Composition and Engineering Properties of Soil. V.

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● SOIL TECHNOLOGY (the composition, geological history, and structure of soil and their effects on its behavior) has been the subject of research conducted by the M.I.T. Soil Engineering Laboratories for about ten years. This paper is the fifth in a series on a phase of this long-range continuing study. The research started with an attempt to correlate soil composition and engineering properties. The results of the research soon showed that not only was the composition of the soil important but also that the arrangement of the individual particles and the geological history of the deposit had a significant influence on the behavior of the soil. Results also showed that mineralogical data alone were insufficient; the nature and amount of exchangeable ions and the characteristics of the pore fluid in the soil must also be considered.

This paper presents compositional data on 33 soils selected from the many on which analyses were made during the past year; it also discusses, in general, composition and engineering behavior of fine-grain soils based on the entire research program to date.

MINERALS OCCURRING IN SOILS

The soils described in this series of papers do not represent a true cross-section of the soils of the world. The majority of soils were investigated because of their unusual or troublesome engineering behavior. Both geographical distribution and mineral species distribution covering the first four papers have been discussed by Martin and Lambe (5). About ¾ of the soils investigated came from the Western Hemisphere and by far the largest group from the United States.

From the 150 analyses reported in the 5 papers of this series, 90 percent of the soils contained phyllosilicate (sheet silicate) minerals as the dominant component. The clay in about 30 percent of the soils was composed of a single phyllosilicate species. Approximately 15 percent of the soils contained 3 phyllosilicate species in about equal proportions. Illite was found in 75 percent of all soils and montmorillonoid in 45 percent. Chlorite occurred as frequently as kaolins, kaolinite, and halloysite; both of these mineral groups were observed in about 25 percent of the soils. In view of the fact that more than one phyllosilicate species occurred in 70 percent of the soils and that the phyllosilicates were usually interstratified, extensive engineering and compositional data are needed on clays containing interstratified phyllosilicate minerals.

METHODS OF ANALYSIS

The methods employed for obtaining mineralogical data as well as a detailed analysis of these data have been discussed extensively by Lambe and Martin (3). One fact that becomes increasingly clear is that the determination of mineralogical composition of fine-grained soils cannot be set up as a routine test. Furthermore, it would probably be undesirable to perform mineralogical analyses according to rigid rules because it might easily obscure an important component or some other factor about which little is known at the present time. For example, it is probable that the mineral described as kaolinite in many early clay mineralogical investigations (4) was actually chlorite. There is need, also, for

vast improvement in the quantitative estimation of mineral percentages and any system of fixed rules would probably hinder progress in this direction.

Research (1, 2, and 6) has established that the engineering behavior of a given clay may vary greatly simply by altering either the kind of exchangeable ion or the concentration of ions in the pore fluid. The effect produced by altering the salt concentration of the pore fluid in many instances is greater than the effect produced by changing the kind of exchangeable ion. Therefore, these two factors should be considered in order to correlate successfully engineering behavior with soil composition.

A very good first approximation to the salt concentration in the pore fluid can be obtained from the measurement of the electrical resistance of a clay suspension. The method employed has been adopted from the Cornell work. Briefly, the procedure is to make a clay slurry, water content of 200 percent[1], and to measure the electrical resistance of the suspension with a calibrated conductivity cell. The conductivity cell was especially designed for use in clay suspensions and the conductivity bridge was an RC-16B.

The exchangeable ions Na, K, Ca, Mg, Fe, and Al are the only exchangeable ions likely to be important in soils for most engineering purposes. Exchangeable Na and K are negligible in soils from the humid regions of the world. Acid soils of the humid regions contain appreciable quantities of exchangeable Fe and Al which are apparently present as complex ions. Unfortunately, both Fe and Al are also frequently present in amorphous materials so that a reliable estimation of the proportion of exchangeable Fe and Al is usually impossible. Determination of exchangeable Fe is further complicated by the fact that a clay will take up Fe to many times the value of the exchange capacity (1). Except on extremely acid soils of humid regions, Ca and Mg generally account for 50 to 95 percent of the exchangeable ions. All the soils studied that contained appreciable Na salts in the

pore fluid also contained calcite and/or dolomite. Therefore, the exchange complex of these soils is going to be predominantly Ca and/or Mg because of preferential sorption of the polyvalent ions. It is concluded, therefore, that although the kind of exchangeable ion has a pronounced influence on the engineering behavior of a clay, the chances are that the exchange complex of a natural soil will be predominantly Ca and/or Mg.

Comments on Table 1

Table 1 presents the compositional analyses of 33 soils selected from the group studied during the past year along with some engineering data on the various soils. Most of the engineering data was furished by the individual or organization who supplied the samples to the M.I.T. Laboratory. All of the compositional analyses and some of the engineering studies were performed in the M.I.T. Laboratories.

Sample 1 is predominatly gibbsite, a two-layer aluminum oxide, and contains considerable ferric oxide. In view of the composition of this soil and its low cation exchange capacity (4 meq per 100 gm) the natural water content and Atterberg limits are surprisingly high and the natural dry density (20 to 39 lb per cu ft) surprisingly low. The apparently unusual properties could be due to the amorphous fraction in the soil, approximately 14 percent.

Samples 3 through 12 are composed essentially of halloysite (4 H_2O). They show the low dry density and high water contents typical of halloysite. The strength of compacted samples of halloysite are much higher than one would expect from such low densities — this also is typical of halloysite.

Samples 15 through 18 are all from Lake Maracaibo in western Venezuela. Samples 16 and 17 are from the same piece of mottled clay; Sample 16 is yellow and 17, gray. The essential difference in composition between the two samples is the higher iron content (3.2 percent vs 0.5 percent) of the yellow sample. This

[1] For soils high in montmorillonoid, a higher water content is necessary.

fact suggests that the yellow portion was at some time subjected to more severe oxidation.

Sample 19 from near St. Louis, Missouri, composed of 35 percent montmorillonite has caused serious trouble as a foundation soil. The soil undergoes considerable alteration in volume with changes in moisture, causing structural failures in the overlying buildings.

Sample 22 is a clay from Vicksburg, Mississippi, which has been used extensively by the Waterways Experiment Station in their laboratory and field compaction studies.

Samples 28 and 29 are from the famous Massina clay of the St. Lawrence Seaway. The soils are well known among engineers because of their high sensitivity; that is, they lose most, if not all, of their strength on remolding. The two Massina clays from Grass River Lock are alike in composition except for the montmorillonite in Sample 29. This montmorillonite content is reflected in the higher cation exchange capacity (20 vs 8 meq per 100 gm) and the higher plasticity index (29 vs 16 percent).

Samples 23, 24, 26, 27, and 30, furnished by the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, have been used in their frost studies.

RELATIONSHIPS BETWEEN SOIL COMPOSITION AND BEHAVIOR

During the entire course of the research, three groups of soil components have consistently indicated that they can have striking effects on soil properties. These three groups are described in the remaining portion of this section.

Minerals with Nonplate-Shaped Particles

Two minerals have been encountered which have nonplate-shaped particles: halloysite and attapulgite. Although the crystal structure of halloysite is a sheet-type similar to kaolinite, the particle of halloysite is a rolled plate. Attapulgite has a chain-like structure similar to the amphibole. Halloysite exists in two extreme forms: halloysite (4 H_2O) with about 11 percent water by weight between the basic sheets and halloysite (2 H_2O) with no water between the sheets. The mineral can easily transform irreversibly from the 4 H_2O form to the 2 H_2O form; a soil can simultaneously contain both forms of halloysite.

The most unusual property of halloysite — especially halloysite (4 H_2O) — is the very low density and high moisture content it usually possesses. Compaction tests have shown maximum dry densities under 70 lb per cu ft and optimum moisture content as high as 50 percent. These soils can exist at much lower natural dry densities and higher water content. For example Sample 4 (Table 1) had a natural dry density under 50 lb per cu ft and a natural moisture content in an excess of 100 percent.

The properties of this mineral are very sensitive to drying. In fact oven drying can make halloysite nonplastic, this phenomenon is shown by Sample 4 in Table 1.

The strength of halloysite is surprisingly high and the permeability is surprisingly low for soil with such low density. Halloysite has been successfully used as a construction material for several dams; for example, South Sasuma Dam, Kenya; Silvan Dam, Victoria, Australia; and Tjipanoendjang Dam, Java. No undesirable properties have been reported from the use of the halloysite in these dams or in other engineering projects. In fact the flat compaction moisture content curve apparently characteristic of halloysite makes it a relatively easy material to handle in the field.

Halloysite, especially Halloysite (4 H_2O), can be much more frost susceptible than would be expected. This fact may not be too important since most deposits of halloysite have been found in warm climates.

The engineering properties of attapulgite are not as well known as those of halloysite. Attapulgite is similar in moisture density characteristics to halloysite and is also highly frost susceptible. Attapulgite can be considerably more plastic than halloysite — a plasticity in-

dex of 130 percent was obtained by the Cornell Research final report. Unlike the halloysite, attapulgite may turn out to be a most difficult soil to handle in the field.

Expansive Minerals

The expansive minerals, particularly the montmorillonoids, can be extremely sensitive to moisture. In fact, most of the soils (encountered in the research) which caused stability or settlement-expansion problems contained montmorillonoids or organic matter. These soils are characterized by their low permeability, slow compression, relatively large secondary compression under load application, high rebound on load removal, and loss of strength in the presence of moisture.

A most striking example of extreme compressibility was exhibited by the foundation soil from the Seven Sisters Dikes, Manitoba, Canada.[2] In the standard consolidation test this soil had a void ratio following rebound higher than the initial void ratio. Sample 19 (Table 1) also rebounds to a higher void ratio than at the start of a standard consolidation test. The fact that the rebound is greater in magnitude than the compression is explainable by the techniques of the standard consolidation test. An unconfined specimen of these soils placed in contact with moisture would, of course, expand. The significant fact illustrated by the Seven Sisters Foundation soil and the St. Louis soil is that very large changes in volume can occur with changes in load or changes in moisture conditions and that these changes are partially reversible. The Atterberg limits of the St. Louis soil (Sample 19; $w_l = 58$, $w_p = 22$) do not suggest such unusual compressibility characteristics.

Laboratory and field data emphasize that the soil engineer should be most cautious when employing soils which contain expansive minerals. However, the mere presence of expansive minerals does not necessarily indicate that these

troubles will occur. There are several conditions where the expansive nature of expansive minerals can be destroyed.

Organic Matter and Aggregants

Organic matter and certain materials which aggregate or cement particles can have large effects on the soil properties even though these components are present in relatively small concentrations. The soil engineer has long recognized the deleterious effects organic matter can have on soil behavior. Relatively little is known, however, about the nature of organic matter occurring in soils or about the mechanics whereby organic matter alters soil behavior. Research on this complex subject is needed.

Two soil components which can aggregate or cement particles are carbonates and iron oxides. The result of such aggregation or cementation is to increase the particle size of its soils. Soils containing these materials are usually stronger, less compressible, and less plastic than would normally be expected from their mineralogical composition.

LIMITATIONS TO THE ENGINEERING USE OF
SOIL COMPOSITIONAL DATA

There are several reasons why compositional data are of limited use to the soil engineer.

Sampling and Analytical Difficulties

The soil engineer has always had considerable trouble determining the properties of a large mass of soil in the field from laboratory tests on small soil samples ranging from 100 to 1000 gm. The problem is greater in compositional analyses where only a 10-gm sample is used. Extreme care must be exercised in selecting the sample for compositional analyses.

Compositional analyses are not a routine proposition. To be most useful the compositional analysis should be made by one who appreciates the engineering use of the data. Not many soil engineer-

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[2] Soil 7 from (*3*) 1956.

ing laboratories have, or will ever have, the personnel and equipment required to make complete soil analyses.

Mineral Properties

A given mineral does not always have the same properties. Since the particle size, degree of weathering, etc., will vary with different deposits of the same minerals, it is not surprising that the properties of these deposits can be quite unlike. The different properties of the same mineral species can be larger than the differences in properties between certain species.

Cementation and Interstratification

Earlier papers in this series have emphasized the extensive cementation of clay fines which occurs in natural soils. This cementation is illustrated in Figure 1, in which clay size (percent minus 2μ) is plotted against clay content as determined by mineralogical analyses. Soils with all particles finer than 2μ plot on the straight line in Figure 1 which is 45 deg to the horizontal. Soils having particles finer than 2μ which are not composed of "clay minerals" plot above the line and soils having clay particles larger than 2μ plot below the diagonal line.
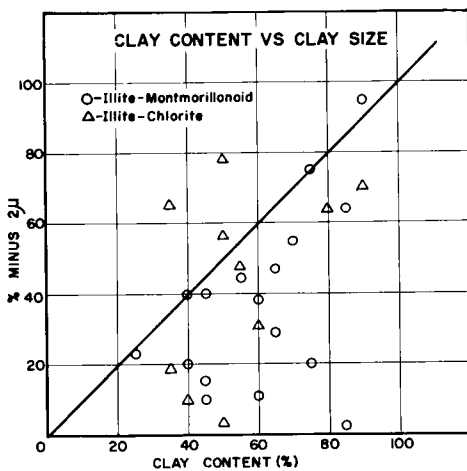

Figure 1.

The data show that the majority of the soils studied contain particles larger than 2μ. This fact indicates cementation or flocculation of particles which were strong enough to resist the chemical and mechanical dispersion given in the normal hydrometer analysis for particle size distribution. Both the illite-montmorillonoid and the illite-chlorite mixtures show cementation or flocculation. The extreme case of flocculation occurred with the montmorillitic soil from Manitoba, Canada, which had 85 percent clay by composition but no particles finer than 2μ.

Cementation usually results in a sharp loss of properties (plasticity, water sensitivity, etc.) usually associated with fine clay particles. This tendency suggests that a particle size analysis on soils which had been given some standard minimum or no particle disaggregation might be more meaningful than the now standard hydrometer test.

Cementation or flocculation does not, however, necessarily destroy clay properties (for example, the plasticity index of 66 for the Canadian soil having no particles finer than 2μ).

Arrangement of Particles and Geological History

The arrangement of particles and the geological history of a fine-grain soil have an effect on the properties of the soils. Two illustrations will emphasize the importance of particle arrangement and interparticle forces:

1. A comparison of samples compacted to the same density, one wet of optimum and one dry of optimum, shows great differences in properties. The sample compacted dry of optimum can have a permeability 100 times that of the sample compacted wet of optimum and a strength 100 or even more times that of the wet sample.

2. Many clays have been encountered which have significant strength in the undisturbed state and essentially no strength after remolding.

These two examples show samples alike in density and composition although they may have very different properties.

VALUE OF COMPOSITIONAL DATA TO THE SOIL ENGINEER

In spite of the serious limitations, compositional data are of considerable value to the soil engineer.

Fundamentals of Soil Behavior

A knowledge of soil composition is essential to an explanation of the behavior of the fine-grain soils. The pioneers in soil mechanics made considerable progress explaining the properties of cohesionless soils by considering them to be composed of discrete particles of unknown composition. This method has, however, been much less successful in explaining such complex phenomena in fine-grain soils as secondary compression, loss of shear strength on remolding, strength-density-moisture content relationships of compacted soils, and soil swelling. The correct explanation of these confusing phenomena must consider in detail the composition of the soil involved.

Prediction of Soil Behavior

The soil engineer can never always predict behavior from compositional data. Figures 2 and 3 illustrate the danger of making predictions of soil behavior from compositional data when the soil contains mixtures of illite and montmorillonoid. Interstratification of montmorillonoid and illite decreases considerably the high water sensitivity of the montmorillonoid.

For soils of a single mineral species or a simple mixture of minerals, predictions of behavior can be made with fair accuracy from a knowledge of soil composition. Since nonplate-like minerals, as halloysite and attapulgite, do not interstratify, predictions of properties for soils containing these minerals can be made with dependability.

In summary, unusual soil behavior can

nearly always be explained in terms of composition. The absence of unusual properties can also be predicted from compositional data. Because of cementa-
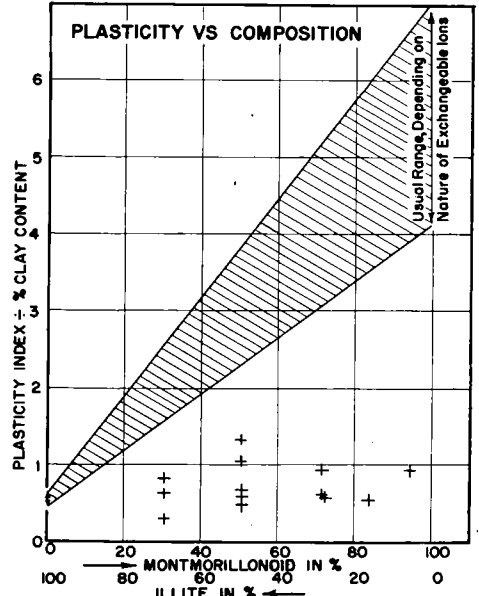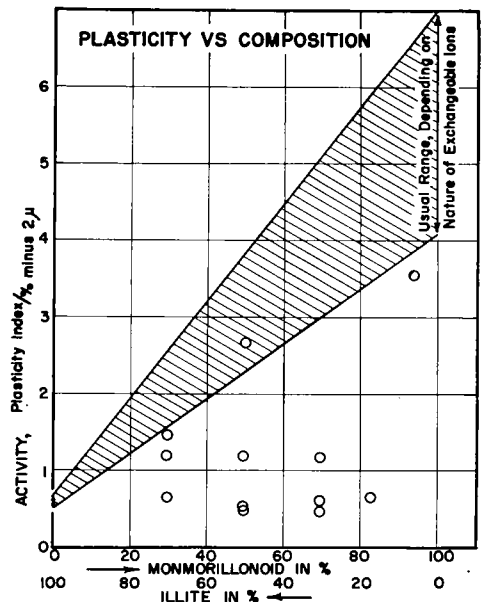
Figure 2.

Figure 3.

tion and interstratification, soils containing montmorillonoid or other expansive minerals do not necessarily possess the unusual water sensitivity properties typical of expansive minerals.

Soil Stabilization

Soil compositional data are almost essential to the intelligent alteration of the properties of the soils. Two illustrations of this importance follow:

1. A very common method of soil treatment is the injection of acid to increase permeability. The results vary from excellent when treating soils high in carbonates to poor when treating soils high in quartz.

2. Extensive experience in the M.I.T. Soil Stabilization Laboratory has shown that the most difficult type of inorganic soils to treat are those containing expansive minerals.

The first step of any extensive soil stabilization study should, therefore, be a compositional analysis on the soil or soils involved. These data guide the study on the selection of type and amount of stabilizer to be tried.

SUMMARY

Mineralogical composition and engineering properties for 33 soils are reported. The discussion, however, embodies the data from the five series papers.

Compositional data are particularly valuable to the soil engineer because: (a) unusual soil behavior can nearly always be explained in terms of composition; (b) the absence of unusual properties can be predicted from compositional data; (c) compositional data are essential to the intelligent alteration of soil properties by the use of chemical treatment. There are certain limitations to the engineer's use of compositional data that arise from: (a) the difficulty in obtaining both a representative sample and the mineralogical data for a particular soil; (b) variations in mineral properties due to cementation, interstratification of minerals, etc.; and (c) the uncertainty as to the geological history of

the soil and how this has affected the arrangement of soil particles. Therefore, while compositional data can explain unusual engineering behavior and can predict the absence of unusual properties, this data cannot be used to predict successfully the engineering behavior of soils where the clays are cemented or interstratified. Cementation or interstratification of clay appears to be the rule rather than the exception.

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TABLE 1
SOIL COMPOSITION AND PROPERTIES

Sample Number	Soil	Supplied By	% Particles Finer than 0.001 mm	% Composition by Weight of Portion Finer than 0.074 mm	Atterberg Limits and Natural Water Content in %	Engineering Properties	Remarks
1	Papaikou Ash, Hawaii (N-1)	Drs. Terzaghi & Peck		Gibbsite = 6.5, Fe_2O_3 = 2.0, O.M. = 1.8	w_L = 118–317, w_p = 253, w_p = 113	Non plastic after air drying; w_L = 0.75–1.5 %, natural w_L = 30.4 to 38.5 lb./ft.^{3}; G_s = 3 to 5 %, natural lb./ft.^{3}	W_n of sample on which limits determined was 330 %; C.E.C. = 4.2, accounted for by organic matter.
2	Sandy Clay from Timba Dam, Cali, Colombia	Mr. John Lowe T-R-N-3		Kaolinite = 6.5, Fe_2O_3 = 1.5, Quartz = 15	w_L = 42, w_p = 48, w_p = 48	w_L = 1.35 %/yr, G_s = 2 %	C.E.C. = 9, pH = 3.7; relatively high C.E.C. attributed to small amount of amorphous material.
3	Clay from Tjipanoendjong Dam, Java	Mr. N.H. Dixon, Howard Humphries		Halloysite = 60, Fe_2O_3 = 10, O.M. = 1			Ratio Halloysite($4H_2O$) to Halloysite($2H_2O$) considerable amorphous material present resulting in high C.E.C. and glycol/saturation. x-ray pattern identical to that of Kenya Dam clay.
4	Clay from Waimea Embankment, Hawaii (N-2)	Drs. Terzaghi & Peck		Halloysite($4H_2O$) = 30, Fe_2O_3 = 10, O.M. = 4.0	w_L = 57–112, w_p = 87, w_p = 78	Non plastic after air drying; w_L = 0.4–1.5 %/yr, natural T_d = 46–66 lb./ft.^{3}	w_n of sample limits determined on = 82 %; C.E.C. = 35, pH = 6.0, past temp. on thermogram is low, indicating unusual Halloysite.
5	Clay from Wilson Tunnel, Oahu, Hawaii (N-3)	Drs. Terzaghi & Peck		Halloysite($4H_2O$) = 55, Fe_2O_3 = 15	w_n = 71	w_L = 0.3 %/yr, w_L = 0.3 %/yr; natural T_d = 49 lb./in.^{3}	C.E.C. = 27, pH = 4.8
6	Clay from Wilson Tunnel, Oahu, Hawaii (N-4)	Drs. Terzaghi & Peck		Halloysite($4H_2O$) = 55, Fe_2O_3 = 12, Gibbsite = 5	w_n = 66	w_L = 0.6 %/yr, w_L = 0.3 %/yr; natural T_d = 55 lb./in.^{3}	C.E.C. = 26, pH = 5.0
7	Clay from North Barrow Area, Alexander Dam, Kauai, Hawaii (N-5)	Drs. Terzaghi & Peck		Halloysite($4H_2O$) = 65, Fe_2O_3 = 20	w_L = 51–66, w_p = 73–74, w_p = 58–60	After drying w_L = 64–67, w_p = 53–55	C.E.C. = 10
8	Clay from South Barrow Area, Alexander Dam, Kauai, Hawaii (N-6)	Drs. Terzaghi & Peck		Halloysite($4H_2O$) = 35, Fe_2O_3 = 20, Gibbsite = 20	w_L = 63, w_p = 65–84, w_p = 75–82	After drying w_L = 63–71, w_p = 58–63	C.E.C. = 15, pH = 4.0
9	Clay from Silvan Dam, Victoria, Australia (B-10)	Mr. N.H. Dixon, Howard Humphries		Halloysite($2H_2O$) = 80, Fe_2O_3 = 11, O.M. = 0.5	w_L = 92, w_p = 56	Standard AASHO: max. T_d = 77 lb./ft.^{3}, w_{opt} = 42, Penetration Resistance = 700 psi	C.E.C. = 10
10	Clay from Silvan Dam, Victoria, Australia (B-11)	Mr. N.H. Dixon, Howard Humphries		Halloysite($2H_2O$) = 90, Fe_2O_3 = 8, O.M. = 0.2	w_L = 80, w_p = 51	Standard AASHO: max. T_d = 76 lb./ft.^{3}, w_{opt} = 43, Penetration Resistance = 750 psi	C.E.C. = 10
11	Clay from Silvan Dam, Victoria, Australia (B-14)	Mr. N.H. Dixon, Howard Humphries		Kaolin = 30, Chlorite = 25, Quartz = 30, Gibbsite = 8, Fe_2O_3 = 1.5	w_L = 46, w_p = 37	Standard AASHO: max. T_d = 86 lb./ft.^{3}, w_{opt} = 30, Penetration Resistance = 1050 psi	C.E.C. = 22
12	Clay from Silvan Dam, Victoria, Australia (B-17)	Mr. N.H. Dixon, Howard Humphries		Kaolin = 25, Chlorite = 33, Quartz = 5, Gibbsite = 6, O.M. = 2.8	w_L = 60, w_p = 31	Standard AASHO: max. T_d = 84 lb./ft.^{3}, w_{opt} = 34, Penetration Resistance = 750 psi	C.E.C. = 22

{ High C.E.C. and glycol retention (65–90 gm. glycol/gm clay) and OH water suggest presence of amorphous hydrous oxides of iron or aluminum. }

{ This soil made an excellent impervious fill for the 180 ft. high Dam which has above good performance over the past 25 years. Although composition and high moisture contents, the shear strength was extremely good. }

TABLE 1 (Continued)

No.	Sample	Source	%	Mineral Composition		Strength / Test Data	Remarks
13	Cheltenham Fire Clay from near St. Louis, Missouri (#2)	H.M. Reitz		Kaolinite = 79, Montmorillonoid = 7, Quartz = 7, Rutile = 1.5, O.M. = 0.1	w_L = 26-26, w_P = 60 ±, w_P = 25-28	q_u = 2.7 - 3.1 T/sf	From an area in which fire clay deposits of commercial value are found.
14	Clay from Ellisville, Missouri (#3)	H.M. Reitz		Kaolin = 35, Illite = 20, Montmorillonoid = 15	w_L = 14, w_P = 14	q_u = 2.25 - 2.75 T/sf	Exhibits good stability for unlined excavations.
15	Silty Clay from Hydraulic Fill, La Salina, Venezuela (#1)	Creole Petroleum Corp.		Kaolinite = 10, Illite = 10, Quartz = 35, Feldspar = 35, Fe_2O_3 = 2.2	w_L = 18, w_P = 34, w_P = 14		C.E.C. = 18, pH = 7.7
16	Mottled Clay from Hydraulic Fill, La Salina, Venezuela (Yellow Layer #2)	Creole Petroleum Corp.		Kaolinite = 10, Montmorillonite = 10, Quartz = 30, Feldspar = 30, Carbonates = ?, Fe_2O_3 = 3.2	w_L = 15, w_P = 30, w_P = 16	q_u = 2.2 T/sf, $\bar{c}_t$ = 8%, $Q(ref)$ = 2200 + σ_c tan 16°, up to σ_c = 4400	C.A.C. = 11, pH = 8.0 / Mottling arises from differences in oxidizing conditions within the soil. Light grey clay results from strong local reducing conditions. / C.E.C. = 12
17	Mottled Clay from Hydraulic Fill, La Salina, Venezuela (Grey Layer #2)	Creole Petroleum Corp.		Kaolinite = 10, Montmorillonoid = 10, Quartz = 30, Carbonates = ?, Feldspar = 30, Fe_2O_3 = 0.5			
18	Clay from Hydraulic Fill, La Salina, Venezuela (#3 & 4)	Creole Petroleum Corp.		Kaolinite = 35, Montmorillonoid = 15, Quartz = 15, Carbonates = 25, Feldspar = ?, Fe_2O_3 = 6.2	w_L = 15, w_P = 36, w_P = 16	q_u = 2.2 - 2.7 T/sf, $\bar{c}_t$ = 4-8%, $Q(ref)$ = (1400-1700) + σ_c tan(6°-6°), up to σ_c = 4400	C.E.C. = 17, pH = 8.1
19	Clay from St. Joseph's Seminary near St. Louis, Missouri (#1)	H.M. Reitz		Illite = 10, Kaolin = trace, Montmorillonite = 55, Quartz = 30, O.M. = 0.2	w_L = 56, w_P = 22	q_u = 3 - 4 T/sf	This soil has swelled under foundations and caused serious structural damage.
20	Clay from Ferguson, North of St. Louis, Missouri (#4)	H.M. Reitz		Illite = 10, Kaolin = trace, Montmorillonite = 35, Quartz = 30, O.M. = 0.1	w_L = 10-25, w_P = 20	q_u = 2.5-3.5 T/sf. Sensitivity to remoulding approximate strength basis is slightly greater than 1.	Nice soil to work with in laboratory, showing good failure planes.
21	Clay from Noxon Rapids Dam, Montana (#640)	Mr. W. Zoino EBASCO	100	Hydrous mica = 90, Quartz = 15, Fe_2O_3 = 2.8	w_L = 31-35, w_P = 58, w_P = 28	Standard Proctor: max. γ_d = 88 lb/ft³, w_{opt} = 23; at w_{opt}: u = 1.3 - 1.5 T/sf, C_c = 0.2½, C_v ≈ 1×10⁻³ cm²/sec, k = 10×10⁻⁹ cm/sec.	Ratio Illite : Montmorillonoid = 5:1, C.E.C. = 29, pH = 5.1. For use as core material.
22	Clay from Vicksburg, Mississippi	WES	97	Hydrous mica = 50, Kaolinite = 25, Feldspar = 15, Carbonates = 1.8, Fe_2O_3 = 0.8	w_L = 36, w_P = 21	Standard AASHO: max. γ_d = 108 lb/ft³, w_{opt} = 18	Ratio Illite : Montmorillonoid = 1:2, C.E.C. = 18, pH = 7.3
23	Clay from Indiana (Frederick)	RCFEL	86	Illite = 10, Montmorillonoid = 20, Chlorite = 40, Quartz = 46, O.M. = 0.6	w_L = 66, w_P = 28	Standard, Modified AASHO: max. γ_d = 92, 107 lb/ft³; w_{opt} = 20%; Frost data at w_n = 21%; γ_d = 105 lb/ft³; heave = 59.0, ave. rate of heave = 0.6 mm/day, R/t_{av} = 48	C.E.C. = 32, pH = 5.4
24	Clay from Indiana (Crosby)	RCFEL	82	Illite = 15, Montmorillonoid = 25, Chlorite = 35, Quartz = 28, Fe_2O_3 = 0.5	w_L = 39, w_P = 21	Standard, Modified AASHO: max. γ_d = 107, 119 lb/ft³; w_{opt} = 19, 14%; Frost data at w_n = 17%, γ_d = 117 lb/ft³; % heave = 19.7, ave. rate of heave = 1.4 mm/day, R/t_{av} = 24	C.E.C. = 16, pH = 4.6
25	Clay from Noxon Rapids Dam, Montana (#639)	Mr. W. Zoino EBASCO		Hydrous mica = 80, Chlorite = 10, Quartz = 10, Fe_2O_3 = 2.2	w_L = 41, w_P = 65, w_P = 25	At estimated overburden pressure: Q_c = 1860 T/sf, k = 1.5×10⁻⁸ cm/sec, C_c = 0.65, C_v = 0.7×10⁻³ cm²/sec.	Ratio Illite : Montmorillonoid = 4:1, C.E.C. = 20, pH = 7.9. Foundation clay, depth = 43.5 ft.

TABLE 1 (Continued)

No.	Description	Source		Mineralogy		Properties	Remarks
26	Silt from Fairbanks, Alaska (#648)	RCFEL		Illite, Kaolinite/Illite, Chlorite, Quartz, Feldspars, Mica, O.M.	= 15, = 20, = 20, = 50, = 10, = 1.0		C.E.C. = 23, pH = 6.2
27	Silt from Fairbanks, Alaska (#649)	RCFEL		Illite, Montmorillonoid, Chlorite, Quartz, Feldspars, O.M.	= 15, = 10, = 25, = 50, = 1.0, = 1.2		C.E.C. = 18, pH = 6.3
28	Massena Clay from Grass River Lock, St. Lawrence Seaway (#15)	Corps of Engineers		Illite, Chlorite, Carbonates, Feldspar, Quartz, Fe₂O₃	= 80, = 15, = 20, = 20, = 1.0, = 0.1	$w_L = 62$, $w_P = 50$, $w_r = 34$	Natural $\gamma_d = 64\,lb/ft^3$; $Q = 1120\,^o/hr$ at $\sigma_c = 1008\,^o/hr$
29	Massena Clay from Grass River Lock, St. Lawrence Seaway (#3)	Corps of Engineers		Illite, Montmorillonoid, Chlorite, Carbonates, Quartz, Fe₂O₃	= 80, = 15, = 20, = 20, = 1.7, = 0.1	$w_L = 47$, $w_P = 60$, $w_r = 31$	Natural $\gamma_d = 77\,lb/ft^3$; $Q = 680\,^o/hr$ at $\sigma_c = 1000\,^o/hr$
30	Gravel from Thule, Greenland (Blue Jay #260)	RCFEL	3	Illite (Chlorite), (Montmorillonoid), Quartz, Feldspar, Mica, Fe₂O₃	= 15, = 40, = 40, = 5.0, = 15	Non-plastic	Providence Vibrated Density = 148 lb/ft³. Frost data at $\gamma_d = 140$–145 lb/ft³; % heave = 6.0–31.8; ave. rate of heave = 0.5–3.5 mm/day; k = 1.1–1.6 × 10⁻⁵ cm/sec
31	Clay from Hartford, Connecticut	Hayden, Harding, & Buchanan	22	Illite, Chlorite, Quartz, Feldspars, Carbonates, Fe₂O₃	= 15, = 5, = 45, = 40, = 5, = 2	$w_L = 30$, $w_P = 16$	On material mined 40 plant; Modified AASHO at $\gamma_d = 9.1$; $T_x = 100$ lb/ft³; $U = 6.0\,^o/hr$, = 2%, $Q_c = 11,500\,^o/hr$, $\sigma_c = 2320\,^o/hr$; $C_v = .05$, $c_v = 5 \times 10^{-3}$ cm²/sec
32	Silt from Equinox Dam, Sandgate, Vermont (#106)	H.P. Aldrich		Mica, Chlorite, Quartz	= 55, = 25, = 20	$w_L = 38$, $w_P = 24$ on minus #40 sieve	Compaction Harvard Miniature (Staggers, 25 blows), 40 lb. tamp); max. $\gamma_d = 121$ lb/ft³; $w_m = 12$; at nat. w_m, $U = 2.02\,^o/hr$; $k = 0.6 \times 10^{-4}$ cm/sec
33	Silt from Equinox Dam, Sandgate, Vermont (#105)	H.P. Aldrich		Kaolinite, Mica, Goethite, Quartz	= 15, = 15, = 15, = 55	$w_L = 32$, $w_P = 23$ on minus #40 sieve	Compaction Harvard Miniature (Staggers, 25 blows, 40 lb. tamp); $\gamma_d = 118$ lb/ft³; $w_m = 16$; at nat. $U = 1.58\,^o/hr$; $k = 3.3 \times 10^{-4}$ cm/sec

Symbols:

w_L = liquid limit
w_P = plastic limit
w_s = shrinkage limit
w_n = natural water content
w_{opt} = optimum water content
w_m = molding water content

* Analysis Reported for Entire Sample

γ_d = dry density in lb/ft³
e = void ratio
p_u = applied pressure in T/sf
q_u = unconfined compression strength on undist. sample in T/sf
q_r = unconfined compression strength on remolded sample in T/sf

u_u = U on sample compacted at w_{opt}
O.M. = Organic matter
Fe_2O_3 = Free iron oxides
( )₁ = interstratification
Q_c = consolidated undrained shear
σ_c = consolidation pressure

C.E.C. = cation exchange capacity in m. eq./100 g
ϵ_f = strain at failure
U = unconsolidated undrained shear strength
k = permeability
C_c = compression index
c_v = coefficient of consolidation