Carolina Highway Department." PROCEEDINGS, Highway Research Board, Vol. 16, pp. 322–349 (1936).
(2) Soil-Cement News, No. 36, April 1951.
(3) MILLS, W. H., JR., "General Procedure, South Carolina Practice." symposium—"Progress in Soil-Cement Construction," PROCEEDINGS, Highway Research Board, Vol. 19, pp. 518–521 (1939).
(4) MILLS, W. H. JR., "Cement-Soil Stabilization." Summary of a Symposium. PROCEEDINGS, Highway Research Board, Vol. 17 (1937).
(5) "Prevention of Moisture Loss in Soil-Cement with Bituminous Materials." Highway Research Board, *Research Report No. 8-F* (1949).
(6) Sec. 227.04, *Road and Bridge Specifications*, Virginia Department of Highways, (Jan. 1, 1947).

CLAY FRACTION IN ENGINEERING SOILS: III. INFLUENCE OF AMOUNT ON PROPERTIES

DONALD T. DAVIDSON, *Associate Professor of Civil Engineering*

AND

JOHN B. SHEELER, *Research Associate, Engineering Experiment Station*
Iowa State College

SYNOPSIS

PART III of the series describes the results of a study of one of the important variables affecting engineering properties of soil: the amount of clay present in the soil. Test data for the deep Wisconsin (Peorian) loess of southwestern Iowa affords a rare opportunity for such a study with natural soil. Graphs show that the liquid limit, plastic limit, plasticity index, shrinkage limit, centrifuge moisture equivalent, hygroscopic moisture, field (in-place) density, and field moisture content have an apparent linear relationship with 0.002-mm.-clay content. No simple relationship was found between the field-moisture equivalent and clay content.

● PARTS I AND II of this series (*1*, *2*), reporting on investigations of the clay fraction in engineering soils, describe tools and methods suitable for engineering-laboratory use by which certain properties of the clay fraction may be analysed. One of the objectives of the investigations, as stated in Part I, is to study the role of the clay fracton in soils to determine the variables involved and their influence on engineering properties, which are those physical properties of soils used in the design and construction of engineering works. This paper reports the results of a study of one of the important variables: the amount of clay present in the soil.

Test data for the deep Wisconsin (Peorian) loess in southwestern Iowa afforded a rare opportunity for such a study with natural soils. The data were obtained as part of the research being done under Project 283-S of the Iowa Engineering Experiment Station. This project, "An Investigation of the Loess and Glacial Till Materials of Iowa," is being carried on under contract with the Iowa State Highway Commission and under the sponsorship of the Iowa Highway Research Board and is supported by funds supplied by the commission and by the U. S. Bureau of Public Roads.

WISCONSIN LOESS OF SOUTHWESTERN IOWA

Four glacial drifts of the Wisconsin stage, Iowan, Tazewell, Cary, and Mankato, have recently been mapped in Northwestern Iowa by R. V. Ruhe.[1] Each of these four glaciations is believed to have contributed to the formation of the composite Wisconsin loess (also called Peorian loess in the geological literature) which forms a massive surface deposit that mantles older loesses and pre-Wisconsin glacial deposits in southwestern Iowa. The evidence available indicates that the main

[1] Personal communication. Ruhe was formerly an assistant professor of geology, Iowa State College.

body of the loess is wind-blown material. Major sources of supply were perhaps the flood plains of valleys draining the drift areas and also the raw surfaces of the newly deposited drifts.

The portion of the Wisconsin loess area being studied by the Iowa Engineering Experiment Station is shown in Figure 1. The thicknesses of the Wisconsin loess in this area have been mapped as greater than 17 ft. on ridges and hilltops (*3*). Along the west boundary, the east valley wall or first bluff line of the Missouri River, the loess thicknesses are much greater, depth measurements of from 60 to over 100 ft. having been made (*4*, *5*). The loess thicknesses are also greater than 17 ft. on hilltops along the north boundary, the Wisconsin (or Iowan) drift border (*6*). The depth of the Wisconsin loess becomes thinner in a southeasterly direction away from the east valley wall of the Missouri River (*5*). It also thins out rather abruptly in a southerly direction from the Wisconsin-drift border.

Over one hundred samples of the Wisconsin loess have been taken along the five traverses shown in Figure 1. Samples were taken at a depth of from 2 to 3 ft. below the top of the C horizon at each of the locations shown on the map; at many of the locations samples were also taken at greater depths. All sampling was done on uneroded ridges or hilltops. A 6-in. soil auger was used for securing samples when suitable road cuts could not be found.

The following tests are being used to evaluate the areal and stratigraphic uniformity of the Wisconsin loess:

1. Liquid limit
2. Plastic limit
3. Plasticity index
4. Shrinkage limit
5. Centrifuge moisture equivalent
6. Field moisture equivalent
7. Hygroscopic moisture (air-dry)
8. Mechanical analysis
9. Specific gravity
10. Field moisture content
11. Field density (in-place)
12. Color, wet and air-dry
13. Textural and engineering classification
14. pH
15. Organic matter content
16. Carbonate content, expressed as percent $CaCO_3$
17. Sulfate content, expressed as percent SO_3
18. Cation exchange capacity (whole soil)

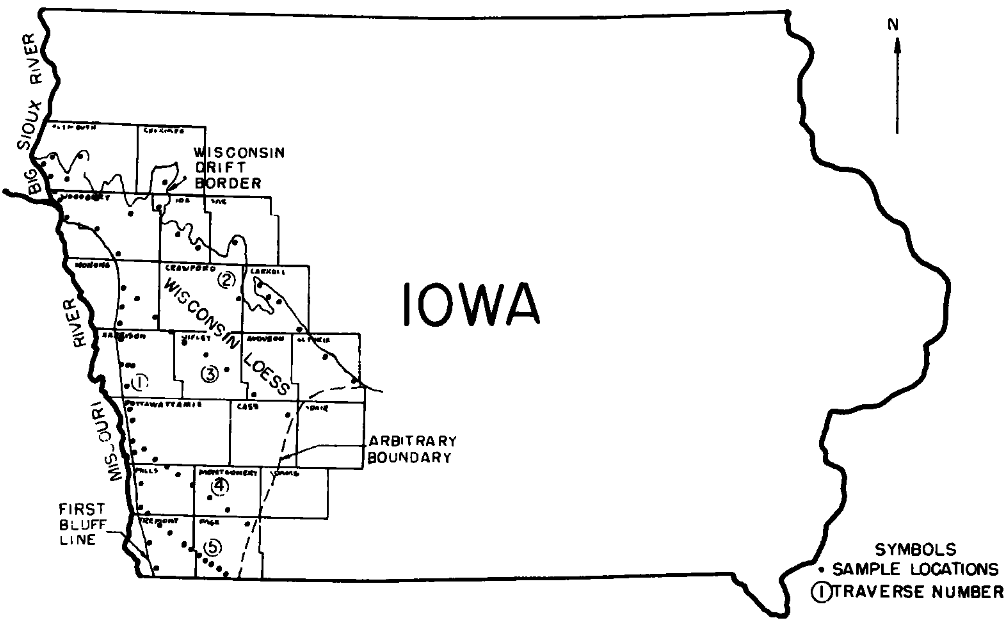

Figure 1. Locations of sampling traverses in deep Wisconsin (Peorian) loess area of southwestern Iowa.

19. Differential thermal analysis
20. Types of exchangeable cations.

These tests have been made on more than fifty of the loess samples at the time of this writing. The data indicate that physical and chemical properties along the north-south first bluff-line traverse (Traverse 1) are remarkably uniform for a natural deposit of soil material. With increasing distance away from the Missouri River valley, however, the properties of samples taken along three of the inland traverses (Traverses 3, 4, 5), reflect a marked increase in plasticity, shrinkage, water-holding capacity, and in-place density; the samples taken along the Wisconsin-drift border (Traverse 2) have not as yet been tested. The data further indicate that this increase is almost wholly due to an increase in the amount of clay in the loess.

On the basis of the mineralogical and chemical data available, the mineralogical nature of the Wisconsin loess seems to be quite uniform; the clay portion being mainly composed of illite- and montmorillonite-type clay minerals with calcium and magnesium as the predominant exchangeable cations. Organic matter and soluble sulfate contents are very low or nonexistent. Aside from variation in amount of clay, the principal variable in the loess appears to be carbonate content. Carbonate percentages, expressed as calcium carbonate were as high as 18 percent along the first bluff-line traverse and decreased to as low as 1 percent in samples taken near the east boundary of the loess area.

CORRELATIONS

The test data for the Wisconsin loess affords an opportunity for correlations of amount of clay and engineering properties, since the amount of clay present in the loess was found to be the major variable responsible for the differences in engineering properties.

In this study clay is defined as the soil particles smaller than 0.002 mm. in equivalent spherical diameter. Atterburg (*7*) recommended this definition of clay in 1912, and more recently it has been given further scientific justification as a result of mineralogical studies of soils by several investigators (*8*, *9*, *10*). The 0.002-mm. upper limit for clay has been adopted by the International Society of Soil Science and the U. S. Department of Agriculture; it is also used in the MIT system of particle-size classification. Trial correlations in the present study showed that the amount of 0.002-mm. clay present in the loess samples correlated better with engineering properties than the amount of 0.005-mm. clay, which is commonly used as the clay portion of soils in current engineering practice.

The properties to be correlated were determined by means of the following test procedures:

1. Mechanical analysis. ASTM Designation: D422-39, with exception of the modifications described in paper by Davidson and Chu (*11*).
2. Liquid limit AASHO designation: T89-49.
3. Plastic limit. AASHO designation: T90-49.
4. Plasticity index. AASHO designation: T91-49.
5. Shrinkage limit. AASHO designation: T92-42.
6. Centrifuge moisture equivalent. AASHO designation: T94-42.
7. Field moisture equivalent. AASHO designation: T93-49.
8. Hygroscopic (air-dry) moisture. ASTM designation: D422-39.
9. Field (in-place) density. The rubber balloon method as described by Hank (*12*) was used.
10. Field moisture content. The method described by Hank (*12*) for material that does not contain aggregate larger than ¼-in. was used.

Complete details on the tests may be obtained from the publications cited. The significance of the tests has been described by Allen (*13*) and others (*14*, *15*).

The influence of the amount of clay on the several engineering properties was determined by plotting on linear graph paper the value of the engineering property of each loess sample against the sample's percentage of 0.002-mm. clay. The results of the correlations are shown in Figures 2 to 10, inclusive. All properties, except the field moisture equivalent, Figure 7, have an apparent linear relationship with 0.002-mm.-clay content. The curves, whose equations are shown on the graphs, were fitted visually by balancing the number of points on either side of the line.

The field-density points, Figure 9, represent only the loess densities as measured at a depth

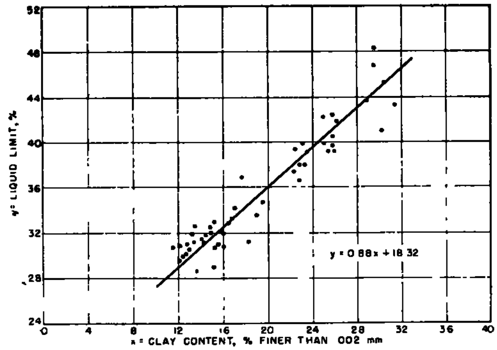

Figure 2. Influence of clay content on liquid limit.

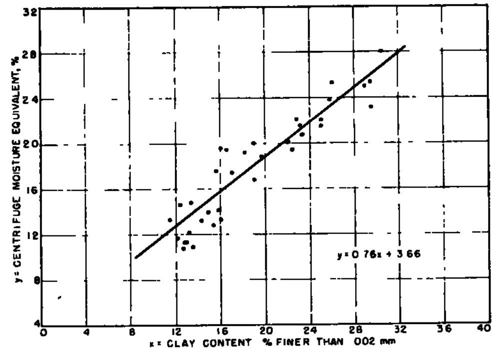

Figure 6. Influence of clay content on centrifuge moisture equivalent.

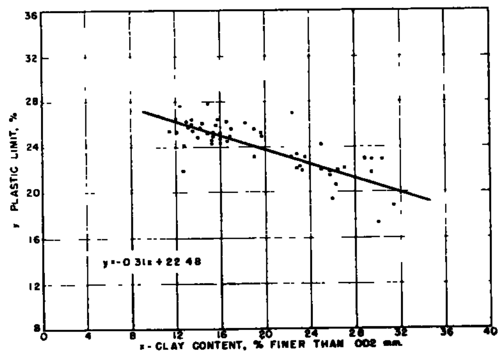

Figure 3. Influence of clay content on plastic limit.

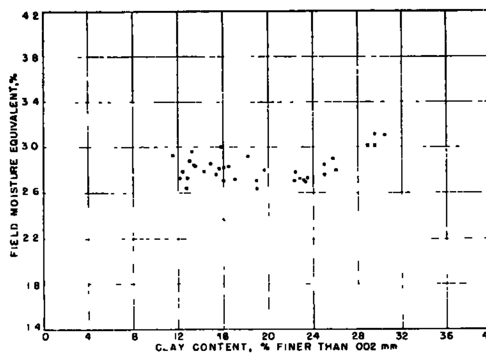

Figure 7. Influence of clay content on field moisture equivalent.

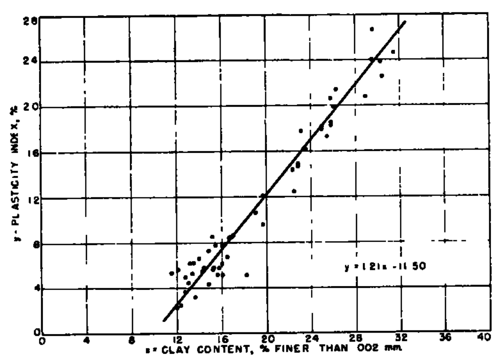

Figure 4. Influence of clay content on plasticity index.

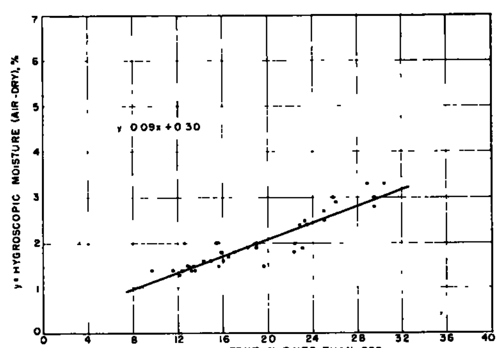

Figure 8. Influence of clay content on hygroscopic moisture.

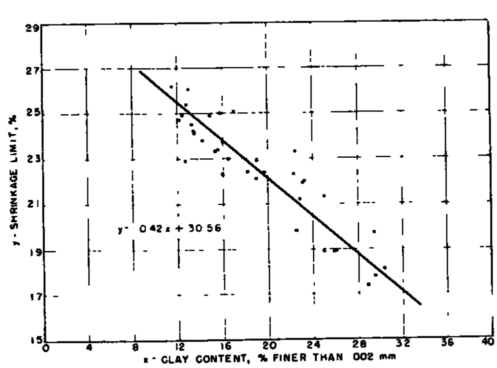

Figure 5. Influence of clay content on shrinkage limit.

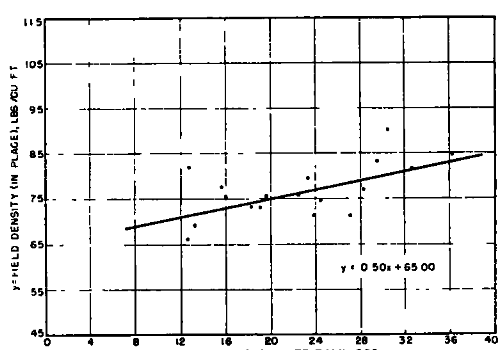

Figure 9. Influence of clay content on field density.

of between 2 and 3 ft. below the top of the C horizon. This was necessary, because in-place density increases with depth in the loess and clay content does not. The graphs for all other properties represent the loess at the 2 to 3 ft. depth and deeper.

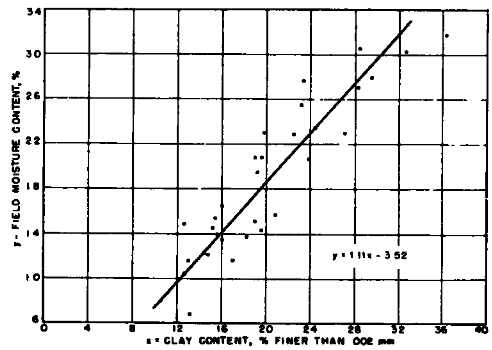

Figure 10. Influence of clay content on field moisture content.

DISCUSSION OF CORRELATIONS

The results of the correlations show that in a soil system where amount of clay is the major variable, the liquid limit, plasticity index, centrifuge-moisture equivalent, hygroscopic moisture, field-moisture content, and field density[2] are directly proportional to the 0.002-mm.-clay content, showing an increase in value with an increase in clay content. The plastic limit and shrinkage limit are also directly proportional to the 0.002-mm.-clay content, but show a decrease in value with an increase in clay content. All of these relationships follow the general equation: $y = mx + b$. In this equation y represents the engineering property; x the 0.002-mm.-clay content; m the slope of the curve which can be positive or negative, depending upon the engineering property under consideration; b is also a constant, depending upon the same engineering property.

The field moisture equivalent shows no simple relationship to the 0.002-mm.-clay content. On the basis of a similar study with British soils, the Road Research Laboratory in England concluded (*16*): "The field moisture equivalent varies only slowly as the clay content increases and even for a given type of soil exhibits considerable variability, the cause of which is not known. Even as an index test, its value seems very doubtful." The data of the present study appear to confirm this statement.

[2] Providing the field-density measurements are made in similar stratigraphic positions.

REFERENCES

1. Hauth, W. E. and Davidson, Donald T., Studies of the Clay Fraction in Engineering Soils: I. Identification by Differential Thermal Analysis. Proceedings Hwy. Res. Bd., *30:* 449–458, 1950.
2. Hauth, W. E. and Davidson, Donald T., Studies of the Clay Fraction in Engineering Soils: II. Particle Size Distribution and Cation Exchange Capacity. Proceedings Hwy. Res. Bd., *30:* 458–464, 1950.
3. Riecken, F. F. and Smith, G. D., Principal Upland Soils of Iowa, Their Occurrence and Important Properties. Agron. 49 (revised), Iowa Agr. Exp. Sta., 1949. (Mimeo. report).
4. Kay, George F. and others, The Pleistocent Geology of Iowa. Iowa Geol. Survey, Special Report, 1944.
5. Hutton, C. E., Studies of Loess-Derived Soils in Southwestern Iowa. Soil Sci. Soc. Am. Proc., *12:* 424–431, 1948.
6. Smith, G. D. and Riecken, F. F. The Iowan Drift Border of Northwestern Iowa. Am. Jour. Sci., *245:* 706–713, 1947.
7. Atterburg, A., Die Mechanische Bodenanalyse und die Klassification de Mineralböden Schwedens. Itern. Mitt. Bodenk., *2:* 312–342, 1912.
8. Robinson, G. W., Soils, Their Origin, Constitution and Classification, 2nd. ed., p. 16. Thomas Murby & Co., London, 1936.
9. Marshall, C. E., Mineralogical Methods for the Study of Silts and Clays. Z. Krist., (*A*) *90:* 8–34, 1935.
10. Truog, E., Taylor, J. R., Pearson, R. W., Weeks, M. E. and Simonson, R. W., Procedure for Special Type of Mechanical and Mineralogical Soil Analysis. Soil Sci. Soc. Am. Proc., *1:* 101–112, 1936.
11. Davidson, Donald T. and Chu, T. Y., Dispersion of Loess for Mechanical Analysis. In preparation for Proceedings Hwy. Res. Bd., 1951.
12. Hank, R. J., Suggested Method of Test for Density of Material in Place (Rubber Balloon Method). Procedures for Testing Soils (ASTM), The Society, Philadelphia, 1950.
13. Allen, Harold, Classification of Soils and Control Procedures Used in Construction of Embankments. Public Roads, *22:* 263–282, 1942.

14. HOGENTOGLER, C. A., WINTERMYER, A. M. AND WILLIS, E. A., The Subgrade Soil Constants, Their Significance, and Their Application in Practice. Public Roads, *12:* 117–144, 1931.
15. WINTERMYER, A. M., WILLIS, E. A. AND THOREEN, R. C., Procedures for Testing Soils for the Determination of the Subgrade Soil Constants. Public Roads, *12:* 197–207, 1931.
16. KNIGHT, B. H., Soil Mechanics for Civil Engineers, p. 126. Edward Arnold & Co., London, 1948.

STATIC AND DYNAMIC SOIL COMPACTION

R. K. BERNHARD, *Professor of Engineering Mechanics, Rutgers University*

SYNOPSIS

THIS PAPER describes an investigation on soil compaction as part of a more comprehensive study on "Dynamic Properties of Soils," sponsored by the New Jersey State Highway Department, the Bureau of Public Roads, and Rutgers University. Methods to produce and measure compaction effects are discussed; laboratory and field experiments have been performed, and static and dynamic compaction efficiencies compared. The results indicate that for certain soils, in particular soils used often as highway subbases, dynamic compaction can produce higher densities and reach deeper strata than static compaction.

● THE CONCEPT of soil as engineering material is only a few decades old. Though the foundations of most of our buildings, in particular our highways, are based on soil, rather little is known about the static characteristics and still less about the dynamic characteristics of soils.

Soil compaction to improve the load-bearing capacity becomes of primary importance whenever necessary to prevent failure of the structure supported by the soil.

PURPOSE

The general purpose of the research project discussed in this paper was to (1) obtain a comparison of compaction effects on confined and nonconfined soils due to static loads, dynamic loads, and a combination of both; and (2) determine efficiency factors referring to static and dynamic compaction methods, or both, for confined and nonconfined soils.

The increasing interest can be deduced from the numerous papers published on these topics (*1* to *5*) in particular, during the last years (*6* to *8*).

ORGANIZATION

A Joint Highway Research Committee consisting of members of the three sponsoring organizations, that is, the New Jersey State Highway Department, the U. S. Bureau of Public Roads, and Rutgers University, together with one member of Princeton University, authorized as one of their projects an investigation on "Compaction and Dynamic Properties of Soils."[1]

This investigation is based on suggestions made by the author in 1937 to the New Jersey State Highway Department and presented again in 1946 as a modified four-year program (*9*) to the committee. Actual work on the project started in 1947.

Eight unpublished reports (*10* to *17*) have been submitted so far to the committee and three published papers (*18* to *20*) preceded and emanated from this work. In this discussion, an attempt is made to summarize some of the results. The project has been subdivided into two parts: applied and fundamental research or, as indicated by the title of the project, first, "Compaction of Soils," and second, "Dynamic Properties of Soils."[2] This report is limited to the first part only, that is, mainly to the engineering aspect in-

[1] The other projects authorized under the same sponsorship are: Engineering Soil Map and Soil Testing, Pavement Roughness and Performance, and Frost Reaction of Soils.

[2] Topics referring to the second part of the project, that is, "Dynamic Properties," are for example: critical frequencies, moduli of elasticity (Young, shear, bulk), characteristic waves (longitudinal, transverse, surface), damping, attenuation, pressure transfer, and density determinations. Investigations of this type are in the pilot stage.