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THE TREATMENT OF CLAYEY SOILS IN THE MOISTURE-DENSITY TEST

by

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B.S., Civil Engineering, University of Kansas, 1976

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

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INTRODUCTION

Along with wood and stone, soil has been employed as a construction material for thousands of years. Its diverse applications have included roles in military fortifications, roadways, and water retention projects.

In addition to improved design techniques, a quality that separates today's earthwork projects from those of the past is improved methods of soil compaction. Compaction of a soil, accomplished through repeated passes of high-weight machinery over the surfaces of successive, thin layers of soil material, improves the characteristics of an earthen structure in three ways. In general, a compacted structure will have increased resistance to shear stress because of the denser arrangement of its soil particles. A compacted earthen structure will also be less susceptible to compression than its uncompacted counterpart because of the lesser volume of voids contained in a given volume of the material. In structures such as earthen dams, where the permeability of the embankment is of prime importance, the permeability characteristics of the structure can be controlled by the amount of compaction to which the embankment is subjected.

The current laboratory methods used to determine the degree to which a soil may be compacted in the field are termed "moisture-density" or "compaction" tests. The basis of today's laboratory compaction techniques was laid by R. R. Proctor in a series of articles published in 1933 (1). His writings detail a method of determining the density to which a soil may be compacted employing the standard compaction techniques of 1933 and the water content at which that density may be most easily obtained. His articles were the forerunner of today's compaction test ASTM D698 (2).

PURPOSE OF THE STUDY

Much research has been done on the moisture-density test (whose basic principles are outlined in the REVIEW OF LITERATURE section of this thesis) to determine what factors influence the test's results. Investigations studying the changes in the compactive effort and its method of application, the changes in the size of soil particles used in the test, variations in the size of the mold, and variations in several other aspects of the test have been pursued. It is recognized that many factors can influence the values obtained from a moisture-density test.

One particular section of ASTM Test D698 reads:

"Note 1 - This procedure has been found satisfactory in most cases. However, in instances where the soil material is fragile in character and will reduce significantly in grain size due to repeated compaction; and in cases where the soil is a heavy-textured clayey material into which it is difficult to incorporate water, a separate and new sample shall be used in each compaction test. In these cases, the separate samples shall be thoroughly mixed with amounts of water sufficient to cause the moisture contents of the samples to vary by approximately two percentage points. The moisture contents selected shall bracket the optimum moisture content, thus providing samples which, when compacted, will increase in weight to the maximum density and then decrease in weight. The soil-water mixtures should be placed in covered containers and allowed to stand for not less than 12 hours before making the moisture-density test." (2)

The foremost purpose of this paper's study is to determine if the special test procedures for clayey soils outlined in the just-quoted ASTM moisture-density test are necessary in the case of several Eastern Kansas clayey soils.

THE SCOPE OF THE STUDY

Four soils were tested in the course of this study. They were sampled from four separate geologic soil groups in Eastern Kansas (See Fig. 1). Three of the four soils were clayey, and would therefore be candidates for the special test procedures that this study investigated. The fourth soil is a silt, which under the current ASTM D698 testing methods would not require the special procedures. It acts as a control for the laboratory experiments performed for this test on the three clayey soils. If the test results for silt are similar to the results for the other samples, those results will be of significance.

Ten moisture-density tests were run on each of the four soils. Five of the ten tests were performed employing the special techniques described in the PURPOSE OF THE STUDY section. The remaining five tests on each soil were run without the special conditions used in the first five tests. This second method is the method employed by many soil testing laboratories regardless of soil type. In it, the same sample is re-used in each step of the test, and the soil sample is not allowed to sit (with a covering) for 12 hours after each addition of water.

An attempt was made to generate five points where dry density and moisture could be measured in each of the forty moisture-density tests performed. In a few cases, fewer than 5 points were obtained. In a few other instances, more than 5 points were obtained.

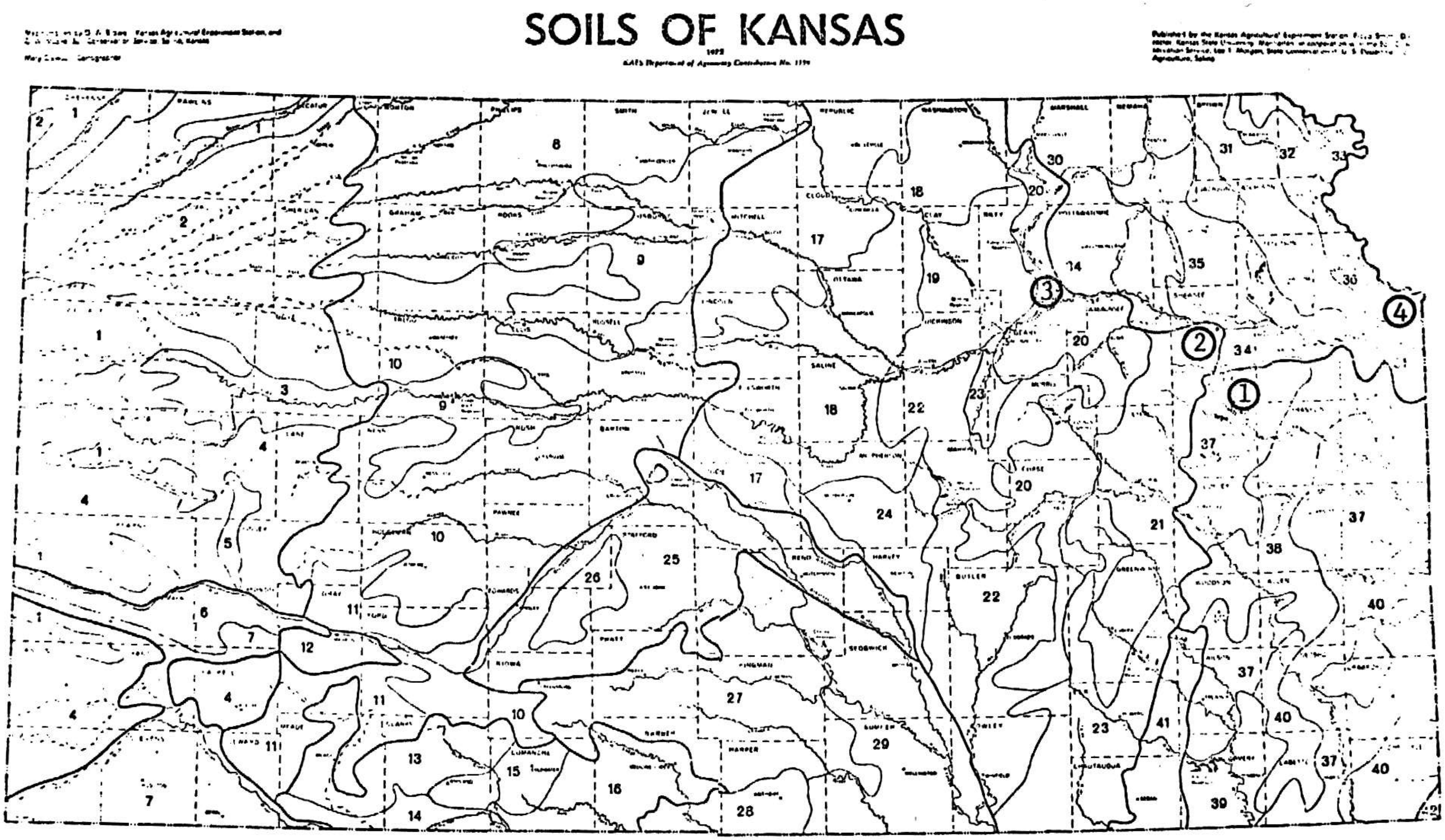

Fig. 1 - Soil Sample Locations

REVIEW OF THE LITERATURE

Proctor's Early Writings

The basic concepts of today's laboratory compaction test were first promulgated by Proctor in his initial articles (1). As a field engineer for the Bureau of Waterworks and Supply of the City of Los Angeles, Proctor's work involved the construction of earthen dams. The permeability of soil is one of the factors that can be controlled by compaction. His test provided a method of determining the most advantageous permeability that could be obtained with the standard field-compaction techniques. Proctor's goal in devising the test was to simulate field compaction operations in the laboratory. From the laboratory results, Proctor set field compaction standards for dry density (and thereby void ratio and permeability) and the moisture content at which to achieve that density.

The test procedure involves dynamic compaction of a soil sample in a cylindrical mold of known size. The soil is placed in the mold in three separate layers. A specified, constant compactive effort is applied to each successive layer. When the mold is filled, the weight of the soil (including the amount of moisture that it contains) is measured. After removing the soil from the mold, a sample of the soil is weighed and placed in the oven to dry in order that the moisture content of the soil may be calculated. From the values for the weight of wet soil in the mold, the volume of the mold, and the water content of the soil, the density of the dry soil particles (or dry density) may be calculated.

The procedure outlined in the previous paragraph is repeated for the same soil at several other moisture contents. The values of dry density and water content for each of the compaction test procedures were plotted on coordinate axes (Fig. 2). Since each of the test repetitions utilizes the same compactive effort--one that simulates as well as possible the compactive effort that the soil will receive under field conditions--then the topmost point on the curve represents the maximum dry density of the soil achievable with the given compactive effort. It also represents the moisture content of the soil at which that density is most easily attainable. These two values are termed the maximum dry density and the optimum water content for a given soil for moisture-density test ASTM D698.

General Background of the Compaction Test

Inspection of Fig. 2 reveals the application of the test. The peak of the curve represents the maximum dry density that can be obtained for a certain soil for the given compactive effort. A field compaction process employing the same compactive effort at any water content other than optimum will result in a dry density lower than maximum. In terms of dollars and cents, this means that at any water content other than optimum, money is being spent on a compactive effort that produces a dry density that is inferior to the best dry density that could be obtained. The soil's qualities of shear strength,

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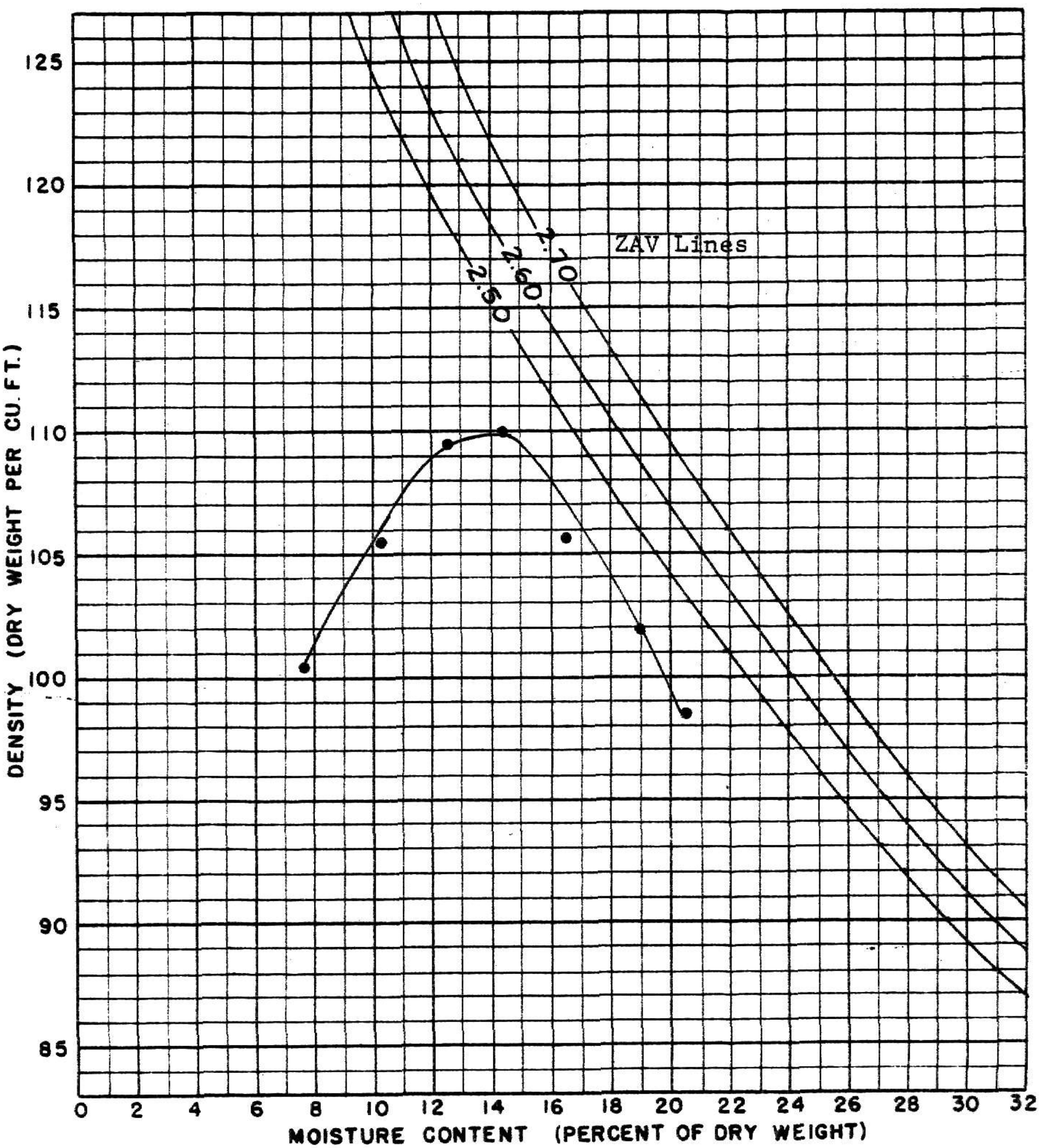


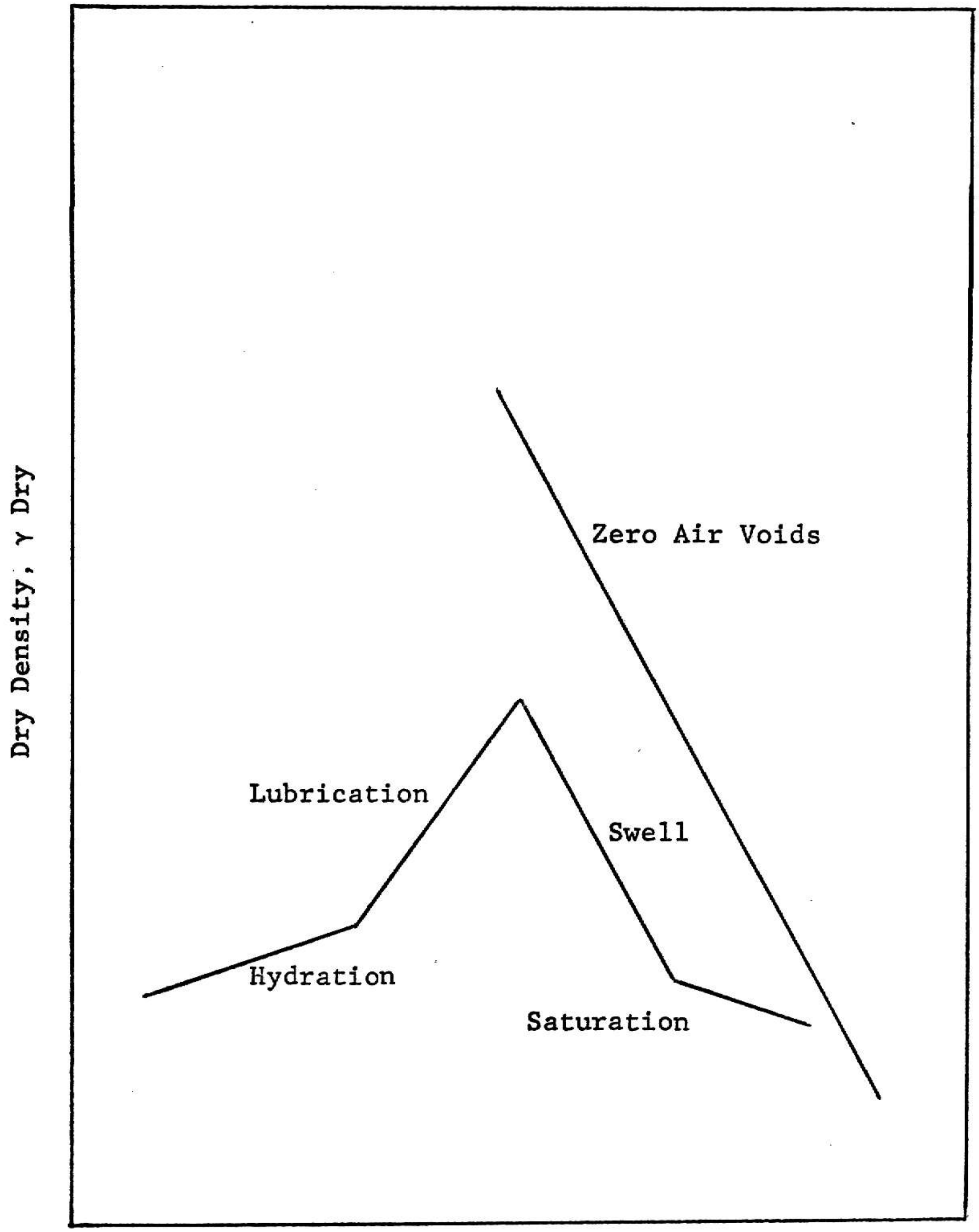
Fig. 2 - A Typical Moisture-Density Curve

impermeability, and ability to resist consolidation are all less than could have been attained. Additionally, if improvement of these factors is to be gained, more funds will need to be spent on additional compactive effort.

Four theories that attempt to explain the moisture-density relationship in cohesive soils expressed by the curve of Fig. 2 are presented by Olson (3). One of the theories was developed by Olson himself; he claims that it best represents what occurs among the individual soil particles during dynamic laboratory compaction. Olson regards the other 3 hypotheses presented in his article as theories that were acceptable to the engineering community when first expounded, but which have become outdated. Each of the four: Proctor's theory of "Capillarity and Lubrication," Hogentogler's theory of "Viscous Water," Lambe's "Surface Chemistry Theory," and Olson's own theory explain the shape of the moisture-density compaction curve for cohesive soils from different approaches.

A description of one of the theories will serve to illustrate qualitatively the nature of the laboratory compaction test. Hogentogler's theory of viscous water (4) bases its explanation of the curve on the statement that the clay particles in a clay-water mixture are surrounded by a tightly-bound layer of adsorbed (adhesive) water. Outside this adsorbed layer is water that is free to move among the clay particles. In the adhesive layer of water, the closer to the clay particle the more viscous the water becomes. If, when performing the compaction test, the water content is quite low relative to the optimum moisture content, the only moisture in the soil is a thin layer of adsorbed, viscous water. The viscosity will endow the soil with a higher shear strength (a higher resistance to the sliding of soil particles past one another) which results in relatively low compaction and dry density. As the water content in the test is increased, at some point the increased amount of water surrounding the particles acts as a lubricant. Shear strength decreases, and higher compaction is attained. This lubrication effect increases up to the point of optimum moisture content. At water contents greater than the optimum moisture content, the increased amount of water among the soil particles takes up volume that could be occupied instead by soil particles. Therefore, dry density decreases.

Figure 3 is an illustration of Hogentogler's viscous water theory. For the portion of the curve labeled "hydration," water is both absorbed and adsorbed by the soil. The second stage of the curve, the "lubrication" portion, indicates how an increased water content significantly increases dry density. After the curve's peak, a point corresponding to maximum dry density and optimum moisture content, the additional water decreases dry density. Along the "swell" portion of the curve, not much of the air that has been occupying portions of the voids between particles is displaced. Along the "saturation" portion of the curve, the air is displaced, and the soil becomes entirely saturated. Saturation indicates that all the space not occupied by solid constituents is occupied by water.



$$\text{Water Content, } w = \frac{\text{Volume of Water}}{\text{Volume (Water + Solids)}}$$

Fig. 3 - Illustration of Hogentogler's Viscous Water Theory

In Fig. 2 and in Fig. 3, lines designated as "zero air voids" (zav) lines may be found to the right of the moisture-density curves. For a soil of a given specific gravity, the zero air voids line represents the moisture-dry density curve for the special condition of complete saturation. This means that the line illustrates how the moisture-density curve looks if all the space not taken up by solid soil constituents is filled by water. In this condition there is no air present in the soil.

During the performance of a compaction test, air is always present in the compacted soil. For any fixed volume of soil constituents in the mold, the remaining volume might be filled with either pure water or with a water-air mixture. The water content of the water-air mixture placed in the remainder of the mold's volume will always be less than that of pure water placed in that same volume. For this reason, for any value of dry density, the point on the moisture-density curve will always be at a lesser water content than the corresponding point on the zero air voids line. Thus, the moisture-density curve will never cross the zero air voids line.

The specific gravity of soils is variable. A dry soil sample weighing 100 lbs. with the specific gravity of 2.75 will not occupy as large a portion of a cylindrical mold as a dry soil sample weighing 100 lb. with a specific gravity of 2.65. Thus, if the remainder of the mold's volume is filled with water, more water can be put into the cylinder when it contains the soil sample of higher specific gravity. The soil sample with the specific gravity of 2.75 thus has a greater water content than the soil sample of lesser specific gravity. This example illustrates how the zero air voids lines are dependent on the specific gravity of the soil undergoing testing. The zero air voids line for a soil of relatively higher specific gravity will be displaced to the right (since it has a higher water content) of a soil of lower specific gravity.

Compaction tests deliver a specified amount of work into the compacted soil. Laboratory test ASTM D698 densifies soil with an effort of 12,375 ft-lb of compactive effort per cubic foot of soil tested. If the amount of work input was to be increased while all other aspects of the test remained constant, a higher degree of density of compacted soil would be expected. The peak of the moisture-density curve would be elevated. However, as has been previously expressed, the moisture-density curve may not cross the zero air voids line. To avoid contact with that line, as compactive effort increases, the moisture-density curve will be displaced higher and to the left (Fig. 4). Laboratory compaction tests have been devised utilizing higher compactive efforts than produced by ASTM test D698. Figure 4 shows the relative positions of moisture-density curves for similar soil samples subjected to varying compactive efforts. The curve corresponding to the highest degree of compaction is leftmost and uppermost. In general, as compactive effort increases, maximum dry density increases, and optimum water content decreases. Although compaction

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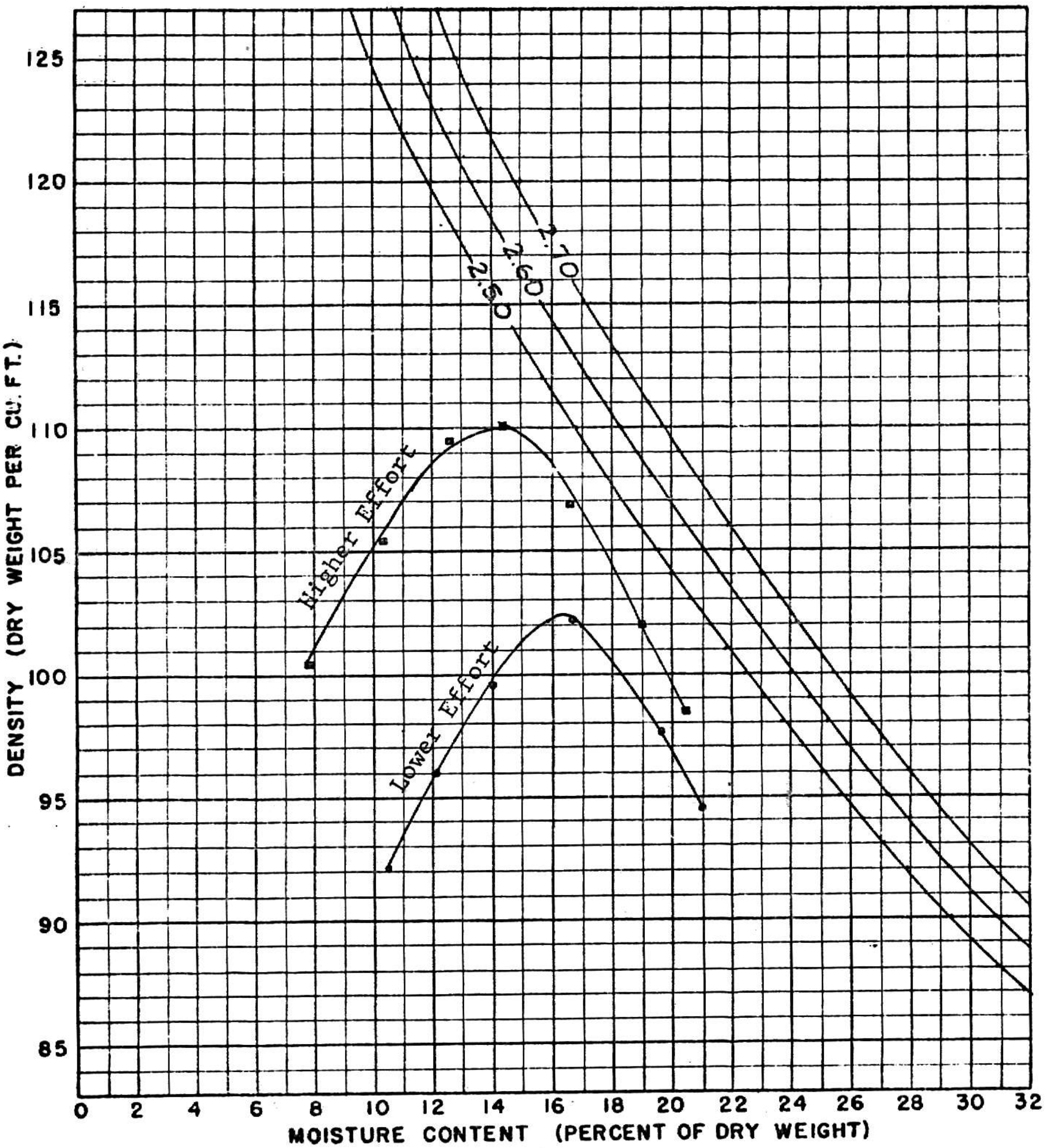


Fig. 4 - Compaction Tests of Different Compactive Efforts

tests with higher compactive efforts than that used in ASTM D698 have been devised, that ASTM test is still a standard in the construction industry.

Jumikis (5) reports the ranges of 75 - 130 lb. per cubic foot and 9 - 35 percentage as normal limits for the values of maximum dry density and optimum moisture content, respectively, that can be obtained after performing the ASTM D698 test. Johnson and Sallberg (6) list the following soils in order of highest maximum dry density and lowest water content to lowest maximum dry density and highest water content:

1. Well-graded loamy sand
2. Well-graded sandy loam
3. Medium-graded sandy loam
4. Lean sandy silty clay
5. Lean silty clay
6. Loessial silt
7. Heavy clay
8. Poorly-graded sand

This order of listing may be explained in terms of Hogentogler's description of the moisture-density curve. The larger-grained materials--sands and silts--require little moisture before the water begins to act as a lubricant. The optimum water content is reached at a low percentage. The low volume of water at optimum percentage means that more space is left to be occupied by soil particles. High maximum dry densities and low moisture contents result. Fine-grained clay soils have a larger amount of surface area per unit volume of material than do sands and silts. To reach the point where all of the clay particles' surfaces are covered with a depth of water sufficient to obtain lubrication requires a high water content. The larger volume of water in the sample leaves less room for soil constituents. A high volume of water and a low volume of soil results in high optimum moisture contents and low maximum dry densities. The last soil listed, poorly-graded sand, seemingly violates Hogentogler's theory. However, its position in the list was not gained because of the size of its grains but by its grains uniformity of size. When all of the grains of the sample are the same size, dense packing is not possible. To gain high density, some smaller grains are needed to fit into the voids between the uniformly-sized grains. Since the smaller grains are not available in the poorly-graded sand, low density results.

In one of his later articles (7), Proctor advises against the common engineering practice of specifying "95% Proctor" or "90% Proctor" as the compaction requirement for soil in a construction project. He states that a soil at 95% of its maximum dry density does not necessarily possess 95% of the shear strength that it would have at maximum dry density. The shear strength may be much less. If an engineer specifies 90% of the maximum dry density without investigating the properties of the soil at that state, he may well be deluding himself concerning the quality of the finished compacted product.

Previous Experiments in the Area of This Thesis

Vast research has been done in the area of mechanical compaction of soils. An almost numberless quantity of articles has been published concerning the results derived from the varying of field parameters during compaction operations. Emphasis has also been placed on the analysis of factors whose variations affect results gained from laboratory compaction tests. The principal objective of this thesis is to discover how the combination of two factors affect the moisture-density curve. Detailed previously in the PURPOSE OF THE STUDY section, these two factors are: 1. the re-use of soil in the compaction test, and, 2. a 12-hour time requirement between additions of water to the soil sample and the performance of the test. Only a small number of articles have been published in previous research of these factors; two such articles will be discussed in the following paragraphs.

In 1949, Nelson and Sowers (8) studied the "effect of re-using soil on moisture-density curves." Their investigations were prompted by contractors' complaints that the maximum dry densities obtained from laboratory compaction tests were not attainable in the field using typical compaction procedure. These complaints led Nelson and Sowers to believe that the peaks of the moisture-density curves derived from laboratory tests were too high. They determined to ascertain if the peaks of the curves were excessive as a result of using the same sample of soil in each of the steps of the laboratory test.

Consequently, they performed compaction tests on 9 different soils. Each soil was tested both re-using the same soil for each point of the curve and using separate, fresh samples of the same soil for every point of the curve. They used testing procedures specified in the American Association of State Highway Officials (AASHO) Test T99, which is the AASHO test corresponding to the ASTM D698 test. They did not wait for a 12-hour time period between addition of water to the sample and performance of the test. For each of the 9 soils, the results of the compaction tests re-using the soil showed a higher maximum dry density than the tests using separate unused soil samples. For 5 of the 9 soils tested, the difference in maximum dry density was one to two lbs. per cubic foot. For the other 4 soils, the difference was three to four lbs. per cubic foot. Nelson and Sowers write in their article:

> "There is a significant difference in the maximum dry density obtained by re-using the same soil throughout the compaction test and the density obtained by using fresh separate samples for each point on the curve. Since in actual construction work, soil is compacted but once and at one water content, it is probable that the method using separate points would give results that are more representative of field conditions."

These investigators give two possible reasons for the differences in the results for the two types of tests. First, they feel that the re-used portions of soil are subjected to a greater compactive effort than a corresponding fresh sample. This is because the re-used sample has been compacted one or more times previously. During the previous compaction, air has been driven from some of the voids in the soil sample. In the intervals between compactions, when water is added and the soil is re-mixed, it is unlikely that any significant portions of the voids have been re-filled with air. Thus, each time the soil is re-used, it is already partially compacted.

Too, the re-use of the soil probably results in a better mixing of the soil and water in the test sample. This may facilitate easier compaction.

The 9 samples tested by Nelson and Sowers represented several soil types. The investigators state, "The soil type apparently does not reflect the magnitude of the difference (in maximum dry density) since the difference is great in both A-3 soils composed of fine silty sand, and also A-7 types that are plastic clays."

Experiments conducted by the Corps of Engineers (9) confirm Nelson's and Sowers' results.

In Geotechnique, Ray and Chapman (10) explored the question of whether or not it is advisable to let a soil sample "mature" for a period of time between the addition of water and the performance of the compaction test. In their experiments, two compaction tests were performed on a soil. The one difference between the two tests was the length of time between addition of water and the application of compactive effort.

In their first method, the compaction was conducted immediately. In their second method, 5 days was allowed to elapse between the addition of water and the physical compaction of the sample. During the 5-day interim, the soil samples were stored in sealed containers.

Ray and Chapman present the results of such a series of tests for only one soil, a clay with a plasticity index of 22 and a liquid limit of 43. An examination of their graphs indicate that only one repetition of each of the two experimental methods was performed. Further inspection of their graphs indicates that the peak of the moisture-density curve of the sample which was allowed to "mature" was approximately one lb. per cubic foot lower than the peak of the curve of the same soil but using the other method.

Ray's and Chapman's experimental work was the only such work located in the review of the literature dealing with the "maturing" aspect of the compaction test. That any conclusions may be drawn from their results seems doubtful for two reasons. First, results for only one soil have been presented. Second, a difference of only one lb. per cubic foot between compaction curve peaks might be viewed as too small to be of significance. Too, it might be only the ±one lb. per cubic foot difference often encountered when performing repetitions of the compaction test on a soil (6).

Imprecision in the instructions of ASTM Test D698 itself offers an opportunity for errors in the determination of maximum dry density. When soil is re-used in the test, ASTM

D698 makes provisions for the soil's separation into individual particles between each moisture content-dry density determination. The soil is to be broken down into individual pieces that can pass U. S. Standard Sieve No. 4. However, the test specifications do not require that the soil be physically passed through the sieve. It requires only that the soil be broken down into particles that will pass the No. 4 sieve "as judged by eye" (2). If the "eye" of the technician allows larger particles to pass his inspection, the material re-used in the next portion of the test will have clumps of pre-compacted material interspersed with the acceptable material. This situation would result in a higher value of maximum dry density than would have otherwise been achieved. Care should be taken in the performance of the moisture-density test to avoid this condition.

DESIGN OF THE EXPERIMENT

The experimental portion of this thesis was designed to test the applicability of "Note 1" of ASTM compaction test D698 to several clayey soil types from Eastern Kansas. Re-use of the soil for each point of the moisture-density curve and a 12-hour maturing procedure before compaction were tested in combination.

Four soil types were tested by the experimental procedures. Three samples were clays and one was a loess. A total of ten compaction tests were performed for each soil type. Five of the tests were run re-using the soil for each curve point; for this first series of tests, no significant maturing period was allowed between the addition of water and the compactive process. Five more tests were then performed on each soil; in this second series of tests, fresh soil samples were used for each point on the curve, and a 12-hour maturing period was allowed to elapse between the addition of water and the initiation of compactive effort.

To evaluate the significance of the experimental results, the data was analyzed by the statistical method of regression.

PROCEDURES AND APPARATUS USED

Preparation of Specimen

Approximately 150 lb. of soil at natural water content was procured for each of the soil types tested. These samples were oven-dried at 220°F in the ovens of the Research and Testing Laboratory of the Kansas Department of Transportation (KDOT) in Topeka, Kansas. The samples were dried to "below 2% moisture content" as judged by KDOT soils testing technicians. Upon removal from the ovens, the soil samples were crushed at the Research and Testing Laboratory. The mechanically degraded material was sieved through a U. S. Standard Sieve No. 4 before its use in the compaction test.

Testing

Testing procedures followed in the laboratory are those outlined in ASTM test D698, Method A. The cylindrical mold in which the soil was compacted is four inches in interior diameter and is 1/30 cubic foot in volume. The rammer is 5.5 lb. in weight and has a two-inch diameter circular face. Soil was placed in the mold in 3 equal layers. Each layer was compacted by 25 blows of the rammer dropped from a height of 12 inches. Upon completion of the compactive process, the compacted soil was removed from the mold, and a sample of that soil was removed for a water content determination.

Water content determinations were performed in accordance with ASTM test D 2216-71.

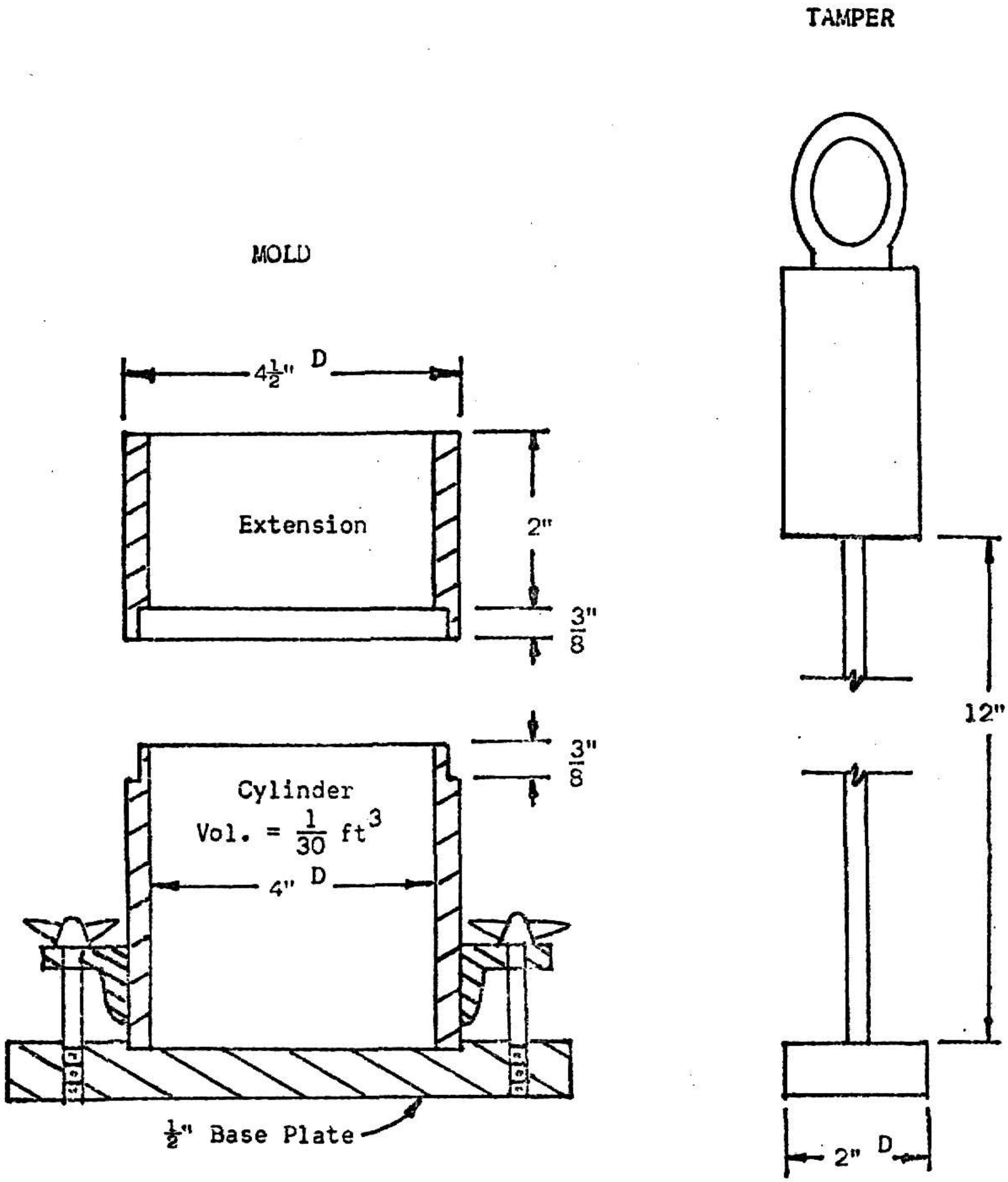


Fig. 5 - Apparatus Used to Determine Moisture-
Density Relationships of Soils

In all phases of the testing procedure, care was taken to insure that the two parameters under investigation were the only two parameters that were allowed to vary in the two series of tests performed for each soil.

PRESENTATION OF DATA

Sample Data Sheet

Figure 6 is an example of the data sheets that were employed to record test data and the results of simple arithmetic operations performed on that data. Forty such sheets were used in the experimental portion of this thesis. For reasons of brevity and expense, the other 39 are not printed here. They are in the possession of the author.

Regression Analysis and Results

In typical practice, only a single compaction test is performed in order to determine the maximum dry density and optimum moisture content of a soil. The results are plotted graphically, and a smooth curve is drawn through the data points. Maximum dry density and optimum moisture content are determined at the peak of that curve.

For this thesis, 8 curves--representing two series of tests on each of 4 soils--were graphed. Since a total of 40 compaction tests were performed, each graph contains the data from 5 separate compaction tests. With 25 points per graph, a smooth curve drawn by the author would not pass through each point. The points chosen through which to pass the curve might reflect the author's bias or whim. To standardize the method of drawing the 8 curves, a computer application of statistical analysis was used. An outline of the approach employed is presented in Appendix B of this thesis.

COMPACTION TEST

SOIL SAMPLE K. C. Loess

TEST NO. 7

DATE June 18, 1977

TESTED BY Lindly

LOCATION

TYPE TEST ASTM D698

BORING NO. SAMPLE DEPTH

MOLD: VOLUME 1/30 Ft.^{3}

SAMPLE NO.

WEIGHT 4.600 Kg.

SPECIFIC GRAVITY, G_s,

DENSITY

DETERMINATION NO.	1	2	3	4	5	6	7
Wt. Mold + Compacted Soil in kg.	6.400	6.475	6.540	6.540	6.495		
Wt. Mold in kg.	4.600	4.600	4.600	4.600	4.600		
Wt. Compacted Soil in kg.	1.800	1.875	1.940	1.940	1.895		
Wet Density in lbs./cf.	119.0	124.0	128.3	128.3	125.3		
Dry Density, γ_d, in lbs./cf.	104.7	107.3	108.2	106.3	102.0		
Void Ratio, e							
Porosity, n							

WATER CONTENT

DETERMINATION NO.	1	2	3	4	5	6	7
Container No.	109	112	113	124	126		
Wt. Container + Wet Soil in g	64.53	75.04	99.60	79.25	76.60		
Wt. Container + Dry Soil in g	59.38	67.80	87.38	69.39	66.46		
Wt. Water, W_w, in g	5.15	7.24	12.22	9.86	10.14		
Wt. Container in g	21.80	21.47	21.72	21.80	21.95		
Wt. Dry Soil, W_s, in g	37.58	46.33	65.66	47.59	44.51		
Water Content w, in %	13.7	15.6	18.6	20.7	22.8		

Fig. 6

The results of the computer analysis are eight computer-drawn second-order or third-order curves through each of the 8 sets of experimental data. They are presented in this thesis as Fig. 7 through Fig. 14.

The graphs in Fig. 7 and Fig. 8 correspond to the two types of compaction tests performed on the loessial soil. Fig. 7 is for the series of tests that re-used the same soil in each portion of a compaction test and did not allow a maturing (12-hour wait) period. Figure 8 corresponds to the series of tests where fresh samples and a 12-hour maturing period were used for each point on the moisture-density curve. The tan-colored, nonplastic loess sample was taken from a loess embankment near the highway I-70 tollgate west of Kansas City, Kansas.

Figure 9 and Fig. 10 show the computer-drawn moisture-density curves for clay sample No. 1. This soil sample, a red-brown colored clay obtained near Highway I-35 in Osage County, has a liquid limit (LL) of 59% and a plasticity index (PI) of 29%.

The two compaction curves for clay sample No. 2 are shown in Fig. 11 and in Fig. 12. Clay No. 2 is a red-colored glacial till from Topeka, Kansas. Its LL is 37%, and it has a PI of 16%.

Clay No. 4 is a soil sampled in the Northview area of Manhattan, Kansas. This grey-colored clay has a LL of 61% and a PI of 34%.

Grain size analysis of the 4 soils sampled are located

Fig. 7 - Compaction Curve for the Loess Sample (Soil Re-used and Non-Maturing Test Procedure)

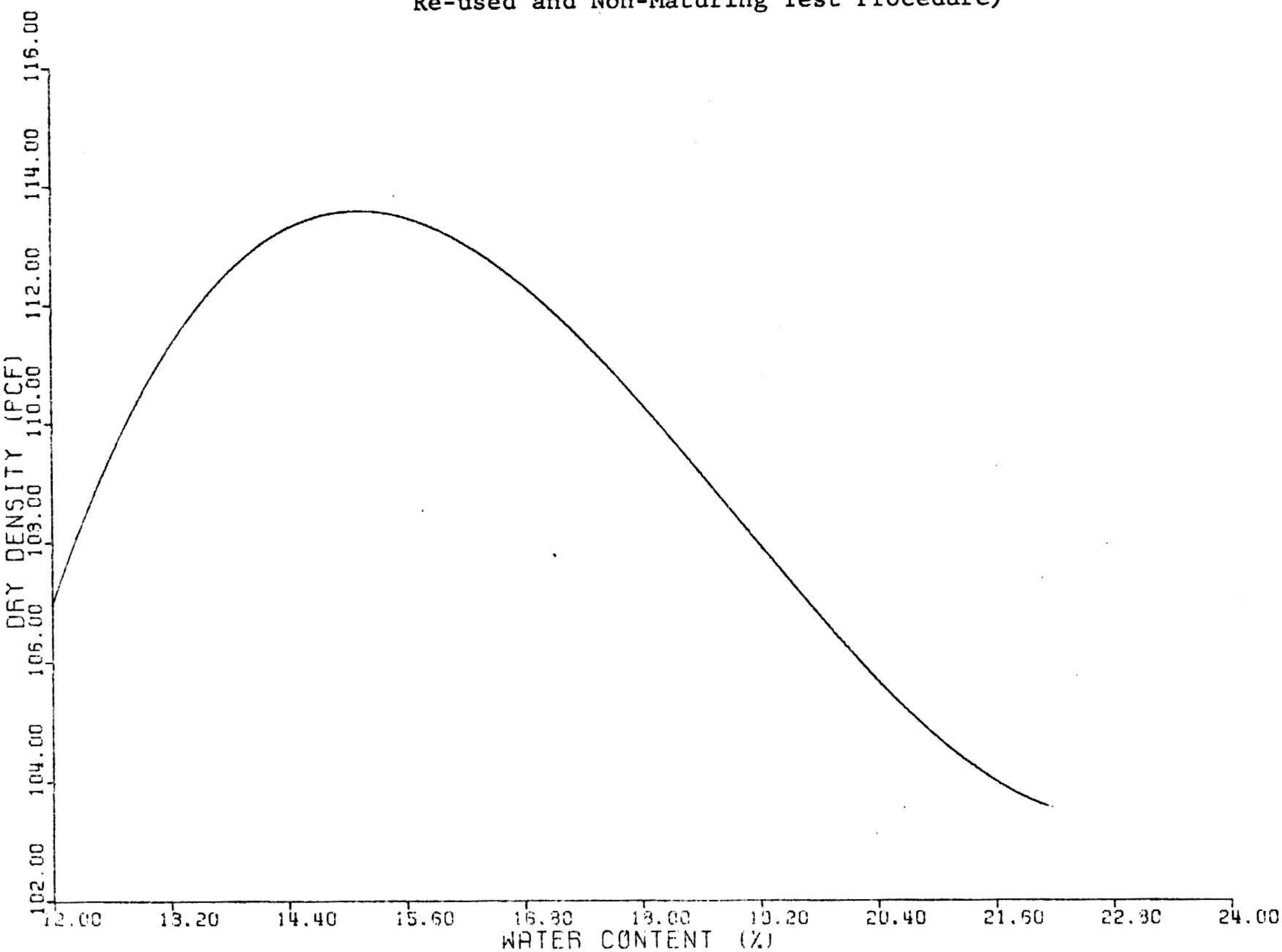


Fig. 8 - Compaction Curve for the Loess Sample (Fresh Sample and Maturing Test Procedure)

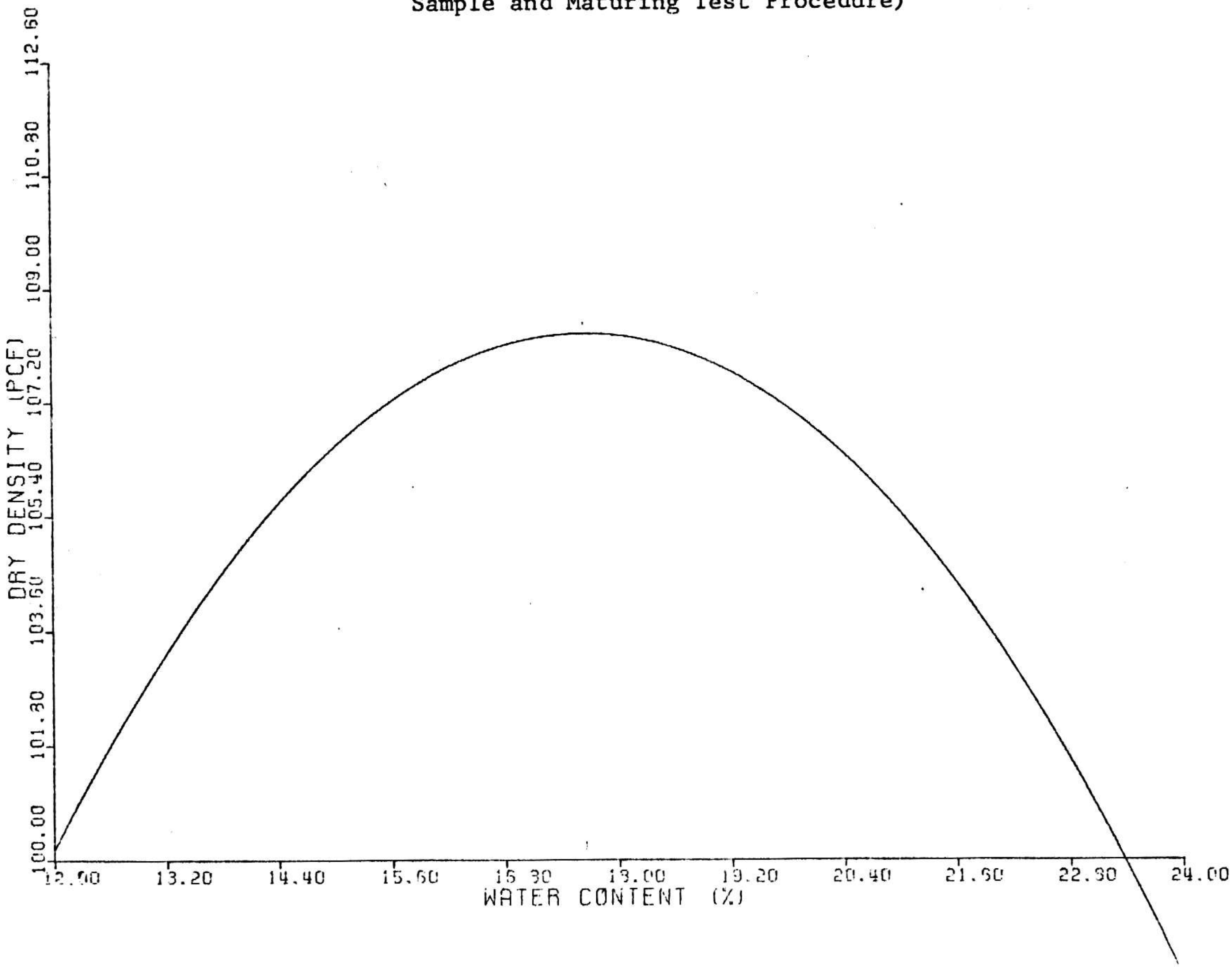


Fig. 9 - Compaction Curve for Clay Sample No. 1 (Soil Re-used and Non-Maturing Test Procedure)

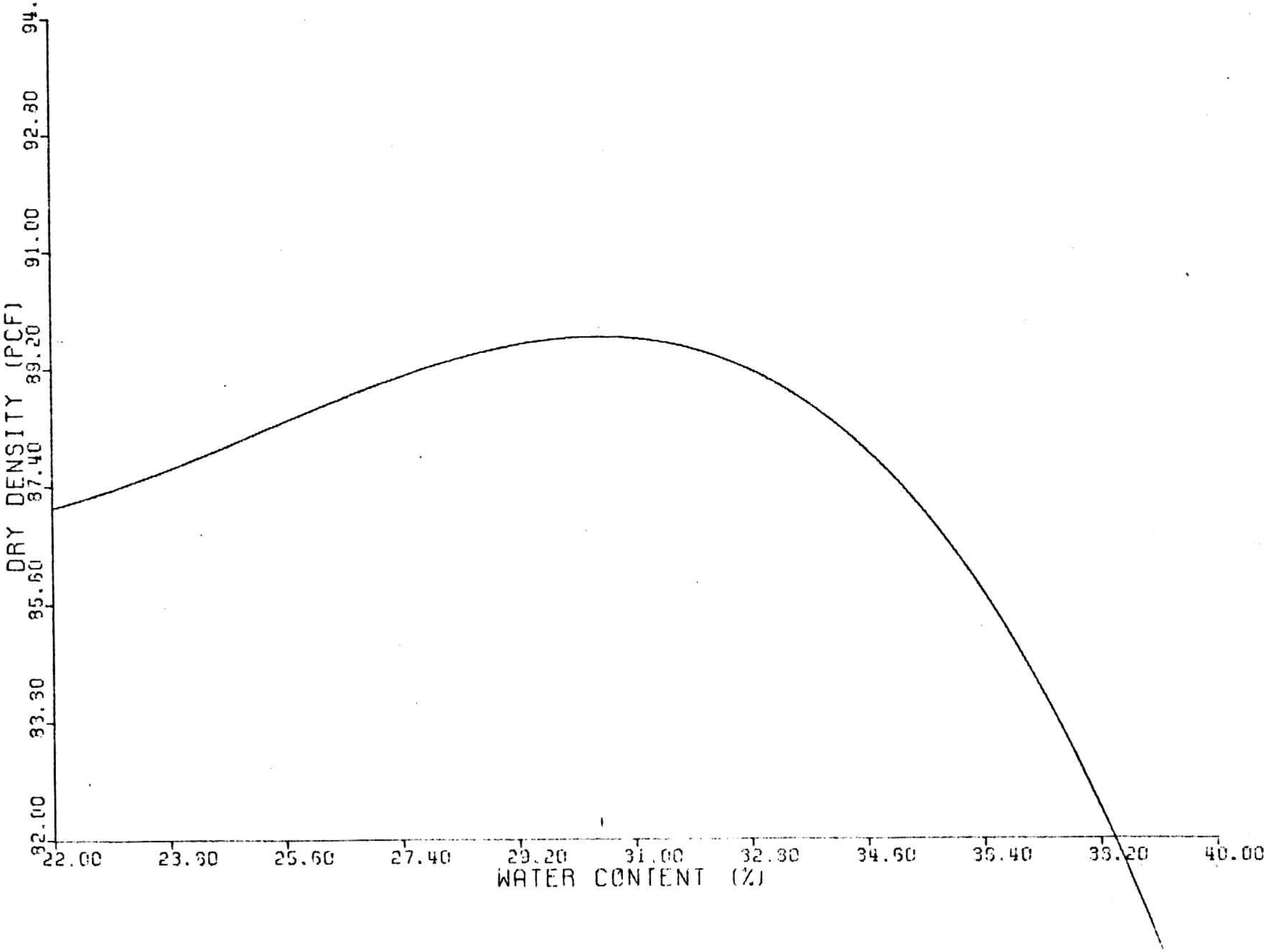


Fig. 10 - Compaction Curve for Clay Sample No. 1 (Fresh Sample and Maturing Test Procedure)

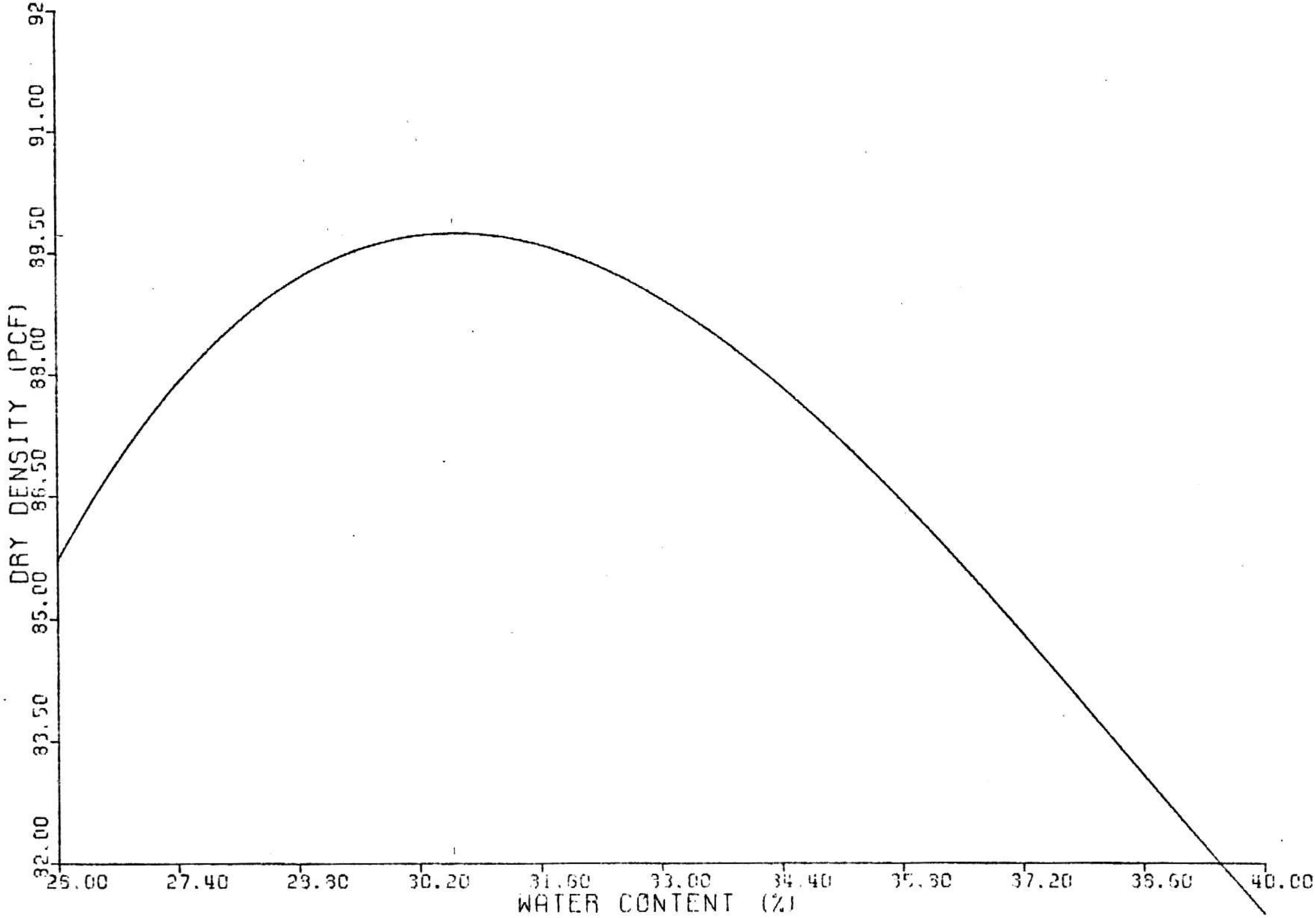


Fig. 11 - Compaction Curve for Clay Sample No. 2 (Soil Re-used and Non-Maturing Test Procedure)

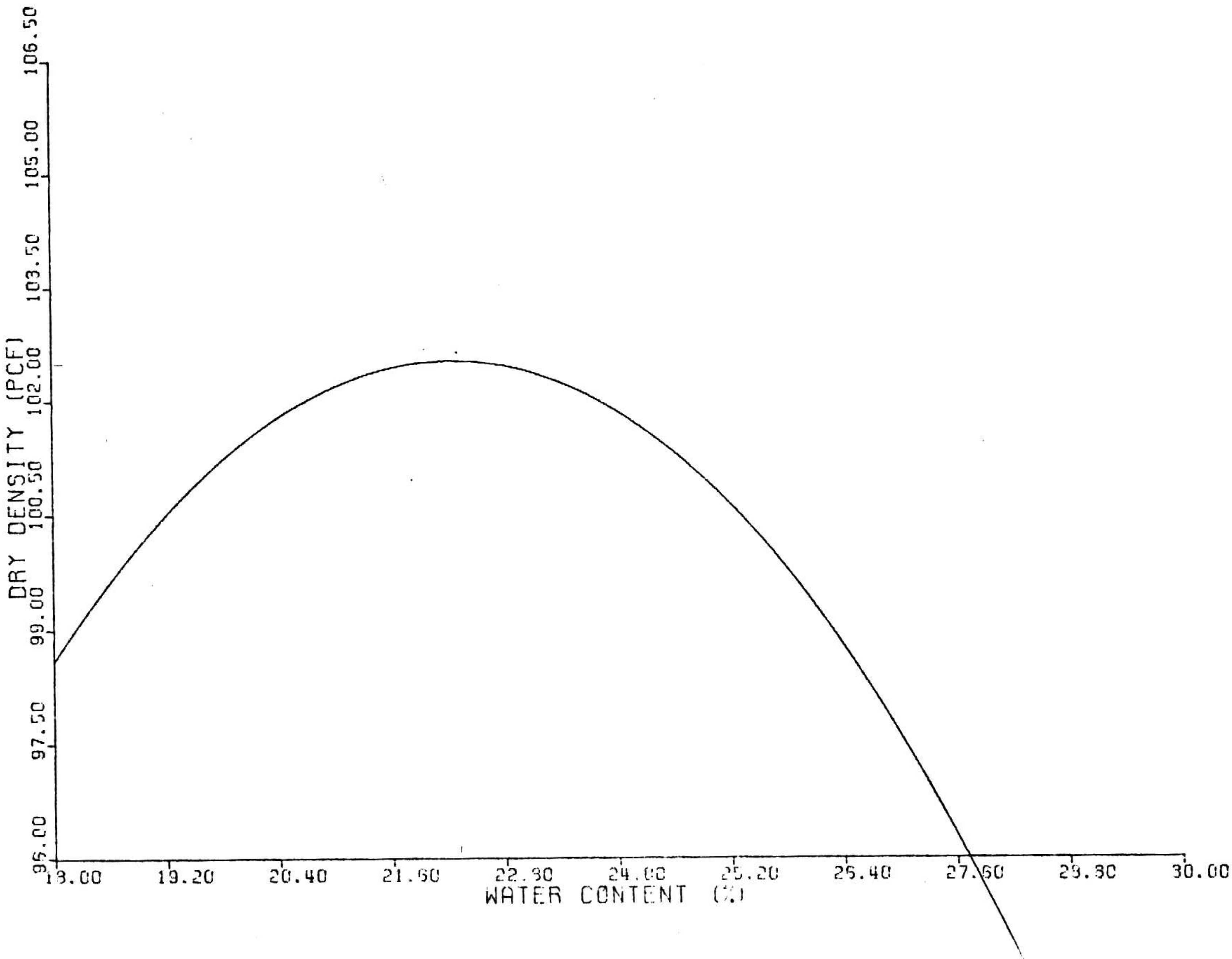


Fig. 12 - Compaction Curve for Clay Sample No. 2 (Fresh Sample and Maturing Test Procedure)

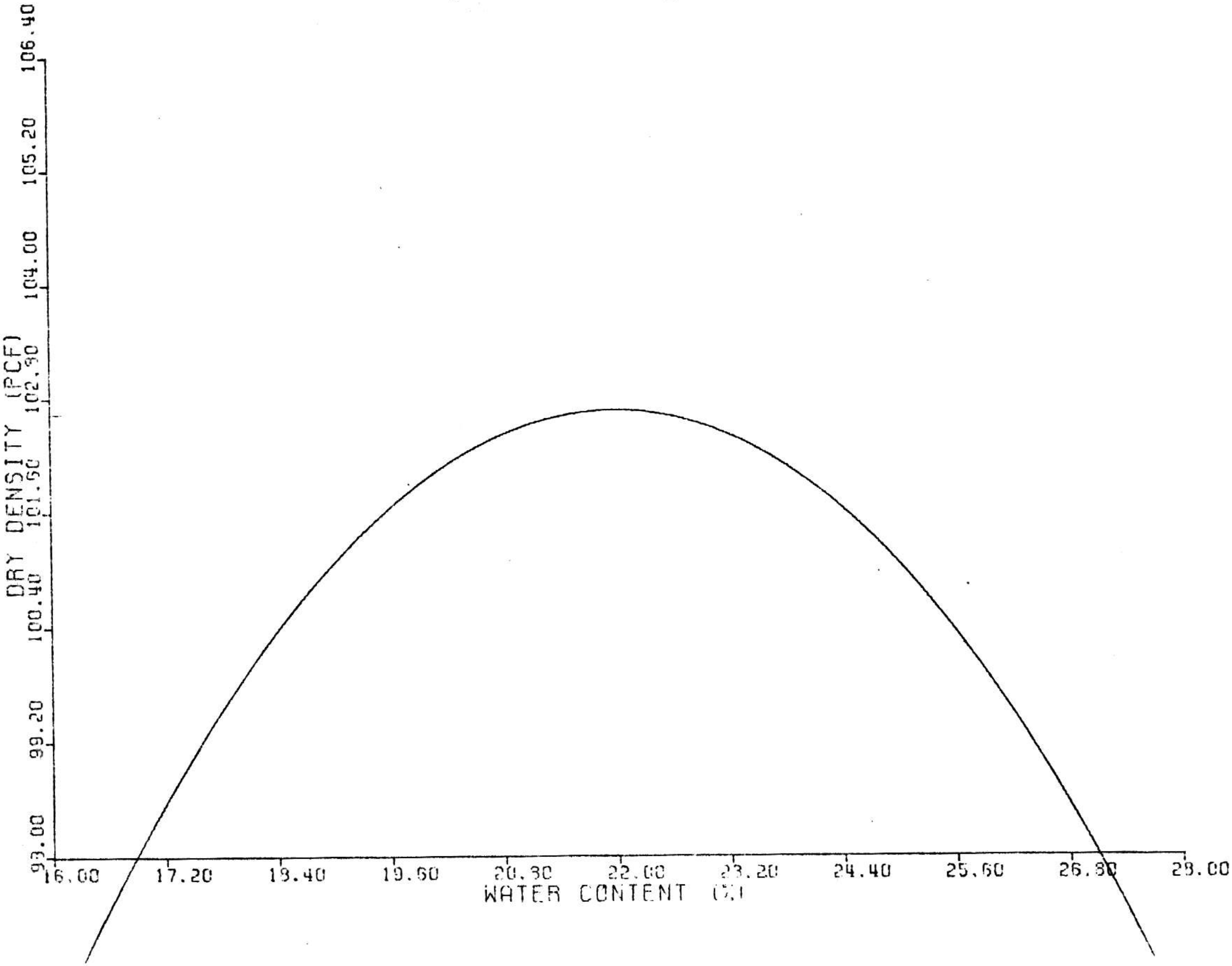


Fig. 13 - Compaction Curve for Clay Sample No. 3 (Soil Re-used and Non-Maturing Test Procedure)

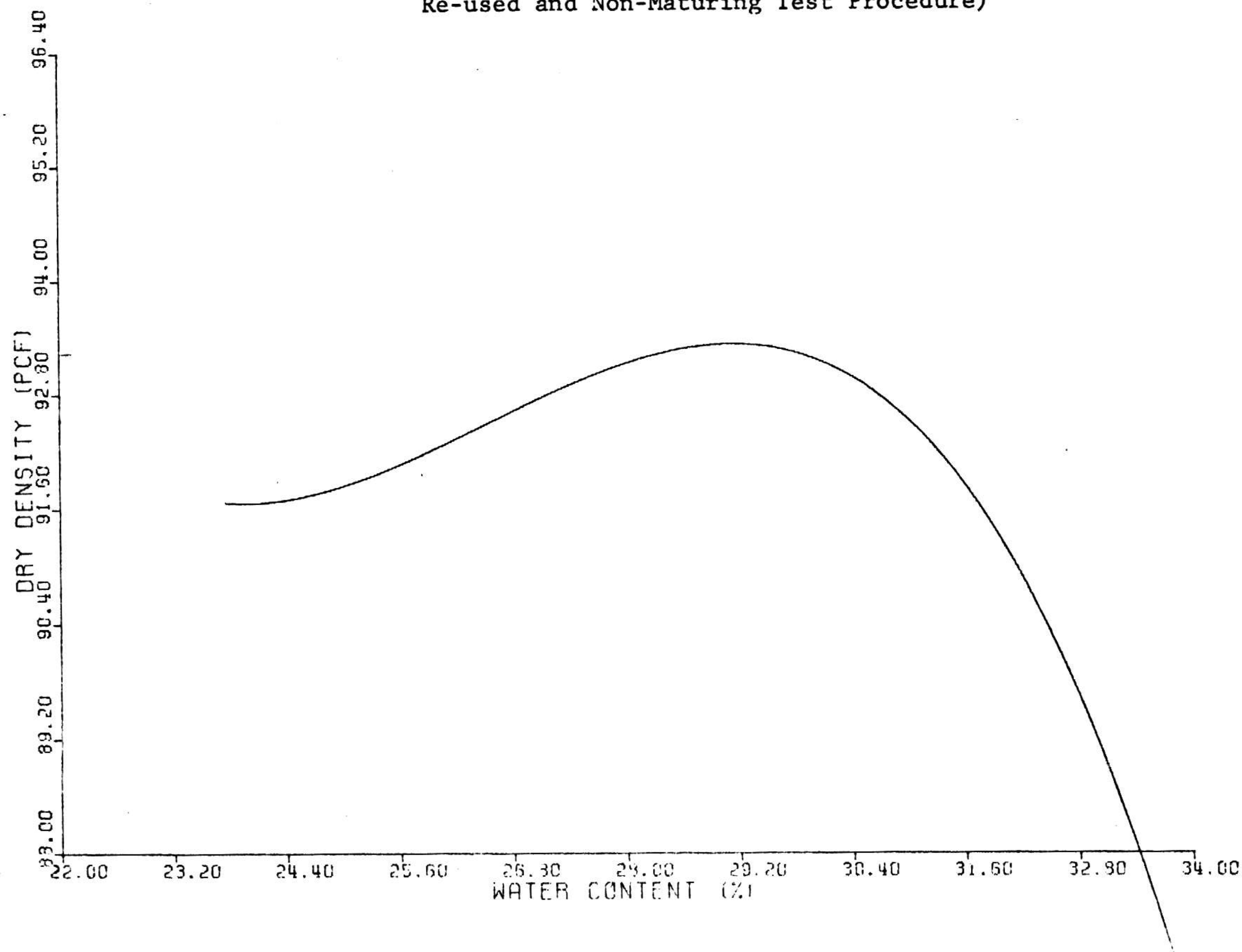
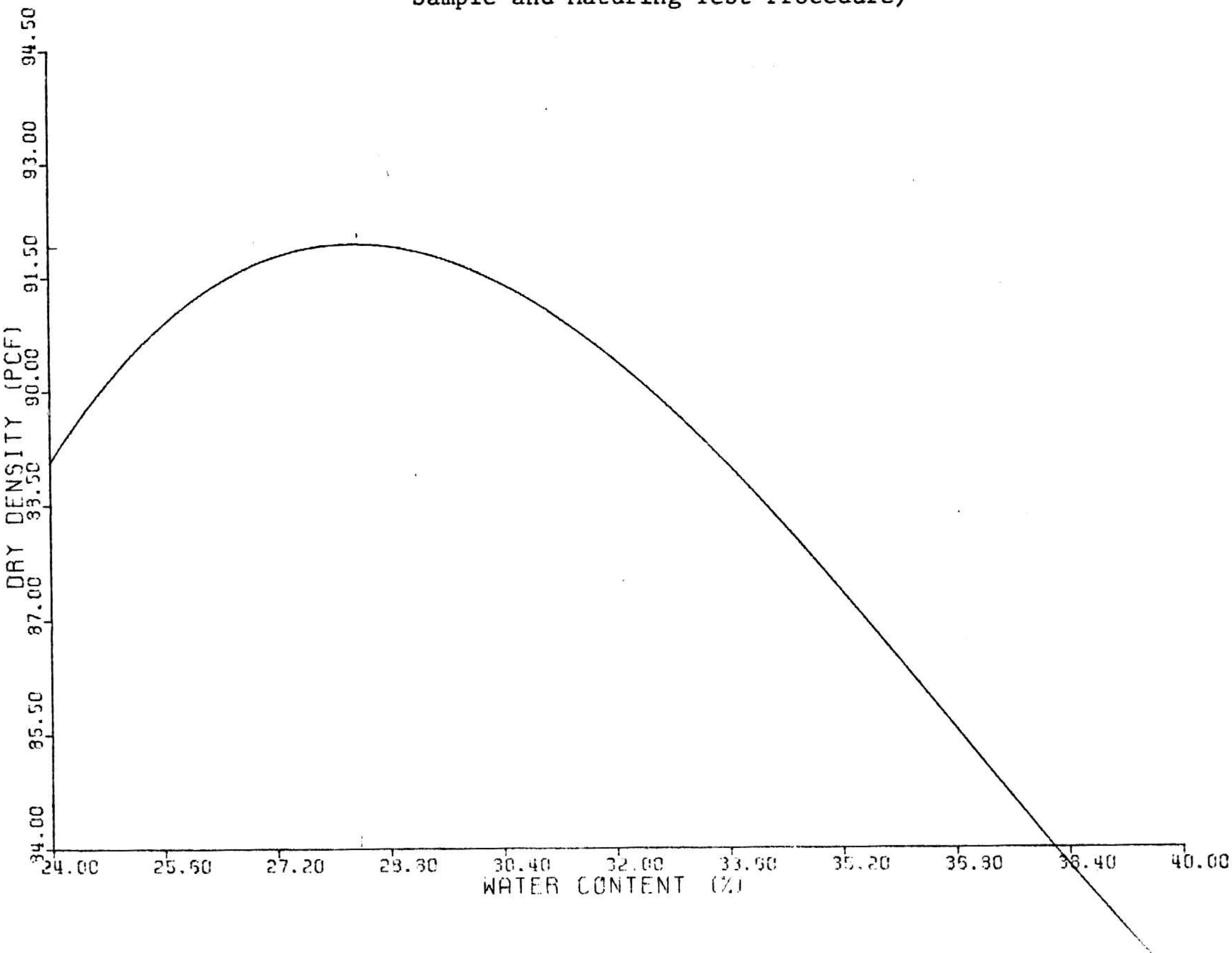


Fig. 14 - Compaction Curve for Clay Sample No. 3 (Fresh Sample and Maturing Test Procedure)



in Appendix A. The system used in this thesis to classify soils is the Unified Soil Classification System.

The following Table is a compilation of the values for maximum dry density and optimum moisture content as read from the 8 compaction curves.

		Soil Re-use and Non-Maturing Test Procedure		Fresh Sample and Maturing Test Procedure	
Soil	Classification	Max. Dry Density, pcf	Opt. Water Content, %	Max. Dry Density, pcf	Opt. Water Content, %
Loess	ML	113.5	15.1	108.3	17.7
Clay No. 1	CH	89.7	30.5	89.8	30.6
Clay No. 2	CL	102.5	22.3	102.7	22.0
Clay No. 3	CH	93.3	29.2	91.9	28.3

Table 1 - Compilation of Test Results

CONCLUSIONS

The purpose of this thesis is to investigate the difference--for clayey soils--in the maximum dry densities obtained by performing the compaction test by two different methods. Three Eastern Kansas clayey soils were tested in these two fashions. For the 3 soils, the differences in maximum dry density, as determined by the two test methods, ranged from 0.1 to 1.4 lb per cubic foot.

Grady (11) writes,

> "Variations of ± two pounds or less in compaction test data are not significant since experimental errors of this magnitude are often found in the in-place density test methods used for the field control of earthwork compactions."

In the light of Grady's comment, the differences in the results obtained for the 3 clayey soils are not significant. It is therefore concluded that for the clayey soils tested in these investigations that the special procedures listed in Note 1 of ASTM D698 are unnecessary.

The larger difference in maximum dry densities for the loess sample will be discussed in the RECOMMENDATIONS FOR FURTHER STUDY section that follows.

RECOMMENDATIONS FOR FURTHER STUDY

In the REVIEW OF THE LITERATURE, Nelson and Sowers (8) were quoted concerning the subject of re-use of soil in the compaction test. They write that any soil type will have a higher maximum dry density when the same sample is re-used in all phases of the compaction test than it will if fresh soil samples are used for each point on the test curve.

In the laboratory experiments performed for this thesis, the only soil type exhibiting a significant difference in maximum dry density when comparing the two laboratory test methods is the loess sample. The three clayey soils did not show this large difference.

It may be hypothesized that a 12-hour maturing period permits more compaction to occur in the clayey soils than would occur in those soils if the sample was not allowed to mature. This effect could counteract some or all of the maximum dry density decrease that resulted from using fresh samples for determining each point. This hypothesized effect would thereby explain the small difference in maximum dry density encountered in the clayey soil samples.

To investigate this hypothesis, two series of compaction tests might be performed on the three clayey soils. In these tests, separate fresh samples should be used in both of the two series. The only parameter to be varied should be the maturing period--in one series there should be no maturing period, and in the other series there should be a 12-hour maturing period.

ACKNOWLEDGMENTS

The author acknowledges the counsel and guidance given by the Major Professor of this study, Professor Wayne W. Williams, Department of Civil Engineering, Kansas State University. His encouragement and efforts in the instillment of fundamental engineering principles helped make possible the completion of this investigation.

Appreciation is due Dr. Robert R. Snell, Head of the Civil Engineering Department, Kansas State University, for his generosity in allowing the author to continue his graduate studies.

The author wishes to express his appreciation to Dr. Henry V. Beck and to Dr. Bob L. Smith for their review of the manuscript and for their role as members of the Advisory Committee.

Acknowledgment is also due the Kansas Department of Transportation for providing the use of laboratory facilities and for the procurement of one of the soil samples used in this study.

Dr. Kenneth E. Kemp and Mr. John Anschutz provided assistance in the area of computer manipulation of the experimental data.

Mrs. Peggy Selvidge is acknowledged for her careful typing of the final manuscript.

BIBLIOGRAPHY

1. Proctor, R. R., "Design and Construction of Rolled Earth Dams," ENGINEERING NEWS RECORD, Vol. 111, No. 9, August 31, pp. 245-248, No. 10, September 7, pp. 286-288, No. 12, September 21, pp. 348-351, No. 13, September 28, pp. 372-376, 1933.

2. American Society for Testing and Materials Part 19, 1977 Book of ASTM Standards, ASTM, 1977.

3. Olson, Roy E., "Effective Stress Theory of Soil Compaction," Journal, Soil Mechanics and Foundations Division, Proceedings, ASCE, Vol. 89, No. SM2, pp. 27-45, 1963.

4. Hogentogler, C. A., "Essentials of Soil Compaction," Proceedings, Highway Research Board, National Research Council, Washington, D. C., pp. 309-316, 1936.

5. Jumikis, A. R., Soil Mechanics, D. Van Nostrand Company, Inc., 1962.

6. Johnson, A. W. and J. R. Sallberg, "Factors Influencing Compaction Test Results," Highway Research Board Bulletin, 319, 148, 1962.

7. Proctor, R. R., "Laboratory Soil Compaction Methods, Penetration Resistance Measurements, and Indicated Saturation Penetration Resistance," Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Vol. 5, pp. 242-247, 1948.

8. Nelson, G. H. and G. W. Sowers, "Effect of Re-using Soil on Moisture-Density Curves," Proceedings, Highway Research Board, Vol. 29, pp. 482-487, 1949.

9. U. S. Corps of Engineers, "Soil Compaction Investigation, Report No. 7: Effect on Soil Compaction of the Pressure and Number of Coverages of Rubber Tired Rollers and Foot Contact Pressure of Sheepsfoot Rollers." U. S. Waterways Experiment Station Technical Memo, 3-271, June, 1956.

10. Ray, P. N. and T. G. Chapman, "The British Standard Compaction Test for Soils: A Study of Some Factors Affecting the Test Results," Geotechnique, 4: No. 4, pp. 167-177, Dec., 1954.

11. Grady, J. D., "Discussion on Effect of Re-using Soil on Moisture-Density Curve," Proceedings, Highway Research Board, Vol. 29, pp. 488-490, 1949.

APPENDIX A

GRAIN SIZE ANALYSES OF THE FOUR SAMPLES

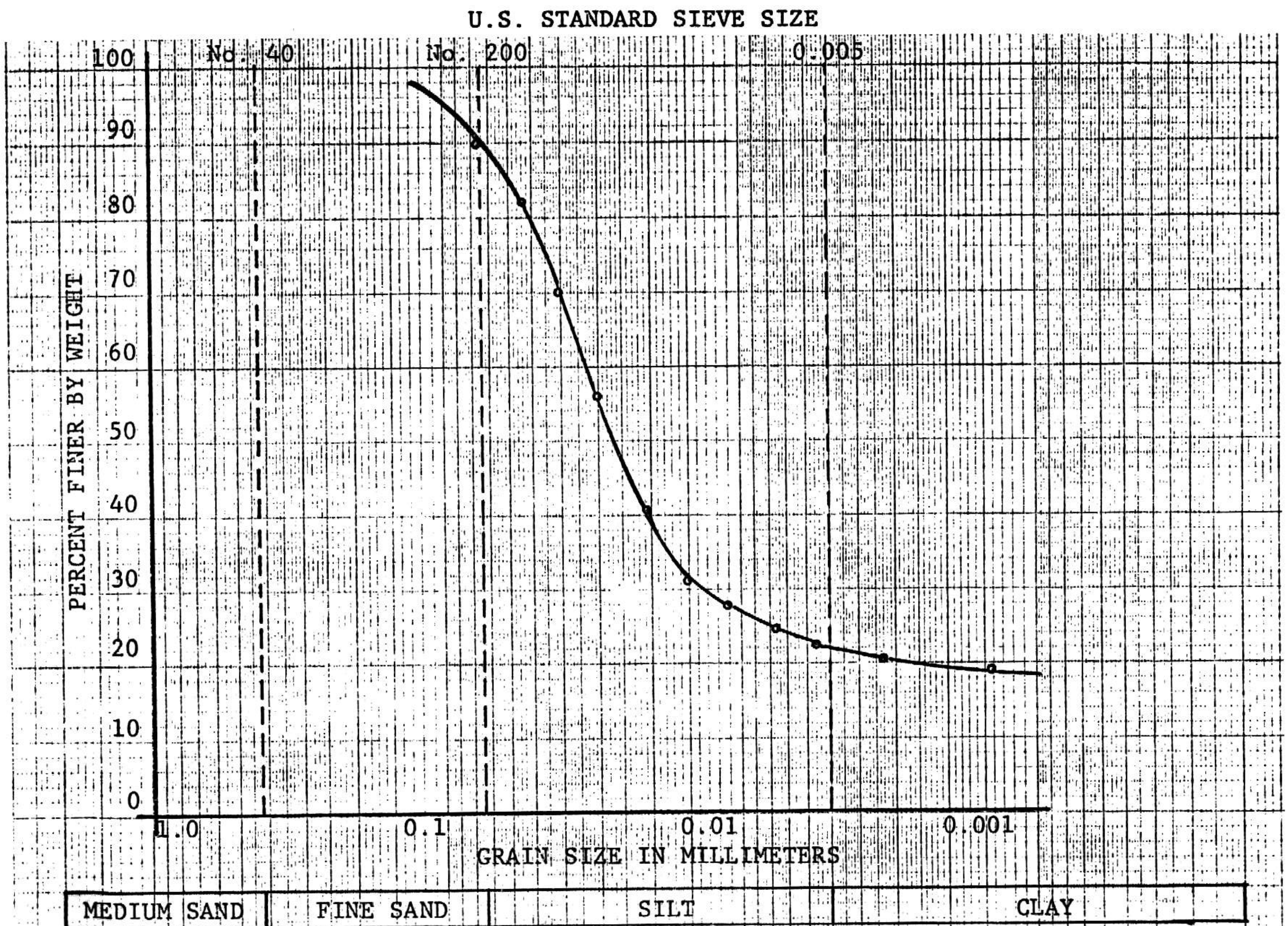


Fig. A1 - Hydrometer Analysis of the Loess Sample

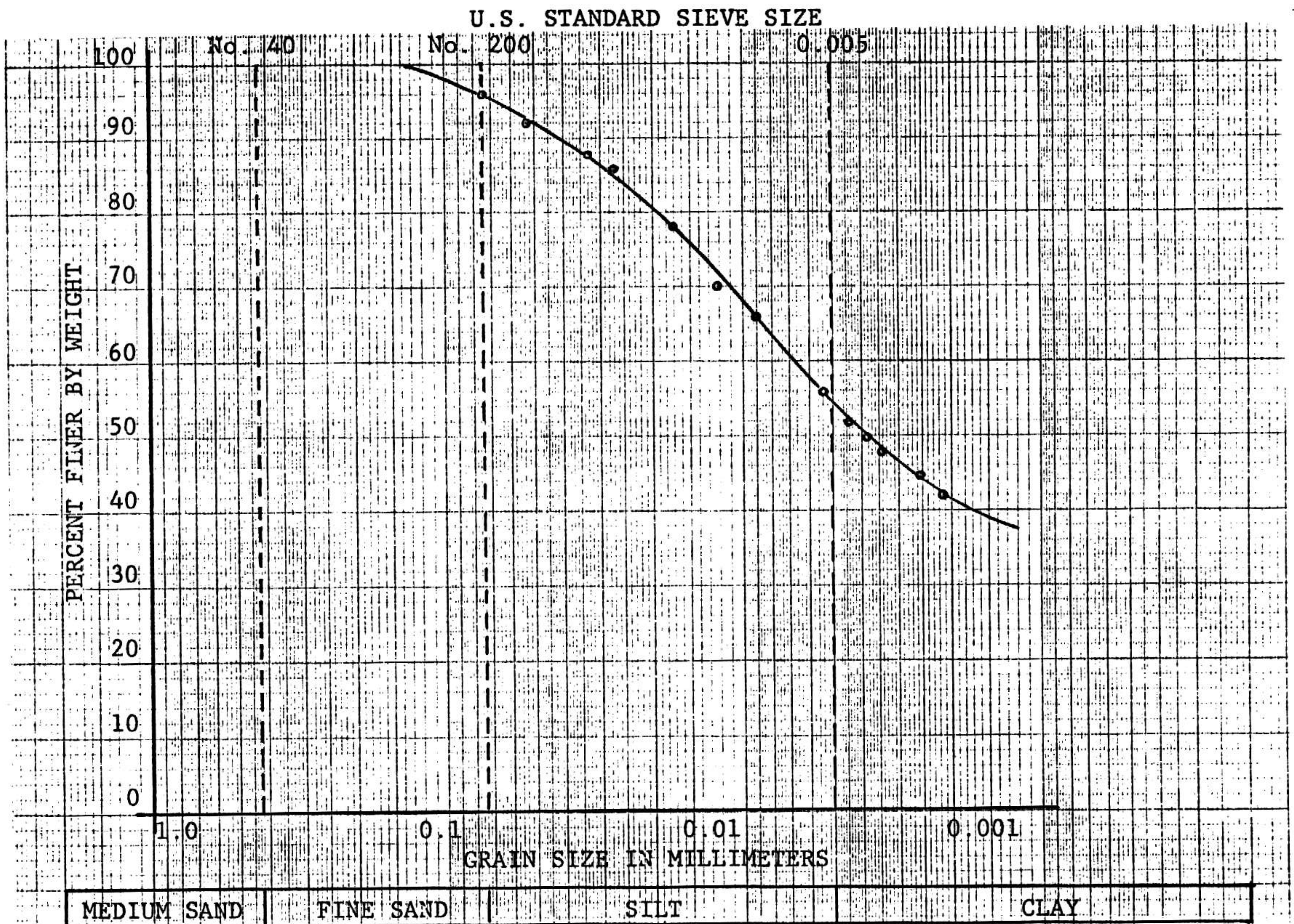


Fig. A2 - Hydrometer Analysis of Clay Sample No. 1

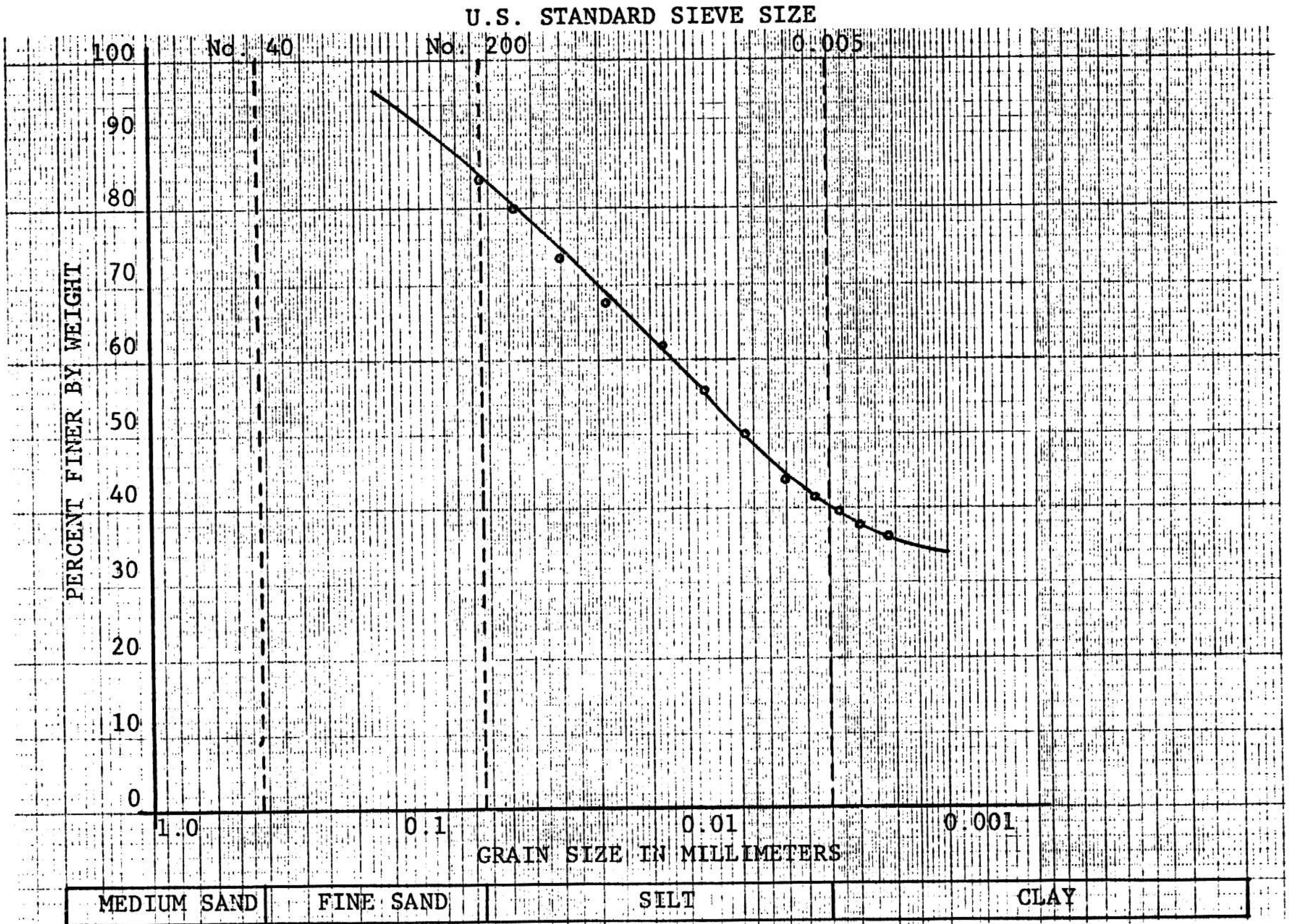


Fig. A3 - Hydrometer Analysis of Clay Sample No. 2

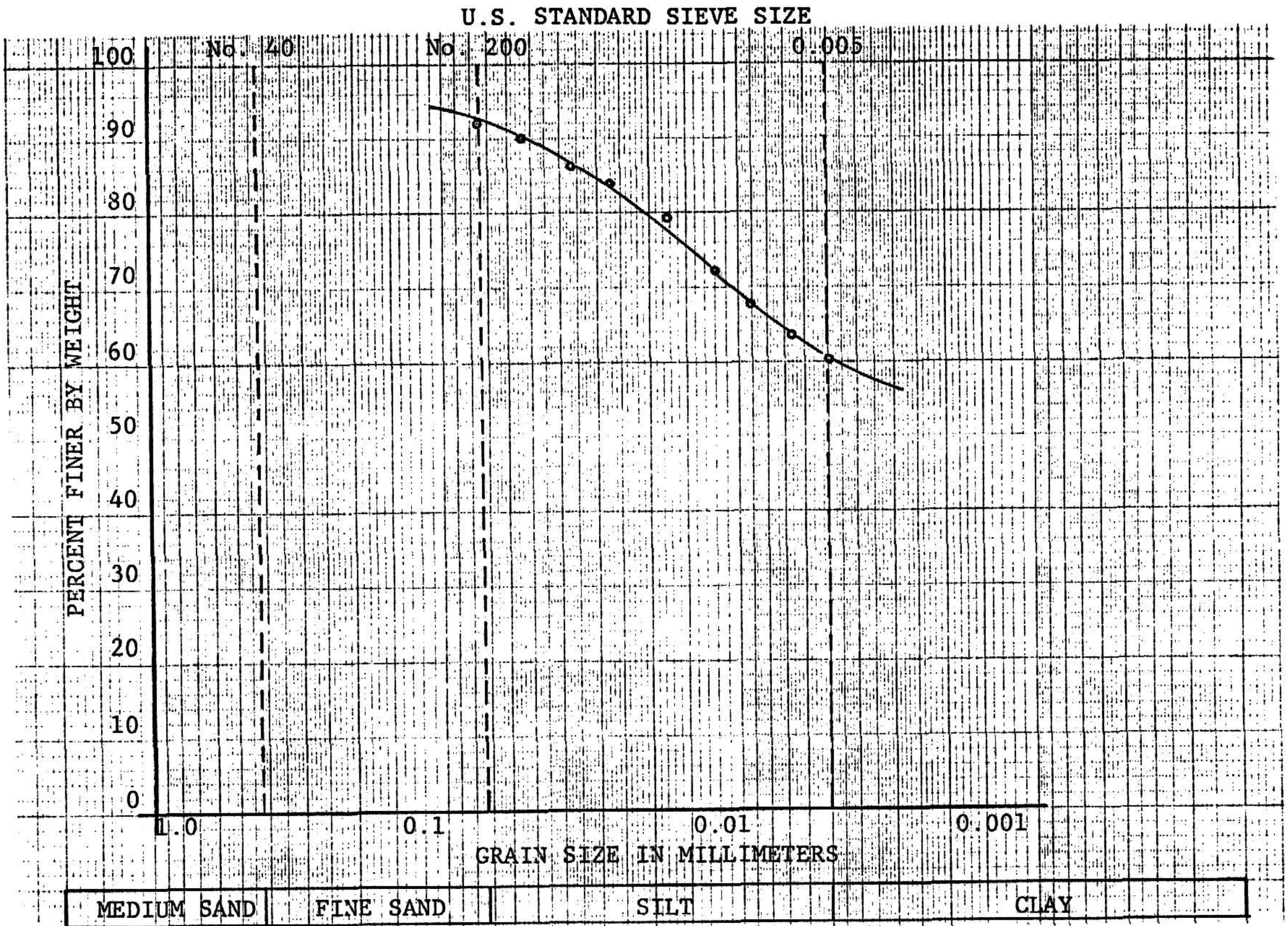


Fig. A4 - Hydrometer Analysis of Clay Sample No. 3

APPENDIX B

COMPUTER REGRESSION ANALYSIS

In mathematics, when one variable Y is dependent on another variable X, Y is termed a function of X. In statistics, the relationship is termed a regression. Y is a regression on X.

In the laboratory portion of this thesis, approximately 200 sets of data were computed. Each data set contained a value for dry density and a value for that dry density's associated moisture content. In this thesis, the dry density values will be named the Y variable and the values for moisture contents will be named the X variable.

The 200 data sets were divided into eight equal groups that correspond to the eight different test series performed in the laboratory. For each group, two mathematical equations were calculated relating values of Y to values of X. These equations are of the form:

$$Y = a + bX_1 + cX_2$$

and

$$Y = a + bX_1 + cX_2 + dX_3$$

where:

a, b, c, and d are constants

$X_1 = X - \bar{X}$

$X_2 = X_1^2$

$X_3 = X_1^3$

Second and third order equations were chosen for their similarity in shape to the moisture-density curve. Constants in the equations were calculated by computer. For the quadratic equation, the constants, a, b, and c were calculated by the equations:

$$a = \bar{Y} - b\bar{X}_1 - c\bar{X}_2$$

$$b = \frac{(\Sigma x_2^2)(\Sigma x_1 y) - (\Sigma x_1 x_2)(\Sigma x_2 y)}{(\Sigma x_1^2)(\Sigma x_2^2) - (\Sigma x_1 x_2)^2}$$

$$c = \frac{(\Sigma x_1^2)(\Sigma x_2 y) - (\Sigma x_1 x_2)(\Sigma x_1 y)}{(\Sigma x_1^2)(\Sigma x_2^2) - (\Sigma x_1 x_2)^2}$$

where

$$x_1 = X_1 - \bar{X}_1$$

$$x_2 = X_2 - \bar{X}_2$$

$$y = Y - \bar{Y}$$

For the third order equations, the computer arrived at values for a, b, c, and d. The method for computing these constants is beyond the scope of this appendix. For a description of the method the computer employed for calculating a, b, c, and d, Chapter 13 of Snedecor and Cochran's Statistical Methods may be consulted.

For each of the two equations computed per test group, the computer also calculated the mean square deviation from regression. This is the value of the average (mean) distance from the curve calculated by the computer-generated equation to the data points obtained from laboratory tests. The equation with the lower value of mean square deviation from regression is the one chosen to be displayed in the PRESENTATION OF DATA section. The eight curves shown there were plotted by computer after values for $\bar{X}$ and for the constants were entered into a computer plotting program. For the eight curves, mean square deviations from regression are given below.

Fig.	Mean Square Deviations
7	0.713
8	1.675
9	0.792
10	0.801
11	0.889
12	1.290
13	1.380
14	0.977

APPENDIX C

TEST RESULTS

LOESS: SOIL RE-USED AND NON-MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5
Dry Density, pcf	110.6	113.3	109.1	104.8	102.9
Water Content, %	13.4	16.4	18.7	20.5	22.5

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	111.6	114.3	111.0	108.3	104.8
Water Content, %	13.2	16.0	17.4	20.0	21.5

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	112.8	113.8	110.3	105.7	103.2
Water Content, %	14.0	15.9	17.5	20.2	22.4

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	111.7	113.2	110.0	106.3	103.1
Water Content, %	14.0	16.0	17.9	19.8	22.5

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	112.6	114.4	110.3	106.0	104.7
Water Content, %	13.3	15.6	17.5	20.1	21.9

LOESS: FRESH SAMPLE AND MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5
Dry Density, pcf	99.7	105.8	108.4	109.7	107.64
Water Content, %	12.0	14.4	16.5	18.1	20.4

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	104.7	107.3	108.2	106.3	102.0
Water Content, %	13.7	15.6	18.6	20.7	22.8

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	101.1	106.5	107.6	106.3	102.6
Water Content, %	13.7	15.4	17.4	19.7	22.4

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	105.7	106.9	107.1	106.4	102.6
Water Content, %	12.9	14.8	17.9	20.2	22.4

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	103.0	105.4	110.5	106.2	103.3
Water Content, %	13.3	15.1	17.3	19.9	21.6

CLAY SAMPLE NO. 1: SOIL RE-USED AND NON-MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5	6
Dry Density, pcf	87.5	87.9	88.3	88.7	86.5	82.8
Water Content, %	20.1	27.1	29.6	31.2	35.2	38.2

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	86.1	88.0	90.1	86.5	84.8
Water Content, %	22.1	24.0	32.8	35.3	37.2

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	89.46	90.77	89.13	84.97	84.72
Water Content, %	28.64	31.15	33.20	36.21	37.39

Test No. 4

Determination No.	1	2	3	4
Dry Density, pcf	91.5	90.7	89.0	86.6
Water Content, %	30.1	31.2	33.0	35.1

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	89.7	89.8	88.5	85.5	83.3
Water Content, %	29.0	31.9	33.8	36.1	38.1

CLAY SAMPLE NO. 1: FRESH SAMPLE AND MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5
Dry Density, pcf	84.0	87.2	87.9	88.9	87.4
Water Content, %	37.7	35.0	33.1	31.3	29.4

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	84.3	86.9	88.2	89.8	88.9
Water Content, %	37.6	35.1	33.4	31.4	29.3

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	82.9	85.7	88.9	90.1	90.6
Water Content, %	38.8	36.6	33.2	31.4	29.2

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	86.5	88.9	91.0	90.6	88.4
Water Content, %	35.7	33.9	31.5	29.1	26.8

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	87.7	88.9	89.2	89.7	85.7
Water Content, %	35.0	33.2	30.5	29.0	26.9

CLAY SAMPLE NO. 2: SOIL RE-USED AND NON-MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3
Dry Density, pcf	101.1	99.1	96.2
Water Content, %	24.9	26.7	27.9

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	101.1	101.7	102.2	100.0	97.1
Water Content, %	19.7	21.6	23.3	25.3	26.9

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	100.1	104.3	102.7	100.2	96.5
Water Content, %	20.3	21.7	24.0	25.5	27.7

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	103.5	102.6	102.6	99.8	97.0
Water Content, %	20.1	22.1	23.8	25.5	27.1

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	100.3	102.9	101.8	99.8	96.8
Water Content, %	20.6	22.2	23.5	25.3	27.1

CLAY SAMPLE NO. 2: FRESH SAMPLE AND MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5
Dry Density, pcf	102.2	102.3	102.5	100.9	98.6
Water Content, %	18.4	19.9	22.6	24.9	26.4

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	99.5	100.8	103.0	102.0	98.8
Water Content, %	18.3	19.7	21.9	24.8	26.8

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	100.6	103.0	103.2	102.5	100.2
Water Content, %	18.3	19.7	22.4	24.2	25.8

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	99.1	100.7	102.2	101.7	98.1
Water Content, %	17.4	20.2	22.3	23.6	27.4

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	98.1	99.2	104.7	101.3	98.5
Water Content, %	17.6	19.9	20.1	24.4	26.2

CLAY SAMPLE NO. 3: SOIL RE-USED AND NON-MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5	6
Dry Density, pcf	92.2	93.6	93.1	93.6	93.9	92.2
Water Content, %	23.4	25.1	27.2	28.7	30.3	31.2

Test No. 2

Determination No.	1	2	3	4	5
Dry Density, pcf	89.5	90.4	92.1	90.2	90.3
Water Content, %	25.2	26.5	28.6	30.9	32.6

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	93.6	94.3	94.4	92.7	90.4
Water Content, %	25.8	27.0	29.2	30.9	32.4

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	92.4	93.3	94.1	91.8	89.4
Water Content, %	26.0	28.3	30.1	31.5	33.1

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	91.5	90.8	93.3	93.4	91.9
Water Content, %	23.9	25.6	27.5	29.6	31.3

CLAY SAMPLE NO. 3: FRESH SAMPLE AND MATURING TEST PROCEDURE

Test No. 1

Determination No.	1	2	3	4	5
Dry Density, pcf	88.5	91.0	92.8	90.6	85.3
Water Content, %	25.5	27.2	28.2	31.4	37.3

Test No. 2

Determination No.	1	2	3	4
Dry Density, pcf	93.0	93.2	90.1	87.1
Water Content, %	26.6	28.8	32.8	35.2

Test No. 3

Determination No.	1	2	3	4	5
Dry Density, pcf	92.2	90.8	92.6	89.2	87.8
Water Content, %	24.9	26.7	29.3	31.9	34.9

Test No. 4

Determination No.	1	2	3	4	5
Dry Density, pcf	90.5	90.8	91.4	89.3	85.8
Water Content, %	25.8	28.2	30.9	33.2	36.3

Test No. 5

Determination No.	1	2	3	4	5
Dry Density, pcf	91.6	91.9	90.0	87.8	83.0
Water Content, %	27.1	28.5	33.0	34.8	39.1

THE TREATMENT OF CLAYEY SOILS IN THE MOISTURE-DENSITY TEST

by

JAY K. LINDLY

B.S., Civil Engineering, University of Kansas, 1976

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

ABSTRACT

ASTM Test D698 is a laboratory test that simulates field compaction of earthen structures. The test includes a section on the special treatment that should be given to clayey soils while conducting the test. This treatment includes the use of a fresh soil sample for each part of the test and a twelve-hour maturing period between each application of water and its associated compaction process.

This thesis investigates the effects of the special treatment afforded clayey soils in ASTM D698. For three eastern Kansas clayey soils tested, results for compaction tests conducted with the special treatment procedures did not differ significantly from results gained after performing compaction tests without the special procedures.