentage points, and 96 percent are within 2.5 percentage points of the optimum moisture contents achieved with the standard Proctor test.

At this stage, the results obtained in this study are not being interpreted on a "pure" energy basis. Correlation on the basis of an exact energy comparison was not feasible at the time of the study due to the impracticalities involved in evaluating (a) the friction factor as reflected by the compaction hammer-soil-mold effect and (b) the exact effect of the spring being incorporated in the compaction hammerhead.

Reproducibility Studies.—Figure 3 shows control specimen numbers vs the attained densities. All these controls were compacted by the same operator using the same apparatus, and were prepared at regular intervals throughout phase 1 of the study which lasted over 4 months. It is obvious that when only one operator and one set of apparatus are involved, and if careful mixing and batching procedures are carried out, the Iowa State apparatus gives more precise results than the standard Proctor apparatus.

When different operators and different Iowa State apparatus sets are involved, and if there is less control over mixing, sampling, and batching, the reproducibility results are not so striking. However, comparison of the raw soil results for soils 1 and 1a, 2 and 2a, 4 and 4a indicate again the superior reproducibility of the Iowa State densities. This is most noticeable when comparing the results obtained with the most difficult of these three soils (No. 4), which is a sand.

Time and Sample Requirements

The Iowa State method takes less materials and is more rapid for studying moisture-density relations. In addition, there is less expenditure of operator energy and less operator fatigue when the Iowa State method is used. This results in more efficient operator output and greater value for the dollar spent.

The following observations were made for comparative purposes during the course of phase 2 of the study. The time required for two technicians, after mixing, to compact, weigh and record data for one standard Proctor specimen is 5.4 min and for one Iowa State specimen is 1.4 min. Between 1,800 and 2,500 g of soil are needed for each Proctor specimen at each moisture content; but only from 180 to 250 g are required for each Iowa State specimen. If, as was done in this study, three 2-in. diameter by 2-in. high specimens are prepared at each moisture content, and if 100 g are used for a moisture content determination, the sample requirement is still only 40 percent of that required for the standard Proctor test; and the time requirement is still more than 25 percent less.

Another factor is that, in moisture-density studies, the Iowa State specimen is small enough to be used for the moisture content sample. This increases investigation accuracy and efficiency under the following circumstances:

1. As a larger soil-moisture sample is taken.
2. As sampling error is eliminated (as is done in many cases) the soil-moisture sample is taken directly from the mixing bowl.
3. As one weighing procedure is eliminated, because the specimen has already been weighed for density purposes.

Use as Soil-Additive Evaluation Test

Although not investigated to a great extent in this study, it is obvious that the Iowa State compaction apparatus may be used to prepare specimens for soil-additive strength evaluation purposes.

Moisture-Density Test.—Figure 2 and Table 7 show that the addition of cement to soils has little effect on the compaction characteristics. Figure 2 shows that for a given soil, the effect on density of the raw soil/compactive energy relationship is the same as that caused by the soil-cement mixture/compactive energy relationship. Table 7 shows that, in general, the same compactive energies may be applied to the soil-cement mixtures as are applied to the raw soil mixtures to attain their equivalent standard Proctor maximum densities.

Strength Test.—The unconfined compression test, which is also simple in procedure and requires little special equipment, is used by many investigators in the study of stabilized soils. Though specimens having a height to diameter ratio of 2:1 are most desirable for this test, there is no reason why the Iowa State specimens may not be used in the preliminary evaluation of the effects of certain additives. After using these more easily prepared specimens for determining the more obvious detrimental or helpful additives or determining suitable percentages of a particular additive, limited numbers of the usual 2:1 cylindrical specimens need only be prepared for the final "finer" analysis.

Other Uses

The Iowa State compaction apparatus has proved its usefulness and convenience for over seven years at Iowa State University. This has led to extensive research regarding other uses for it, besides being used in moisture-density and unconfined compressive strength studies. The apparatus is being modified to give densities correlating with those obtained with the modified AASHO (Proctor) test procedure. A miniature bearing test, capable of simulating the California Bearing Ratio test, has been developed and is being evaluated. In addition, a practical freeze and thaw test, similar to that used in England and Belgium but using the 2-in. diameter by 2-in. high specimen, is being extensively studied (13).

SUMMARY AND CONCLUSIONS

1. The Iowa State compaction apparatus and procedure can be used within field- and laboratory-attainable accuracies to obtain the same maximum dry densities and optimum moisture contents of soils as determined by the standard AASHO-ASTM (or standard Proctor) test.

2. The Iowa State compaction test can be used within field- and laboratory-attainable accuracies to obtain the same maximum dry densities and optimum moisture contents of soil-cement mixtures as determined by the standard AASHO-ASTM (or standard Proctor) test. There appears to be no reason why it cannot be used in other soil-additive/moisture density studies.

3. Use of the Iowa State compaction test to obtain standard Proctor moisture-density relationships requires that the compactive effort be varied according to soil type. The Iowa State compaction test energies to use with various soil types are given in Table 6. The soil type is based on the AASHO system; the soil is classified after being passed through the No. 4 sieve.

4. The Iowa State compaction test is reliable; it is more precise, and it requires less time and materials than the standard Proctor test.

5. There is a straight-line relationship between compactive energies and the maximum densities attained at these energies, and between compactive energies and the optimum moisture contents attained at these energies. As the compactive energy increases, the maximum density also increases. As the compactive energy increases, the optimum moisture contents decrease.

6. The Iowa State apparatus and procedures can be used very readily and economically in soil stabilization strength studies involving the unconfined compressive strength test.

ACKNOWLEDGMENTS

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REFERENCES

1. Proctor, R. R., "Fundamental Principles of Soil Compaction." Eng. News-Record, 111:No. 9, pp. 245-248 (1933).
2. "1961 Book of ASTM Standards." Part 4, American Society for Testing and Materials (1961).
3. "Tests and Specifications." Part 3, American Society of State Highway Officials, 7th ed. (1958).
4. "Soil Mechanics for Road Engineers." Great Britain, Department of Scientific and Industrial Research, Road Research Laboratory (1952).

5. Little, A. L., "Laboratory Compaction Technique." Internat. Conf. on Soil Mechanics and Foundation Engineering, Proc., 2:224-226 (1948).
6. Wilson, S. D., "Small Soil Compaction Apparatus Duplicates Field Results Closely." Eng. News-Record, 145:No. 18, pp. 34-35 (1950).
7. Chu, T. Y., and Davidson, D. T., "Some Laboratory Tests for the Evaluation of Stabilized Soils." Iowa Engineering Experiment Station Bull. 192, 243-256 (1960).
8. Viskochil, R. H., "Effects of Density on Unconfined Compressive Strength, Absorption and Volume Change of Lime and Fly Ash Stabilized Soils." M. S. thesis, Iowa State University (1962).
9. O'Flaherty, C. A., "New Techniques for Data Evaluation and Control in Soil Engineering Investigations." Ph. D. thesis, Iowa State University (1962).
10. Edgar, C. E., "Use of the Iowa State Drop-Hammer Apparatus in the Study of the Moisture-Density Relations of Soils and Soil-Cement." M. S. thesis, Iowa State University (1962).
11. Davidson, D. T., and Chu, T. Y., "Calculations of Standard Proctor Density and Optimum Moisture Content from Mechanical Analysis, Shrinkage Factors, and Plasticity Index." HRB Proc., 29:480-481 (1949).
12. Austin, K. B., "Use of the Iowa Drop-Hammer Apparatus in Studying Moisture-Density Relations of Soils." M. S. thesis, Iowa State University (1961).
13. George, K. P., "Development of a Freeze-Thaw Test for Evaluating Stabilized Soil." M. S. thesis, Iowa State University (1961).
14. Porter, O. J., "The Preparation of Subgrades." HRB Proc., 18:324-331 (1938).
15. Catton, M. D., "Research on the Physical Relations of Soil and Soil-Cement Mixtures." HRB Proc., 20:821-855 (1940).

Discussion

W. H. CAMPEN and L. G. ERICKSON, Omaha Testing Laboratories, Omaha, Nebraska—The authors are to be complimented for doing a tremendous amount of research in an orderly manner. However, as often is the case, the end results are the opposite of what was anticipated. In other words, their data show that the proposed method does not duplicate the results obtained by the standard Proctor method.

To substantiate this contention the authors' data in phase 1 of the research are used because of the better-controlled conditions in that phase. Table 8 shows the relationship between soil type in respect to plasticity index and blows required in the Iowa State method to produce the same maximum density obtained by the standard Proctor method.

The data show that the energy required for maximum density varies inversely with the plasticity index. For instance, nonplastic sandy soil No. 4 requires 42 times more energy than very plastic No. 3. This finding is the reverse of what is known to be the

TABLE 8

RELATIONSHIP BETWEEN SOIL TYPE AND PLASTICITY INDEX AND NUMBER OF BLOWS

Soil No.	Plasticity Index	No. of Blows
4	0	42
1	7	12
2	11	6
5	18	3
3	48	1

TABLE 9

BRITISH FIELD COMPACTION TEST RESULTS

Soil No.	Plasticity Index	Passes Required to Develop 100 Psf Dry Wt.
4	8	1.4
5	19	2.5
6	52	10.5

fact. It is well known by both engineers and contractors that low PI and sandy soils can be compacted easily, whereas heavy clays offer high resistance to compaction.

In 1945, the writers presented a paper (16, Fig. 2) showing that to obtain a dry weight of 110 pcf soil 2 (PI = 10.5) required 235 foot-poundals, whereas soil 13 (PI = 21.1) required 1,170 foot-poundals.

Table 9 gives the results of field compaction tests conducted by the British, showing relationships between plasticity index and energy requirements. Compaction was done with a 9½-ton three-wheel roller.

REFERENCE

16. Campen, W. H., and Smith, J. R., "Bearing Index of Soil as a Criterion for the Maximum Density Requirement." HRB Proc., 25:96-99 (1945).

CHARLES E. EDGAR, III, Closure—The authors wish to thank Messers. Campen and Erickson for their review of this paper. We quite agree with their discussion that sands compact easily in the field. It is precisely for this reason that one would expect a higher laboratory compactive energy (blow) requirement for sands to achieve the duplication of field results. The findings, as presented, speak for themselves. Further, when using this apparatus, there is much more of a "rebound" effect when compacting sands; there is little or no rebound with clay soils. Also, the Iowa State compaction method does not attempt to simulate the method by which maximum density is obtained either by the standard Proctor apparatus or in the field itself—it only attempts to duplicate the end results.

The reviewers have not refuted these findings. Rather, to the contrary, they have added even more support to the conclusions that the Iowa State compaction method will duplicate standard Proctor results.