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CHARACTERISTICS OF IRREGULARLY SHAPED COMPACTION CURVES OF SOILS

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Although the curve of dry density versus moisture content commonly yielded by the standard AASHO compaction tests contains a single maximum, some soils have produced more complicated curves. Because these soils have not been well studied, extensive work has been carried out to establish the existence of irregularly shaped curves. The primary effort was focused on examining, from both a macroscopic and a microscopic level, the characteristics that lead to such curves. The investigation has established 4 types of compaction curves: one with a single peak, one with an irregular 1½ peak, one with a double peak, and one that is almost a straight line with no distinct maximum dry density or optimum water content noted. There is a correspondence between the index properties on the modified Casagrande's chart and the kind of curve. The mineral constituents of the soil samples also affect the shape of the moisture-density compaction curve.

•SOILS with different physical properties react differently when exposed to the compaction process. Some clays and other highly cohesive soils are very unstable materials. As a result, use of such material is usually avoided in engineering construction. However, extensive areas of the world are covered by such soils, and they must often be used because it is economically unfeasible to bypass them or replace them with more suitable material.

As a consequence, typical soils have been subjected to standard compaction tests in which the maximum dry density achievable with given amounts of compaction is determined as a function of moisture content. The tests yield curves (Fig. 1) with a single peak for most soils and with irregular shapes for some soils (1, 2, 3, 4, 5, 6, 7). Because there are insufficient data on those soils, existing theories of compaction have not been extended to cover adequately the irregular curves.

The phenomena occurring during compaction are not completely understood. Nevertheless, 4 theories exist: Proctor's capillarity and lubrication theory (8), Hogentogler's viscous water theory (9), Lambe's physicochemical theory (10, 11), and Olson's effective stress theory (1). None of these adequately explains the irregularly shaped compaction curves found.

Olson obtained 2 peaks in the moisture-density curve for illitic clay. Lacking a diagnostic laboratory study, he gave only a tentative explanation of the results. He considered the concave portion of the curve between the 2 peaks to be governed by negative pore-water pressure. The formation of pore-water menisci between soil particles at their contact points caused an increase in effective stress from the surface tension of the pore fluid. The minimum dry density between 2 peaks occurred when all the menisci were fully developed. Beyond this point flattening of the menisci reduced the pressure differential across the surface, whereupon lubrication and double water layers helped to develop a more dispersed structure. The resulting increase in dry density continued until the second peak of optimum water was obtained. With only inconclusive data available, Olson suggested that a double-peak compaction curve could form only

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in soils containing a dominant percentage of plate-like colloidal particles. He also noted that a double-peak curve has not been observed with soils containing only a small amount of clay. However, Johnson and Sallberg (2) found that some sands exhibit very irregular compaction curves that are almost straight lines. They also noted that clay soils that are often highly structured may yield irregular compaction curves when tested by the standard AASHO Method T 99-57. Lambe (7) explained that the $1\frac{1}{2}$-peak curve for sandy soils may be due to a capillary force phenomenon known as bulking. The existing theories could not be applied to these unusual compaction curves.

Soil to be used as engineering material must behave in a definite, explainable manner. However, present available data are incomplete, and the full range of soils exhibiting irregularly shaped curves is not known. Determining the optimum water content to achieve maximum dry density for soils exhibiting such characteristics could present a problem to the engineer. A system of classification aids the engineer in analyzing a soil so it can be used effectively as an engineering material. No one has attempted to group soils according to their compaction behavior. Such a system would further aid the engineer in evaluating a soil for earthwork construction.

An investigation was carried out to examine the existence of irregularly shaped moisture-density compaction curves. The experiments had 2 objectives: to establish the existence of irregularly shaped compaction curves and to examine from both a macroscopic and a microscopic level characteristics of soils that produce irregularly shaped compaction curves.

The results of this study confirm the existence of irregularly shaped compaction curves and also provide information on whether a correlation of compaction curve shapes and index properties exists. Knowing effects of various mineral constituents on the shape of the compaction curve increases one's understanding of soil behavior. In addition, the effect of varying the time between preparation of the sample and testing time was also investigated.

LABORATORY INVESTIGATION

Soil Test Specimens

To study more than one aspect of this investigation at one time, we followed a testing program that combined a number of variables (for the purpose of obtaining various shapes of compaction curves). Soil samples having different physical properties were tested. Because of the cost and time involved, it would have been quite difficult to obtain from different parts of the country a large number of soil specimens that would exhibit different physical properties. It is also difficult to determine exact mineral percentages of soil samples through X-ray diffraction analysis. Therefore, so that test samples would exhibit a wide range of physical properties and at the same time the exact mineral percentages of each specimen would be known, soil samples were combined from known minerals. The 5 most important and common minerals found in soils are kaolinite, montmorillonite, illite, quartz, and feldspar (12). It is known that more than 90 percent of all soils in the world are made up of silicate minerals. Kaolinite is the most common 2-layered silicate mineral encountered by engineers. The 2 most common 3-layered structures in soil are montmorillonite and illite. Feldspar and quartz make up a framework silicate structure. Because they are common rock-forming minerals, the frameworks are abundant in soils and also are found in pure deposits commonly known as sand. As a result 4 primary samples consisting of kaolinite, montmorillonite, illite, and sand, which was locally available, were obtained. The sand sample consisted primarily of feldspar. From these 4 samples an additional 24 samples were obtained by mixing arbitrary combinations of each (Table 1). In addition 7 natural samples, typically encountered in engineering construction from various locations in the country, were also tested as a basis of comparison (Table 2).

Test Procedure

Three types of compaction effort are frequently used in compaction tests: impact, kneading, and vibratory. Static compaction is also used on a limited scale in the preparation of test specimens. In addition to the differences in types of compaction effort,

Figure 1. Typical single-peak and irregularly shaped compaction curves.

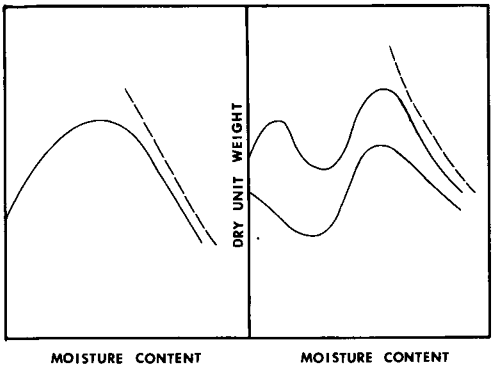


Table 1. Arbitrary-combination soil samples.

Sample	Sand[a] (percent)	Montmorillonite[b] (percent)	Illite[c] (percent)	Kaolinite[d] (percent)	Liquid Limit	Plasticity Index
1	0	0	0	100	35	5
2	0	0	100	0	51	21
3	0	100	0	0	548	500
4	100	0	0	0	0	NP
5	0	50	0	50	226	174
6	50	50	0	0	230	198
7	25	0	50	25	40	19
8	25	25	50	0	102	78
9	50	25	0	25	117	106
10	25	50	25	0	172	142
11	0	50	50	0	170	129
12	25	0	25	50	30	6
13	25	50	0	25	161	132
14	0	0	50	50	43	16
15	50	25	25	0	72	50
16	50	0	25	25	22	5
17	25	25	0	50	112	86
18	0	25	25	50	90	57
19	50	0	50	0	27	8
20	50	0	0	50	18	4
21	0	25	50	25	105	73
22	0	50	25	25	196	157
23	85	15	0	0	51	26
24	85	0	15	0	13	NP
25	85	0	0	15	11	NP
26	60	0	10	30	18	4
27	75	0	0	25	13	NP
28	75	0	25	0	17	NP

Note: All percentages identified by X-ray diffraction.

[a] Pure sand obtained locally.

[b] Bentonite obtained from Baroid Division of National Lead Company, Houston.

[c] Grundite obtained from Green Refractionery Company, Morris, Illinois.

[d] Clay hydrite-121 obtained from Thompson-Hayward Chemical Company, Kansas City, Kansas.

Table 2. Natural soil samples.

Sample	Soil	Liquid Limit	Plasticity Index
29	Pierre bentonite	310	244
30	Oregon clay, gray	70	32
31	Washington clay, red	30	8
32	Texas clay, light brown	82	47
33	Pierre shale, sample 1	68	29
34	Pierre shale, sample 2	110	66
35	New Orleans clay, gray	78	29

there are other variations that influence the moisture content-unit weight relations. These include size of mold, amount of compaction effort, maximum size of aggregates permitted, method of supporting the mold, and method of preparing the soil for testing. As a result, the standard methods have been set up for the various types of compaction. The most commonly and widely used is the standard AASHO method also identified as ASTM Designation D 698-70. In this method the soil fraction passing through the No. 4 sieve (4.76 mm) is compacted in 3 layers in a 4-in. diameter mold by dropping a 5.5-lb hammer 25 times per layer from a height of 12 in. In this investigation, we were interested only in the shape of moisture-density curves produced by this standard method. With the exception of the wetting period, other differences in apparatus and procedures are not covered within this investigation.

Because this investigation was concerned with the irregularly shaped compaction curves, much effort was focused on the low water content range. To diagnose the possible cause of such irregular curves, we varied the wetting period of the cohesive samples. The alteration of the procedure consisted of running the compaction test immediately after the preparation of the sample and then breaking each sample down and passing it through a No. 4 sieve. Thereafter the samples were kept in a control room for a period of 7 days, after which they were tested again. Because highly cohesive soils were used as the test specimens, the water content increments were varied by approximately 2 percent. The index properties consisting of plastic limit and liquid limit were determined for each test sample.

DISCUSSION OF TEST RESULTS

The extensive laboratory investigation involving 35 different soil samples and more than 700 standard compaction tests revealed many irregularly shaped compaction curves. Figures 2 through 7 show examples of the results obtained in this laboratory investigation. The existence of irregularly shaped compaction curves is clearly shown by the results of this study. Some of the curves (Fig. 2) clearly reveal the existence of double peaks, which were noted by Olson. A number of the irregular shapes resemble the 1½-peak curve (Fig. 3) that was found to be characteristic of some sandy soil specimens. Some of the test samples that had a large percentage of montmorillonite exhibit an oddly shaped curve with no distinct maximum optimum water content (Fig. 4).

A correlation was performed of the index properties (Table 1) and the compaction curve shapes. The results, shown in Figure 5, indicate an approximate range of soils that will produce irregularly shaped compaction curves. The soil samples tested with a liquid limit between 30 and 70 usually yield the typical single-peak compaction curve. However, the results indicated an exception to this range. Sample 23 (Fig. 3) exhibits a curve that is irregularly shaped. Soil test samples with liquid limit less than 30 and greater than 70 usually produce irregularly shaped curves. However, this range also had a discrepancy. Sample 20 located in the lower range near the boundary of irregularly shaped curves resulted in a typical single peak. It must be remembered that the liquid limit of 30 and 70 enclose only an approximate range of typical single-peak curves.

The discrepancies might be caused by the various mineral constituents of the test samples. Irregularly shaped curves resulted in the arbitrary combinations whenever montmorillonite was present. It is evident from the data that 50 percent or more of sand also caused irregularly shaped compaction curves. The only exception to this was sample 20, which had 50 percent sand and 50 percent kaolinite. The resulting index properties of this sample (LL = 18 and PL = 4) places it in the lower region of irregularly shaped curves. The compaction test, however, resulted in a curve that was typical.

Sample 23 consisted of 85 percent sand and 15 percent montmorillonite. It would be expected that this curve would be in the lower region of irregularly shaped compaction curves. The small amount of montmorillonite present yielded a liquid limit of 51. At the same time, however, the compaction test resulted in a distinct, irregularly shaped compaction curve if it is present in amounts of 15 percent or greater. Montmorillonite is an extremely plastic soil, and the small amount of only 15 percent combined with 85 percent sand, which is extremely nonplastic, yielded a liquid limit of 51 and plastic limit of 26. This is quite significant because in the Triangle Textural classification of

Figure 2. Double-peak compaction curves.

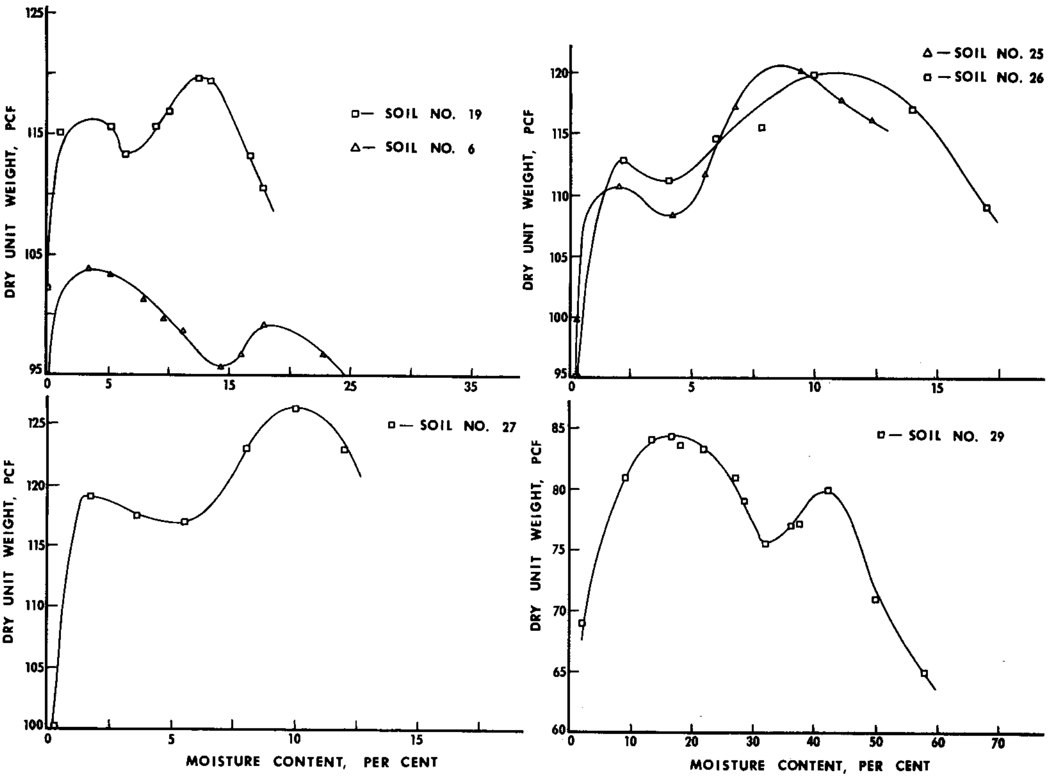


Figure 3. One and one-half peak compaction curve.

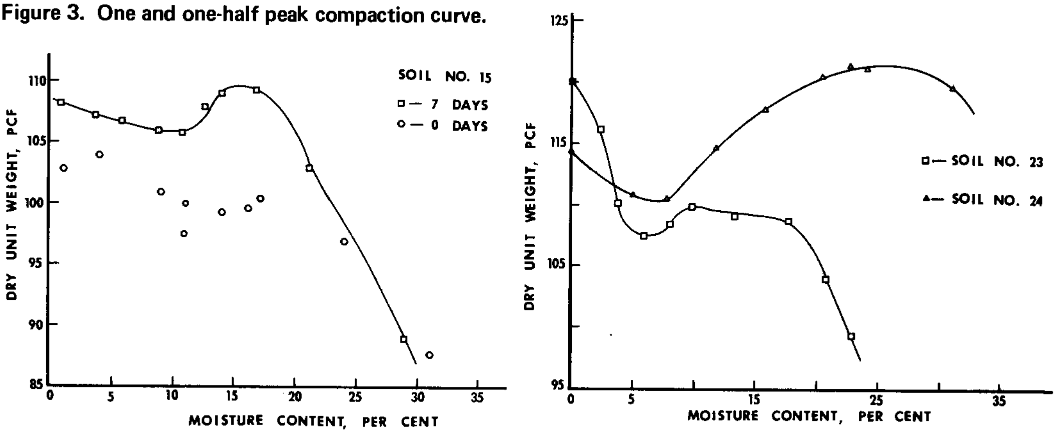


Figure 4. Oddly shaped compaction curves.

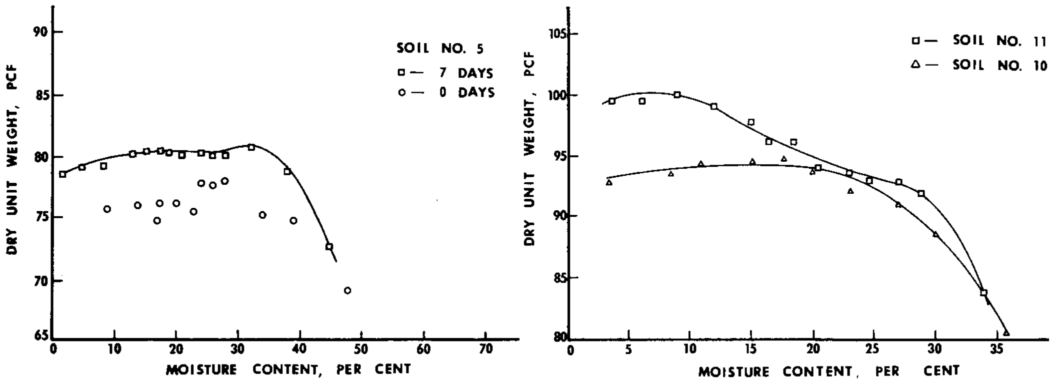


Figure 5. Correlation of laboratory results using modified Casagrande's classification.

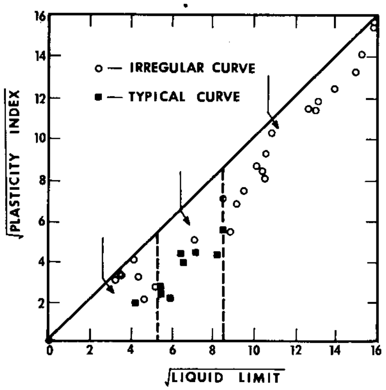


Figure 6. Compaction curves of kaolinite and illite.

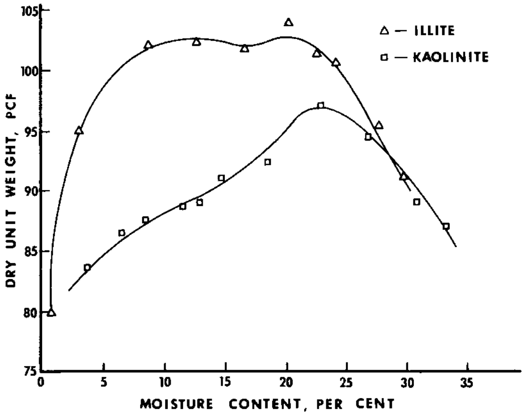


Figure 7. Four types of compaction curves found from laboratory investigation.

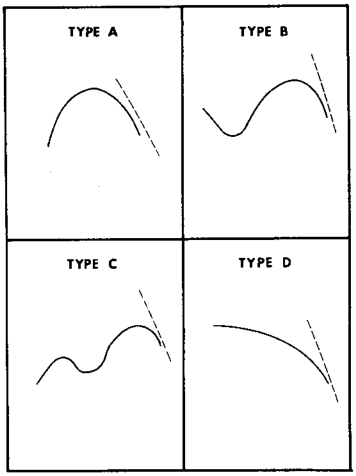
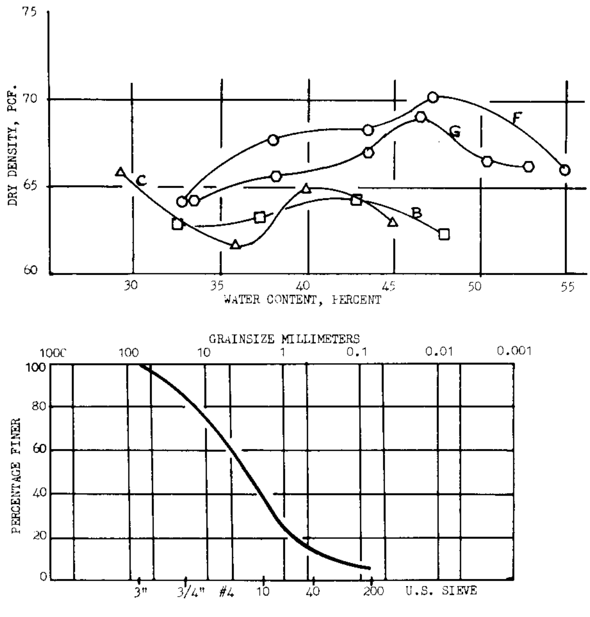


Figure 8. Moisture-density relations and grain-size distribution in Pennsylvania tests.



soils, which is based on the relative percentages of sand, silt, and clay, a soil sample containing 80 percent or more of sand and 20 percent or less of clay or silt is classified as sand. The compaction curve shape of this sample (Fig. 3) is characteristic of sand specimens, but the large liquid limit places it in the category of clays according to Casagrande's classification system.

The curve that is characteristic of soil containing 100 percent or a dominant percentage of sand and the remaining portion containing a certain amount of illite and montmorillonite is the 1½-peak curve (Fig. 3). In these curves a very high dry density is obtained at zero water content. This was a unique characteristic of some of the sandy samples tested. Under those circumstances water acts like an antilubricant. Observations by Horn (13) have shown that water is indeed an antilubricant for 3-dimensional network silicates such as quartz and feldspar. Negative pore-water pressure can also play a part in the compaction of sandy samples. At low water content some menisci begin to form in sandy samples because only a small portion of the water is absorbed by the particles themselves. These menisci tend to hold the particles together, thus increasing the shear strength and decreasing the density. Upon the addition of more water, the negative pore-water pressure and the antilubrication effect come in balance. Then if more water is added lubrication proceeds and the particles slide over one another, thus increasing the dry density. This phenomenon progresses until enough water is added so that it begins to displace the soil particles; this occurs at maximum dry density. Then the dry density decreases as the water displaces the soil particles.

Kaolinite yields typical single-peak compaction curve. The compaction curves produced by illite show the shape somewhat between single peak and slightly double peak (Fig. 6). When small amounts of kaolinite were combined with a large percentage of sand such as in samples 25, 26, and 27, the resulting curves were distinct double peaks (Fig. 2). Kaolinite is a bulky material, and evidently particular structure and size play an important part in the compaction process. Kaolinite has a particle thickness from ⅓ d to $\frac{1}{10}$ d where d varies from 0.3 to 3 μm. Kaolinite is also a 2-layered silicate sheet structure. Illite and montmorillonite are common 3-layered silicate sheet structures. Illite has a thickness of $\frac{1}{10}$ d where d varies from 0.1 to 2 μm. In the lower region, it is interesting to note the variation in the compaction curves with the differences in mineral structures present. The 1½ peaks have illite or montmorillonite present with a large percentage of sand, and the double-peak curves have a small percentage of kaolinite and a dominant percentage of sand present.

It is difficult to incorporate water into highly cohesive, heavy-textured clayey material. Because water plays an important part in the compaction process, the effects of the wetting period were also investigated. The wetting period is defined as the time that a sample is allowed to set at a controlled temperature and the water is permitted to become evenly distributed throughout the sample. This problem has been known for some time; as a result, the ASTM specifications require a minimum wetting period of 12 hours for highly cohesive materials. In this test, the samples were run at time = 0 or immediately after preparation and then again at time = 7 days. Some results showed a marked increase in the maximum dry density for most of the soil test samples (sample 15, Fig. 3, and sample 5, Fig. 4). A 7-day wetting period also resulted in a smoother curve. Highly cohesive soils tend to form small packets in which the water is concentrated. This phenomenon causes the water content of the sample to be unevenly distributed, and as a result the compaction curve may be very uneven. Therefore, this confirms the necessity of a wetting period for complete distribution of water. It also emphasizes the lubrication effect of water, which was recognized earlier by Proctor.

SUMMARY AND CONCLUSIONS

Seven hundred compaction tests on 35 soil samples exhibiting the physical properties given in Tables 1 and 2 did confirm the existence of irregularly shaped compaction curves. Certain characteristics of such curves were also established.

When the various compaction curves were correlated with index properties of the test samples following the modified Casagrande's classification scheme, 2 kinds of soils exhibiting irregularly shaped compaction curves were indicated. One consisted of highly cohesive soils with liquid limits greater than 70; the other consisted of soils with liquid limits less than 30. There were some exceptions to this macroscopic correlation. Although the index properties attempt to give a quantitative measure of the composite effects of all basic properties of a soil, they are not wholly sufficient. Nevertheless, the simple index tests usually identify soils exhibiting irregularly shaped compaction curves. If possible, however, they should be supplemented by a mineralogical investigation.

Properties of a clay are determined fundamentally by the physicochemical characteristics of the various mineral constituents present. This investigation revealed that the mineral constituents of the soil samples definitely affect the shape of the moisture-density compaction curve. Indeed, the clay mineral montmorillonite will affect the shape of the compaction curve when it is present in a soil in amounts of 15 percent or more. When the samples in the lower range containing a dominant percentage of framework minerals are combined with the 3-layered silicates, illite or montmorillonite, the result is 1½-peak curve. When more than 50 percent of the framework minerals are combined with the 2-layered silicate, kaolinite, the double-peak curve resulted. The impact of the various minerals on the compaction curve shape is evident. Soils with more than 50 percent of montmorillonite, highly cohesive soils (LL > 100), usually yield oddly shaped compaction curves.

According to this investigation, 4 types of curves exist (Fig. 7). In addition to the typical single-peak compaction curve (type A), the results indicated a 1½-peak curve (type B), a double-peak curve (type C), and a curve with no distinct optimum water content or oddly shaped curve (type D). According to the modified Casagrande's scheme, typical single-peak compaction curves appear between the approximate liquid limit boundaries of 30 and 70. In soils with a liquid limit greater than 70 both double-peak curves and oddly shaped curves are present. Soils with a liquid limit of less than 30 usually produce both double-peak curves and 1½-peak curves.

In highly cohesive soils the wetting period influences the distribution of water throughout a sample and as a result also affects the maximum dry density. When water was first added to a dry sample, it tended to form "packets" consisting of small amounts of soil and a large concentration of water. This uneven distribution of water resulted in scattered compaction data and an uneven curve. However, after a period of time (7 days) the water became evenly distributed. The result was an increase in dry density and a smoother curve. Results have shown that the water becomes evenly distributed after 12 hours. The effect of a wetting period was not so pronounced in soils with low liquid limits.

ACKNOWLEDGMENTS

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DISCUSSION

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The authors have presented an interesting paper on a very practical subject. Although irregularity in the shape of compaction curves for some soils is well known, it is often viewed with suspicion in actual practice and even rejected without much justification. This paper will undoubtedly aid in a better understanding of the irregularly shaped compaction curves. The paper primarily deals with compaction characteristics of soils and presents a correlation of compaction curve shapes with index properties.

Recently, the Pennsylvania Department of Transportation made a study on the compaction characteristics of Pulaski granulated slag. Irregularity in the shapes of the compaction curves for the slag was observed. The shape of the compaction curve for the slag has one of the following characteristics: $1\frac{1}{2}$ peak (type B) or double peak (type C). The slag falls in the category of soils having liquid limit less than 30 and thus confirms the correlation between liquid limit and shape of compaction curve presented by the authors.

The grain-size distribution curve and compaction curves (determined by Pennsylvania test method 106, equivalent to AASHO T-99) for a few samples that were tested are shown in Figure 8.