DEPARTMENT OF SOILS, GEOLOGY AND FOUNDATIONS

Composition and Engineering Properties of Soil (IV)

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• THIS paper, the fourth of a series by the authors, is a progress report on a long range study conducted in the Massachusetts Institute of Technology Soil Stabilization Laboratory. It is aimed at perfecting methods of determining soil composition and then correlating soil composition with engineering behavior.

An earlier paper (1) pointed out some of the limitations of predicting behavior of a soil from its composition. Not only is the nature of the components of a soil important, but also the manner in which these components are arranged and the geological history of the soil can have considerable influence on the properties of the soil. These three factors are, however, interrelated so that sometimes knowledge of the composition alone will permit some estimate of the other factors, and thus, the engineering properties.

The soils used in this study were selected from those which came into the Massachusetts Institute of Technology Soils Laboratory through its research program and the consulting work of the staff plus those sent by soil engineers from various parts of the world. The authors welcomed samples of soils, particularly those involved in engineering failures. The nature of the soil samples—sometimes small and often disturbed—usually precluded the obtaining of complete engineering data. Much of the engineering data listed in this paper was supplied by engineers furnishing the sample.

The studies reported in the four papers of this series, (1, 2, 3 and current report) have brought out a number of significant facts as

summarized below:

- A. Occurrence of Minerals
 - 1. Quartz and feldspars are the most common minerals in sands and silts; these minerals also commonly occur in clay sizes.
 - 2. Clays are predominately crystalline.
 - 3. Illite, nontronite, and chlorite are very abundant clay-size minerals.
 - 4. Mixtures of minerals in soil fines are the rule rather than the exception.
 - 5. Interstratification of minerals is very common.
- B. Correlation of Composition and Behavior
 - 1. Attapulgite and halloysite can cause unusual engineering properties, such as low compacted density, high molding water content, and high frost susceptibility.
 - 2. Halloysite can be plastic.
 - 3. Montmorillonoids and organic matter appear in a high percentage of soils involved in engineering failures caused by soil rupture or volume change.
 - 4. Many clays have part of their fines firmly cemented—in these soils the percentage minus 2μ fails to indicate the percentage of clay present.

C. Difficulties in Soil Analysis

The complete compositional analysis of a fine grained soil can be very difficult; several pretreatments of the soil and several analytical



Figure 1. Scheme for classification of soil composition.

determinations may be required. A careful definition of the various end-member minerals is necessary before quantitative analysis can be made. Since these definitions must often be arbitrary, the quantitative analysis of certain borderline minerals may not be significant. The difficulties involved in completely analyzing certain soils are illustrated in this paper wherein the analyses of several soils are discussed in detail.

COMPOSITIONAL ANALYSES

Classification and Definition of Minerals

The composition of soils throughout the world exhibits a very wide range; however, from a consideration of the various components the classification in Figure 1 is sufficiently general to include nearly any soil. About 90 percent by weight of all crystalline minerals are silicates and probably 90 percent by weight of all soils are tecto (framework) and phyllo (sheet) silicates. In Figure 1 all important minerals likely to be encountered in soil are included; a complete mineralogical classification is not, however, intended.

The subdivisions of the silicate group are based on the geometric arrangement of the (SiO₄) tetrahedrons.¹ Within the phyllosilicate group, subdivision is determined by the number of silica and gibbsite or brucite sheets that are very strongly bonded together. Variations in chemical constitution of the bonding ion or molecule that holds the three-layer units together and to some extent bond strength, determine the subdivision of the three-layer phyllosilicates. Classification of the mineral names in the phyllosilicate sub-group have been given previously (3); however, modification and additional criteria now can be given to further aid in the classification of a clay.

Kaolin. The kaolin group is composed of kaolinite, halloysite $(4H_2O)$, or hydrated halloysite and halloysite $(2H_2O)$ or dehydrated halloysite. Halloysite with no suffix designated indicates either or both forms.²

Halloysite $(4H_2O)$ is readily identifiable by the 10A x-ray reflection of the moist clay which contracts to 7.2A upon drying of the specimen; however, the differentiation between halloysite

¹ Use of these prefixes to designate the spatial configuration of the (SiO₄) tetrahedrons has been adapted from Winchell and Winchell (4): tecto = framework, phyllo = sheet, ino = chain, cyclo = ring, and neso = island. ² The nomenclature of the halloysite minerals continues

^a The nomenclature of the halloysite minerals continues to be debated in the literature (δ) ; however, since the terms used here are descriptive, they will be employed until some agreement is reached.

 $(2H_{\bullet}O)$ and kaolinite is more complex. By use of the electron microscope the platev morphology of kaolinite is easily distinguished from the tubular morphology of hallovsite. X-ray diffraction also can be used to observe the effect of this difference in morphology.³ The halloysite tubes prevent extensive particle orientation whereas the kaolinite plates permit a well oriented aggregate to form. If the specimen is kaolinite, the basal spacings of an oriented aggregate will become very intense and the (hk0) reflections become weak when the aggregate is placed in the x-ray beam at a very low angle (designated "parallel to the x-ray beam"). This same aggregate placed in the x-ray beam at a high angle (designated "perpendicular to x-ray beam"), will show strong hk0 reflections and weak 00L reflections. If the sample is halloysite, the x-ray patterns from the oriented aggregated examined parallel and perpendicular to the x-ray beam show very little difference.

Other differences between hallovsite and kaolinite are that hallovsite has (1) a higher cation exchange capacity, (2) a higher glycol retention, and (3) a higher slope ratio for the 600°C endothermic peak. Sand and Ormsby (6) also have noted the consistently higher cation exchange capacity of halloysite. Bramao *et al.* (7) proposed the slope ratio test for differentiating halloysite from kaolinite. Experience in the MIT Soils Laboratory indicates that a slope ratio of <2.5 is no guarantee that the sample is kaolinite; however, if the slope ratio is greater than 2.5 the sample has always been verified as being predominately hallovsite. These differentiating characteristics between kaolinite and halloysite are not, however, infallible, especially when the soil in question is a mixture of minerals, i. e., kaolinite and hallovsite, or even mixtures of twoand three-layer phyllosilicates.

Mica. Differentiation within the mica group for clay size particles still remains a problem. Any clay that meets the x-ray criteria for illite as stated by Brown (8) is called illite. For the computation of illite percentages, the following are used: Potash content = 6 percent K_2O ; cation exchange capacity = 25 mEq./ 100 g.; glycol retention = 80 mg./g. Van der Marel (9) gives x-ray criteria for distinguishing between illite and muscovite; however, since Levinson (10) has clearly indicated that illite may exist in several polymorphic forms, it seems more likely that van der Marel's data are for two different mica polymorphs. Differential thermal analysis has sometimes been used to show that the clay mica is illite rather than muscovite or biotite; again, this difference may simply be an expression of two different mica polymorphs. Extensive research on the mica group is needed.

Variable d Spacing Minerals. Hallovsite $(4H_2O)$, montmorillonoid, and vermiculite are frequently called expanding lattice minerals because the d(00L) x-ray spacing will change with moisture content of the clay. The use of this term has proved misleading in that it implies an expansion within the crystal unit cell-this does not occur. Expansion or contraction takes place between crystalline units in a sufficiently regular manner that x-ray diffraction effects are observed. The primary valence bonds of the silicate layers are not affected by the change in d spacing. Use of the term "variable d spacing" is suggested to avoid the confusion which the term "expanding lattice" implies.

Walker (11) defined vermiculite as a threelayer phyllosilicate that, upon glycerol treatment of a Ca or Mg-saturated specimen, gave a 14–15A reflection which upon K or NH_4 saturation gave a 10.5A line. Soils are frequently encountered which give a 14-15A line that does not contract upon K or NH₄ saturation. The 14–15A reflection of these soils is clearly not due to a chlorite component. Walker, who has in the past few years continued his work on vermiculites, now recommends that a variable d spacing mineral where the maximum d value is 14–15A upon glycerol treatment be designated vermiculite whether or not K saturation contracts the spacing to 10.5A.4

Montmorillonoid is a variable d spacing mineral that upon glycerol treatment gives a 17-18A d value which upon oven drying gives a 10-11A line. As noted in the discussion of the mineral analyses, this new distinction between vermiculite and montmorillonoid is more consistent with other data for many clays, such as cation exchange capacity and glycol retention.

^a This method was suggested to the authors by G. F. Walker of C.S.I.R.O., Division of Industrial Chemistry, Melbourne, Australia.

 $^{^4}$ From private conversation with G. F. Walker, October 1955.

TABLE 1 REFERENCE DATA FOR PHYLLOSILICATES; -2μ SIZE

Clay	dool	Glycol, mg./g.	C.E.C., m- Eq./100 g.
Kaolin Kaolinite Halloysite (2H ₂ O) Halloysite (4H ₂ O)	7 7 10	$\left. \begin{array}{c} 18\\ 60 \end{array} \right\}$	3 12
Mica Illite Vermieulite Montmorillonoid Chlorite	$10\\10-14\\10-18\\14$	80 150 260 30	25 150 85 40

Chlorite. Chlorite is a mineral in which the negatively charged three-layer units are bonded together by a positively charged brucite sheet. In very general terms, the major difference between mica and chlorite is that in mica the three-layer units are bonded by K^+ and in chlorite by a charged brucite sheet. For this reason, the authors prefer to classify chlorite as a three-layer phyllosilicate rather than as a separate group. The identification of chlorite is based on the x-ray data given by Brindly and Robinson (12).

Table 1 summarizes reference data for the phyllosilicates. The definitions given have been largely on the (00L) x-ray reflections; however, other data, x-ray, differential thermal analysis, glycol, exchange capacity, etc., must be consistent with a given mineral before the identification can be considered as completely verified.

Hudrous Mica. Hydrous mica is a general name for mixed layer clays occurring in the three-layer phyllosilicates; by this definition. hydrous mica includes various combinations of illite and montmorillonoid, vermiculite, and chlorite. When the components of hydrous mica can be properly identified, according to criteria given above, then mineral percentages are computed in terms of end members. Crude as the calculated percentages may be, it is felt that if progress is to be made in the correlation of composition with engineering properties, numerical values for the amounts of different minerals are essential. Calculation in terms of end members is believed to be the most satisfactory method because by this method the soil composition is expressed as a function of the physiochemical properties of soil.

Clay. The nomenclature problem is not confined to the individual mineral species. One may well ask, what is a clay mineral? Should chlorite and vermiculite be called clay minerals? Both occur in clay and under these conditions, satisfy the definition of clay regardless of how one defines clay; i. e., by size, plasticity, composition, or structure. However, both chlorite and vermiculite also occur as gravel-size particles and certainly these rock particles do not exhibit clay properties. In an attempt to circumvent the difficulty regarding what is a "clay mineral," it is suggested that perhaps the term should not be used. Any term that has been so widely used in the literature will undoubtedly continue to be used. Many instances where "clay mineral" has caused confusion have led the authors to discontinue the use of the term. Clay is used to describe a natural soil with plasticity.

Methods of Analysis

The general scheme of analysis, method of sample preparation, and description of most of the test procedures, have been given previously (1). For convenient reference, salient features of differential thermal and x-ray diffraction techniques are summarized.

Thermograms given in this paper were obtained under the following experimental conditions:

- Heating rate: 12.5° C/min. with a maximum variation of less than 1° C/min. Thermocouples: Pt-Pt (10 per cent Rh)
- Sample pretreatment: 7 days over saturated $Ca(NO_3)_2 \cdot 3H_2O$ solution.
- Temperature thermocouple: In Ni steel block; peak temperatures uncorrected.
- Calibration: 50-50 quartz: BaCO₃ mixture. Quartz $\alpha \leftrightarrows \beta$ at 573 \pm 3° C. BaCO₃ to α at 819 \pm 3° C. BaCO₃ to β at 988 \pm 3° C.

Since the differential thermal behavior of the common minerals is well known, thermograms are presented merely to illustrate specific points brought out in the following discussion.

X-ray patterns were obtained with unfiltered chromium radiation in an evacuated powder camera of 114.6-mm. diameter. This system permits recording of d values up to 27A. Sample treatments used prior to x-ray examination were:

- Glycerol: Clay and glycerol are worked into a thick paste with a spatula.
- Heat: Samples are heated at 550° C for 30 minutes, then air-quenched.

Oriented aggregate: (Sample also may have had glycerol and/or heat treatment). This method is similar to that of Mitchell (13) in which the sample is oriented by the application of pressure to give a film about 0.3 mm. thick. The specimen cut from the clay film and mounted for x-ray diffraction has sufficient cohesion to withstand evacuation during the exposure. Since no backing support is necessary, the sample may be examined in a horizontal position to enhance the (00L) lines or in a vertical position to enhance the (hk0) lines.

Cation exchange capacity (C.E.C.) was determined by the ammonium acetate method, Peech (14) slightly modified. A 50-200 mg. sample, depending on the exchange capacity of the material, is extracted five times with 1N ammonium acetate at pH 7.0, the excess salt is removed by leaching with ethanol, and NH₄ adsorbed on the clay is displaced by leaching with an acidified (pH 2.3) 10% NaCl solution. The NH₄ in the NaCl solution is determined by Nesslerization.

DISCUSSION OF COMPOSITIONAL ANALYSIS Organic Soils

Soils 1 and 2 (Table 7) are peats and contain no detectable phyllosilicate minerals in the -2μ fraction after destruction of organic matter. Because the organic matter is high, the composition is given for the whole soil.

Hydrous Mica Clays

Illite-Montmorillonoid. X-ray diffraction clearly shows that Soils 3-12 contain clay of illite-montmorillonoid type since the 17-18A reflection on the glycerol-treated clay contracts to 10A after heat treatment. In Sample 8 the 18A reflection on the normal powder pattern is very poorly defined but the 18A reflection is quite sharp on the oriented aggregate pattern. Samples 3 and 5 have a strong reflection at 26-27A as well as the d(00L) of 17 and 10 characteristic of hydrous micas of illite-montmorillonoid type. The 26–27A reflection is believed to arise from interstratification of illite and montmorillonoid layers. Mielenz (15) has reported a montmorillonoid with d(00L) of 26-28A; however, in Samples 3 and 5 illite layers are very definitely present so the 26-27A line should be ascribed to interstratification. Higher orders of this large d value are poorly defined even in oriented aggregate specimens. Since the thermograms of Soils 3-12 show a 600° C endotherm but a very small 720 $\pm 20^{\circ}$ C endotherm, the montmorillonoid is probably nontronite. Typical thermograms for soils containing illite-montmorillonoid are shown by the thermograms of Soils 3, 5, and 8 in Figure 2. From the shape of the 600° C peak



Figure 2. Representative thermograms for soils containing illite-montmorillonoid type clay. All soils -74μ and at 50 percent relative humidity; 3. reddish brown silty clay from Cincinnati, Ohio; 5, stiff dark grey clay from Bayou Cocodrie, Louisiana; 8, clay from North Ridge Dam, Alberta, Canada; 11, sandy clay from Vereeniging, South Africa.

on the thermograms of Samples 11 and 12, (see thermograms for Soil 11 in Figure 2), it would appear that these samples contain a kaolin mineral. X-ray diffraction gave no evidence of a kaolin mineral. This narrow 600° C endothermic peak is fairly frequently observed for hydrous micas and appears to be related to the interstratification of the illite and montmorillonoid layers.

After the presence of illite and montmorillonoid has been established, percentage of each in the -2μ fraction was first computed. The percentage of illite is calculated from the potash content on the assumption that ideal illite contains 6% K₂O. Glycol retention reouired for the calculated illite percentage is subtracted from the observed glycol retention of the clay and this excess glycol was attributed to montmorillonoid. To compute the percent illite and montmorillonoid in the -74μ fraction, the ratio of the amplitude of the 600° C endotherm for the -74μ to that for the -2μ fraction was used. The data used in performing these calculations are given in Table 2.

Although this is an arbitrary method of computation, the mineral percentages so obtained are thought to be as reasonable a quantitative estimate of clay components as can be obtained. As a check on the validity of the calculated mineral percentages, the observed and computed cation exchange capacities for the -74μ fraction of a large number of illite-montmorillonoid type soils have been compared. The extent of agreement is illustrated in the last two columns of Table 2.

Illite-Chlorite. Samples 13-16 are hydrous

TABLE 2 DATA FOR SOILS CONTAINING ILLITE-MONTMORILLONOID TYPE CLAY

Sample No.	K2O in Percent (on -2µ)	Glycol in mg./g. (on -2μ)	Ratio of Amplitude of 600°C Endotherm	Cation Exchange Capacity in mEq./100 g. (on -74μ fraction)		
			$\left(\frac{-74\mu}{-2\mu}\right)$	Ob- served	Calcul- ated	
3	4.0	92	0.48	14	16	
4	3.2	125	0.78	26	31	
5	2.3	153	0.55	29	27	
6	2.8	142	0.47	17	22	
7	3.0	154	0.85	46	45	
8	3.3	143	0.94	34	42	
9	1.2	130	0.56	38	30	
10	1.0	146	0.67		32	
11	1.0	172	0.78	35	41	
12	1.0	162	0.46	35	29	
<u> </u>					·	

micas of illite-chlorite type. X-ray diffraction patterns clearly show reflections characteristic of illite and chlorite. After heat treatment, the 14A reflection becomes much stronger while the 7A line practically disappears and the 10A illite line remains unchanged. Illite and chlorite are the only minerals contributing to the diffraction patterns of Samples 13 and 14. Samples 15 and 16 contain, in addition to illite and chlorite, feldspar and a strong persistent reflection at 8.4A. X-ray reflections assigned to feldspar agree well with the plagioclase group but not with the potash feldspars.

Amphiboles give a reflection about 8.4A and a number of other fairly strong amphibole lines could be contributing to the observed intensity of some of the reflections assigned to illite and chlorite: however, the strongest amphibole line about 3.10A is not observed on any of the x-ray patterns; therefore, there is little justification for assignment of the 8.4A reflection to an amphibole. Further, the 8.4A line has very nearly the same intensity in the -74, -2, and -1μ fractions. The persistence of the 8.4A in the different size fractions and to heat treatment suggests that this reflection arises from an interstratified illite-chlorite mixture. Qualitatively, the presence of chlorite in Samples 13-16 is established; however, quantitative estimation is very difficult.

On the assumption that the same chlorite mineral is present in all four samples, the x-ray data indicate that Sample 14 contains the most chlorite followed by Samples 15, 16, and 13 in that order. There is apparently considerable difference in the interstratification of illite and chlorite between Samples 13 and 14, and Samples 15 and 16. However, the similar effect that heat treatment has on the 14 and 7A reflections of all samples lends evidence to the assumption that the chlorite mineral is the same in these samples. The relative amount of chlorite present in Samples 13-16 can also be crudely estimated from the thermograms of the clay size fraction (see Figure 3) in two ways: (a) the size of the endothermic peak at 650° C and (b) the height of the exothermic plateau above 800° C. The results of this comparison show that in general, both ways of estimating chlorite by differential thermal analysis substantiate each other and agree with the amount indicated by the x-ray data. If the endothermic peaks at 720 and 775 on Samples 15 and 14, respectively, arise from a chlorite component, this is another indication that Samples 14 and 15 contain more chlorite than Samples 13 and 16.

The percentage illite in the -2μ fraction determined from the 600° C endotherm and from the potash content are in substantial agreement; accordingly, the illite percentage for the -74μ fraction was obtained directly from the amplitude of the 600° C endotherm on the -74μ fraction.

Chlorite percentages were obtained in the following manner: Qualitatively the x-ray and differential thermal analysis data indicate that Sample 14 contains the most chlorite, Sample 15 somewhat less than 14, and Samples 13 and 16 considerably less than Sample 15. Twenty-five percent chlorite in Sample 14 brings the total mineral percentage to 100. The percentage for the other samples was arbitrarily assigned in accordance with the qualitative data discussed above. There are, unfortunately, no reliable methods for quantitative determination of chlorite when mixed with other phyllosilicate minerals.

Illite-Vermiculite. The variable spacing mineral in Sample 17 is called vermiculite rather than montmorillonoid because the first basal spacing has a maximum 14.7 rather than the 17.5 characteristic of montmorillonoid. Since the glycol retention of vermiculite is considerably lower than that of montmorillonoid, the percentage will be greater if the glycol excess is computed as vermiculite rather than as montmorillonoid. The cation exchange capacity of vermiculite is greater than that of montmorillonoid so that by attributing the 14.7A line mineral to vermiculite rather than montmorillonoid, the calculated cation exchange capacity will be much greater than if the variable d spacing mineral is called montmorillonoid. The calculated and observed cation exchange capacities were the same within experimental error of the cation exchange capacity determination. Quartz and feldspar estimations on Sample 17 are very uncertain because the differential thermal rerun, from which the percentage quartz is generally determined, was very erratic, making estimation of quartz difficult and since the percentage feldspar hinges on the amount of quartz, the feldspar percentage is likewise uncertain.

Illite-Kaolin-Montmorillonoid or Vermiculite. Thermograms on the clay fraction of Samples 18-21 have a large adsorbed water peak (150° C), suggestive of a hydrous mica of illite-montmorillonoid or illite-vermiculite type; the breadth of the 600° endotherm substantiates the illite-montmorillonoid possibility. The large amplitude of the 600° C endotherm for the -2μ fraction indictes the presence of a kaolin or chlorite mineral in addition to the hydrous mica.

X-ray patterns of Sample 18-21 show that these soils contain illite, kaolin, and a variable d spacing mineral. The variable d spacing mineral in Sample 18 behaves like vermiculite. On Samples 19-21, the variable d spacing is 25-26A after glycerol treatment and 14A after heat treatment. This behavior of the variable d spacing component could be explained as: (a) simple stratified illite vermiculite; (b) complex stratified illite, montmorillonoid; or (c) a montmorillonoid with $d_{001} = 25$ A similar to that reported by Mielenz (15). Differential thermal and x-ray data indicate that illite. kaolinite, and montmorillonoid or vermiculite are the clay components of Soils 19-21. Whether the variable *d* spacing component is



Figure 3. Thermograms for illite-chlorite clays. All samples -2μ ; 13, sllty grey clay from Portland, Maine; 14, grey clay from Chicago; 15, dark grey clay from Beauharnois, Quebec, Canada; 16, dark grey clay from St. Lawrence River basin.

montmorillonoid or vermiculite cannot be ascertained until quantitative analysis of the data is complete.

The amplitude of the 600° C endotherm is

TABLE 3 COMPARISON OF CALCULATED AND OBSERVED CATION EXCHANGE CAPACITY



* See text for explanation.



Figure 4. Thermograms for soils illustrating abnormal carbonate peaks. All samples -74μ ; 19, red sandy clay from Amuay, Venezuela, 50 percent relative humidity; 20, blue clay from Amuay, Venezuela, 50 percent relative humidity; 19–CO₂, soil 19 after removal of carbonate minerals with acetic acid; 20–CO₃ soil 20 after removal of carbonate minerals with acetic acid.

attributed to kaolinite because the 600° C thermal reaction of kaolinite is so much stronger than that for illite, montmorillonoid or vermiculite. Illite percentage is obtained from the potash content. After allocation of illite and kaolin, the glycol excess can be ascribed to montmorillonoid or vermiculite. For Sample 18 the amount of vermiculite obtained in this manner gave a calculated cation exchange capacity in excellent agreement with the observed value of 22 mEq./100 g. For Samples 19-21, the observed cation exchange capacity was lower than the calculated if the glycol excess is calculated as vermiculite; however, if the glycol excess is calculated as montmorillonoid, then the computed and observed cation exchange capacity show good agreement.

Since the observed cation exchange capacities show a much closer correspondence to the calculated values when the variable d spacing mineral was attributed to montmorillonoid, and the x-ray and differential thermal data can be interpreted as montmorillonoid or vermiculite, the variable d value component is concluded to be montmorillonoid.

Thermograms of Soils 19 and 20 in Figure 4 show that the influence of carbonate minerals on the differential thermal properties of a soil are unpredictable. X-ray diffraction patterns clearly indicate that in Soil 19 the carbonate is dolomite and in Soil 20, calcite. After removal of carbonates with acetic acid, the thermograms of Soils 19 and 20 are almost identical (see Figure 4).

Kaolin-Mica. Soils 22, 23, 24, and 25 are representative soils of the Southern Piedmont. Kaolin and mica in one form or another dominate the composition of these soils. Quantitative estimation of the mica components in Samples 22–25 was obtained by methods not previously discussed; therefore, the analyses of Samples 22–25 will be considered in some detail.

The composition of the -2μ fraction of Soil 22 as indicated by the thermogram is 65 percent kaolin and 35 percent gibbsite; x-ray data confirm that kaolin and gibbsite are the only crystalline components. The kaolin mineral is halloysite (2H₂O) rather than kaolinite because x-ray diffraction of an oriented aggregate showed essentially no change in intensity of the ((00L) or (kh0) reflections whether placed perpendicular or parallel to the x-ray beam. Further, the glycol retention of the clay is much too large for kaolinite. The glycol retention of gibbsite is negligible. Differential thermal analysis and x-ray data for the -2μ fraction for Samples 23, 24, and 25 indicate that kaolin is the dominant clay component. X-ray diffraction patterns on Samples 23 and 24 show the presence of hydrous mica, predominately illite in Sample 24 and illite-vermiculite in Sample 23. The kaolin mineral is probably hallovsite (2H₂O) because if it were kaolinite there would be a rather large glycol excess that could not be assigned to any mineral. There was not sufficient sample to make exchange capacity determination on all samples but for Sample 23 the measured cation exchange capacity was 28 mEq./100 g. If the kaolin component is hallovsite then the calculated exchange capacity would be 22 mEq./100 g., while, if the kaolin mineral were kaolinite, the calculated exchange capacity would be 41 mEq./100 g. The higher calculated exchange capacity assuming the kaolin to be kaolinite arises because the percentage vermiculite must be increased appreciably to account for the glycol retention. If the kaolin in Samples 24 and 25 were kaolinite there would be a glycol excess equivalent to 15 percent vermiculite which would certainly show on the x-ray patterns.

Table 4 summarizes the results of differential thermal analysis, x-ray diffraction analyses, and potash, glycol and cation exchange capacity determinations for the -2μ fraction. The 7 and 8 percent illite-vermiculite respectively, in Sample 23 should more properly be considered as 15 percent hydrous mica of illite-

 TABLE 4

 PERCENT COMPOSITION OF -2µ FRACTION

 OF SAMPLES 22-25

 (in percent by weight)

	-	-			
	Hallowsita		Hydro		
Sample	(2H ₂ O)	Gibbsite	lllite	Vermi- culite	Fe2O3
22 23 24 25	60 55 50 70	32 13 12 nil	nil 7* 23 18	none 8* 0 0	nil 11 11 —

* See text for explanation.

vermiculite type where the illite, vermiculite ratio is 1:1.

Petrographic examination of the 0.10–0.25mm. sand fraction revealed only traces of accessory minerals and no feldspars. Even in Sample 22, feldspars were completely decomposed. Optical properties (light brown in color, N_y 1.60–1.64, and biaxial negative with a very small 2E) of the mica flakes indicate hydrobiotite. The amount of mica and quartz was determined from grain counts where the total number of grains counted was approximately 500 for each sample. The coarse and finer sand appeared to have about the same proportion of mica and quartz as the 0.12–0.25-mm. fraction, but grain counts were made only on the 0.10 and 0.25-mm. fraction.

The mica is not a true mica but is a degraded mica as evidenced by the x-ray, potash, and cation exchange capacity data. X-ray data in Table 5 show that the mica flakes range from the very complex mixed layers of Sample 24 to essentially hydrobiotite in Sample 25. Data given in Tables 5 and 6 were obtained on mica

Sample 23				Sample 24				Sample 25			
K + Gt		Mg + G†		it No treatment		Mg -	⊢ G†	No trea	atment	Mg +	Gt
d	I	d	I	d	I	d	I	đ	I	d	Ι
10.0 5.0 4.46	$\frac{10}{3}$	$ \begin{array}{c} 14.0\\ 10.0\\ \hline 5.0\\ 4.47 \end{array} $	$\frac{\frac{4}{7}}{\frac{2}{7}}$	25.3 11.5 9.9 	7 7 7 1	$26.0 \\ 13.6 \\ 11.7 \\ 10.1 \\ 6.0 \\ 5.4 \\ 4.47 \\ $	$ \begin{array}{r} 10 \\ 4 \\ 10 \\ 6 \\ 2 \\ 2 \\ 2 \end{array} $	10.8 5.0 4.47 —	$ \begin{array}{c} 10 \\ 2 \\ 4 \\ \end{array} $	10.8 5.0 4.47	

TABLE 5 X-RAY DATA FOR MICA FLAKES FROM SAMPLES 23, 24, AND 25*

* Lines for d < 4.47 omitted.

+ K + G = potassium saturated plus glycerol treatment; Mg + G = magnesium saturated plus glycerol treatment; d = d value in A. I = relative diffracted intensity estimated visually.

	Sample Number				
	22	23	24	25	
1. Potash Content (Percent K ₄ O) a. Whole soil b. Mica flakes c2µ 2.]Cation Exchange Capacity	$\frac{1.1}{\text{nil}}$	$1.6 \\ 4.2 \\ 0.4$	$1.7 \\ 3.7 \\ 1.4$	$0.5 \\ 1.9 \\ 1.1$	
 (mEq./100 g.) a. Whole soil (observed) b. Whole soil (calculated) c. Mica flakes (observed) 3. Glycol Retention (mg./g.) 	9 7	21 20 18	14 12 18	11 10 15	
a. -2μ 4. Mica	34	50	50	60	
b. Percent in whole soil com-	67	67	50	50	
puted 1. From K ₂ O 2. Relative to quartz	24 27	36 38	33 23	25 25	

TABLE 6DATA FOR SOUTH PIEDMONT SOILS*

* See text for explanations.

flakes that had been washed with water to remove the kaolin. X-ray diffraction of the mica flakes from Sample 25 prior to water washing indicated kaolin and hydrobiotite. The 20 to 74μ size fraction of Sample 25 gives an x-ray pattern identical with that for the large mica flakes. Differential thermal analysis of the 20 to 74μ fraction showed that this coarse silt contained only 10 percent less kaolin than the -2μ fraction. Since the kaolin component is so abundant in the coarser fractions, the mineral analyses were performed on the whole soil.

Halloysite (2H₂O), gibbsite, and quartz percentages in the whole soil are obtained directly from the thermogram. Hydrous mica in the whole soil is divided into two forms; hydrous mica (illite and vermiculite) in the clay size fraction and weathered mica or hydrobiotite in the coarser fractions. The amount of hydrous mica in the whole soil is obtained in the usual manner by the relative amplitude of the 600° C endotherm on the whole soil to that of the -2μ fraction. Mica percentage was determined from the amount of mica present relative to quartz in the 0.10-0.25 mm. fraction and from the potash content of the whole soil. The potash content of the whole soil was corrected for the K_2O present in the clay size hydrous mica. Also, it was assumed that the mica in Samples 22, 23, and 24 contained 4 percent K_2O and in Sample 25, 2 percent K_{2O} (see Table 6). Both methods give comparable mica percentages. The percentage recorded in Table 7 is the average rounded off to the nearest five. The reliability of the calculated mineral percentages is at least somewhat justified by the close correspondence of the calculated and observed cation exchange capacity in Table 6.

Differential thermal analysis of Soil 26 (see Figure 5) indicates that the sample does not contain clay. Thermograms determined after various pretreatments, fraction, removal of organic matter, or removal of free iron oxides, were essentially the same as on the original soil. X-ray diffraction patterns of oriented aggregates revealed very poorly crystallized kaolin, and hydrous mica of the illite-montmorillonoid type. From the potash content $(0.7 \text{ percent } K_2O)$ and the glycol retention (256 mg./g.) of the -2μ fraction 10 percent illite and 85 percent montmorillonoid may be calculated. X-ray data support this calculation but differential thermal analysis does not and no allowance has been made for the kaolin indicated on the x-ray patterns. In addition, if the percentage of montmorillonoid is this high, then the cation exchange capacity of the soil should be 65 mEq./100 g, but the measexchange ured cation capacity is 27mEq./100g.

There is less than 5 percent sand coarser than 0.074 mm. whose composition is predominately amphiboles. Appreciable amounts of volcanic glass fragments can be observed along with the accessory minerals, sphene, garnet, and zircon. An indication of the severe weathering in this volcanic soil is revealed from the petrographic study. Mineral grains that exhibit the form and zone appearance characteristic of feldspars are, in fact, wholly composed of gibbsite. Another unusual feature of this soil is that it could only be dispersed at a pH of 3.

ENGINEERING SIGNIFICANCE OF RESULTS

General

In spite of the difficulties and limitations of determining the soil composition and then correlating this composition with the engineering behavior of soil, the study described in this and earlier papers is producing qualitative and semiquantitative information of importance to the soil engineer. Some of these findings are discussed in the remaining part of this section.

Nature of Fines

Table 7 lists the complete compositional analysis and a summary of the engineering properties of 26 soils. The following list indicates the percentage of the 26 soils in which each of the following components was found:

Quartz	85%
Fe_2O_3	73%
Illite	73%
Montmorillonoid	50%
Carbonates.	42%
Organic Matter	42%
Feldspars	35%
Kaolinite	20%
Chlorite	15%
Halloysite	15%
Gibbsite	15%
Vermiculite	8%

Because of the abundance of quartz as a rockforming mineral and because of its high resistance to physical and chemical weathering, the very common occurrence of quartz as a soil mineral is to be expected. Feldspar, also a very abundant rock-forming mineral, is generally a component of fine grained soils; the concentration is generally low because most feldspar species have a low resistance to physical and chemical weathering. The occurrence of Fe₂O₃, carbonates, organic matter, and halloysite was found to be more common than would normally be expected, and kaolinite, less common.

Cementation of Fines

In the second paper of this series (2), the authors discussed the occurrence and engineering importance of the cementation of soil fines. This study of cementation is continued for the soils described in this paper as indicated in Figure 6 which is a plot of the percentage clay size versus the percentage of minerals normally considered "clay minerals." In Figure 6, the number by each point indicates sample number and the diagonal line represents the condition where the material less than 2 microns is all clay and the material larger than 2 microns is all non-clay minerals. Points falling to the right of the diagonal represent samples having cementation or aggregation of fines or clay mineral individual particles larger than 2 microns-the last is not too common. A rather unusual aggregation of fines occurs in Soils 22



Figure 5. Thermograms for Soil 26, red clay from Tokyo, Japan. Treatments: -74μ –Fe and O.M., treated with Na₂S₂O₄ to remove free iron oxides and with H₂O₂ to remove organic matter; -2μ less than 2 micron fraction; -2μ –Fe, less than 2 micron fraction, treated with Na₂S₂O₄ to remove free iron oxides.

	F	Kemarks	"Extraordinar- ily" high dry strength 49.7 %	Ignition loss = 63% Soil occurred in 1 foot stratum, which was over- lain by 20' peat and underlying by 2' peat. Com- position analyses on minus #60 sieve portion.	Ref: Mitchell (16)	Ref: Mitchell (16)	Ref: Mitchell (16)	Ref: Mitchell (16)	Severe floccula- tion of soil in water slurry.	
	Engineering Properties Field vane shear strength = 0.125 T/ft. ² Lab vane shear strength = 0.060 T/ft. ²		Field vane shear strength = 0.125 T/ft.^2 Lab vane shear strength = 0.060 T/ft.^2	Vane shear strength = 0.12 T/ft.^2	$\begin{array}{l} V_{u} = 1130 \ \mathrm{psf}, \sigma_{c} = 2.7 \ \mathrm{kg./cm.^{2}} \\ V_{r} = 500 \ \mathrm{psf} \\ k_{u}/k_{r} = 0.87 \\ k_{z}/k_{z} = 3 \end{array}$	$k_x/k_x = 4$	$V_{r} = 1730 \text{ pst, } \sigma_{r} = 2.2 \text{ kg./cm.}^{2}$ $k_{r}/k_{r} = 4$ $k_{r}/k_{r} = 4$	$V_r = 1800$ $V_r = 740$	U = 0.8 to 1.0 kg./cm. ³ Dikes failed 2 to 3 years after construction.	U = 1.3 kg./cm. ³ Dam failed during construction when fill was 50 to 55' high-design height = 70'
N AND PROPERTIES	Atterberg Limits and	Percent	$w_n = 680$ $w_1 = 537; = 228$ after $w_p = 273; = 148$ oven drying	$w_{n} = 650$	$w_n = 23$ $w_1 = 30$ $w_p = 17$	$w_n = 19.1$ $w_p = 25$ $w_p = 25$	$w_n = \frac{40}{74}$ $w_l = 74$ $w_p = 26$	$u_n = 51$ $w_1 = 79$ $w_2 = 26$	$w_n = 46$ $w_1 = 100$ $w_p = 34$	<i>w</i> _n = 36
OLLISOA	/eight, of	0.074 mm.	= 60 = 15	= = 55 55	= 30 = 10 = 35 = 3.7	= 40 = 25 = 3.3	= 20 = 15 = 0.9	1.0 1.0 1.0 1.0 1.0 1.0 1.0	= = 40) = 2 2 3	= 50) = 75
SULL CUM	Composition, by W	Portion Finer than	Organic matter Quartz Feldspars	Organic matter Aragonite	(Illite Montmorillonoid Quartz Fe2O3 Organic matter	(Illite Montmorillonoid Quartz Fe20s Carbonates	(Illite Montmorillonoid Quartz FesOs Organic matter	(Illite Montmorillonoid Quartz Carbonates Fe±Oa Organic matter	(Illite Montmorillonoid Calcite Organic matter	(Illite Montmorillonoid Organic matter
	Particles than:	0.002 mm.	16 organic tion)		20	47	40	20	1	64
ĺ	Percent Finer	0.074 mm.	91 (or inc port		80	96	100	85		85 73
	Supplied By	for particular	IIamilton Gray	Hamilton Gray					Prairie Farm Rehabilitation Administra- tion	Prairie Farm Rehabilitation Administra- tion
	Soil		Organic silt from swamp neur Freedom, Maine	Organic silt from Burn- Maine Swamp. Maine	Reddish brown silty clay from Cincinnati, Ohio	Very stiff fis- sured yellow clay from Texas	Stiff dark grey clay from Bayou Coco- drie Control Structure, Louisiana	Stiff grey clay from New Or- leans, Louisi- ana	Clay from foun- dation of Seven Sisters Dikes, Mani- toba, Canada	Clay from foun- dation of North Ridge Dam, Alberta, Canada
	Sam- Dle	Ňo.		3	ę	4	τ	ç	~	œ

TABLE 7 SOIL COMPOSITION AND PROPER

grade soil for italies described 1 "Cooperative tudy of Strue- ral Design of conrigid Pave- conts," Public coats, Vol. 25, coats, Vol. 25,	grade material aving high to ery high frost usceptibility tef: ACFFL 1950)	own locally as expansive clay"	own locally as expansive clay"	f: Mitchell (16)	f: Mitchell (16)	f: Mitchell (16)	f: Mitchell (16)	bgrade materiul aaving frost sus- eptibility classi- ication of very nigh. Ref: ACFEL (1952- 953) (18)
13 8.80 34 6443 S	S S S S S S S S S S S S S S S S S S S	K,	М. М.	Re	Re	Re	Re	s
$w_{\rm opt} = 16\%$ $\gamma d \max = 113 {\rm lb} / {\rm ft} {\rm s}$				$V_{xx}^{1} = 900 \text{ lb./ft.}^{2}$ $k_{xx}/k_{x} = 0.9$ $k_{xx}/k_{z} = 2.2$	$\begin{array}{ll} V_{v} &= 970 \ \mathrm{Ib./ft.}^{2} \\ V_{\tau} &= 390 \ \mathrm{Ib./ft.}^{2} \\ k_{u}/k_{\tau} &= 3.0 \\ k_{x}/k_{z} &= 2.7 \\ k_{x}/k_{z} &= 3.8 \ \mathrm{kg./cm.}^{2} \end{array}$	$ \begin{aligned} & \prod_{r_{T}}^{u} = 350 \ \text{Ib}, /\text{ft},^{2} \\ & \sum_{r_{T}}^{r_{T}} = 651 \ \text{Ib}, /\text{ft},^{2} \\ & k_{T}/k_{T} = 2.3 \\ & \sigma_{c} = 0.5 \ \text{kg}, \text{com}.^{2} \end{aligned} $	$V_{x} = \frac{910}{V_{x}} \frac{1b_{x}(t_{x}^{2})}{1b_{x}(t_{x}^{2})} = \frac{910}{4.0} \frac{1b_{x}(t_{x}^{2})}{1b_{x}(t_{x}^{2})}$ $k_{x}(t_{x}^{2}) = \frac{2.9}{2.9}$	
$w_p = \frac{45}{23}$	$w_1 = 24.4$ $w_p = 15.6$ $w_1 = 46.6$ on portion $w_p = 24.3$ mm. 0.074	$w_1 = 55$ $w_p = 25$ $w_s = 13$	$w_1 = 45$ $w_p = 21$ $w_s = 10$	$w_n = 41.5$ $w_1 = 48.8$ $w_p = 21.0$	$w_n = 39.7$ $w_1 = 57.9$ $w_p = 20.6$	$w_n = 61.3$ $w_1 = 56.0$ $w_p = 22.0$	$w_n = 53.6$ $w_1 = 55.2$ $w_p = 22.1$	$w_p = 25$ $w_p = 18$
2 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0	2 2 2 3 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	$= 45 \\ = 10 \\ = 25 \\ = 2.3$	= 35 = 2.5	+ 10 + 10 + 10 + 10	= 55 = 10 = 10	1.5 1.5 1.5 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0	100 100 100 100 100 100 100 100 100 100	= = = = = = = = = = = = = = = = = = =
Montmorillonoid Illite Feldspurs Fe ₂ O ₃	(Montmorillonoid Illite Quartz Feldspars Carbonates Organie matter	(Montmorillonoid (Illite Pe2Os Fe2Os	(Montmorillonoid (Illite Quartz Feldspars Fe20:	(Illite (Chlorite Quartz Feldspars Fe2O3	(Illite (Chlorite Quartz Carbonates	(Illite Cchlorite Carbonate Quartz Feldspars Fe2Oa	(Illite (Chlorite Carbonate Quartz Feldspars Fe2Oa	(Illite Vermiculite Dolomite Feldspars Quartz FeeOa
1	15	45	39	48	64	56	78	2 ++
 22	40	99	09	06	100	100	100	15
Bureau of Pub- lic Roads, Washington	Arctic Construc- tion and Frost Effects Lab- ratory, Corps of Engineers, Boston, Mas- sachusetts	National Build- ing Research Institute, South Africa	National Build- ing Research Institute, South Africa	D. W. Taylor, MIT				Arctic Construc- tion and Frost Effects Labo- ratory, Corps of Engineers, Boston, Mas- sachusetts
Clay from Hy- bla. Virginia, near Washing- ton	Clayey sand from Lowry Air Force Base, Denver, Colorado	Sandy clay from Vereeniging, South Africa	Sandy clay from Vereeniging, South Africa	Silty grey clay from Port- land, Maine	Grey clay from Chicago, Illi- nois	Dark grey clay from Beau- harnois, Que- bec, Canada	Dark grey clay from St. Law- rence River	Silty, clayey gravel from Clinton County Air Force Base, Wilmington, Ohio
<u>م</u>	10	11	12	13	14	15	16	17

		Remarks	Frost susceptibil- ity classification of low to high. Ref: ACFEL (1952- 1953) (18)	This soil used for clay blanket: Permeability at $w_{opt} < 10^{-8}$ cm./ sec.		This soil used for clay blanket and dam core: Per- meability at w_{opt} = 1 × 10 ⁻⁹ cm./	Ref: ASCE Sep. 425, "Soil and Geologic Fea- tures of the Bu- ford Project," W. V. Conn, March 1954 (19)	Ref: ASCE Sep. 425, "Soil and Geologic Fea- tures of the Bu- ford Project," W. V. Conn, March 1954 (19)	Ref: ASCE Sep. 425, "Soil and Geologic Fea- tures of the Bu- ford Project," W. V. Conn. March 1954 (19)
	Engineering Properties $\gamma d = 133.1 \text{ Ib./ft.}^2 \text{ Mod. AASHO}$ $w_{\text{opt}} = 9.4\%$		$\gamma d = 116 \text{ lb./ft.}^3$ $w_{\text{opt}} = 15\%$	$U = 1200 \text{ lb./ft.}^2$ (undisturbed) $U = 1080 \text{ lb./ft.}^2$ (remolded)	$\gamma d = 108 \text{lb./ft.}^3$ $w_{\text{opt}} = 21\%$		$\gamma d_{\rm max} = 87 {\rm lb./ft.}_3$ $w_{\rm opt} = 29\%$		
	Atterberg Limits and	Ivatural water content in Percent	$w_p = 24.7$ $w_p = 16.6$	$w_1 = 33$ $w_p = 18$	$\begin{array}{l} w_n = 23\\ w_1 = 37\\ w_p = 19\\ w_s = 19, 2\\ w_s = 15.2 \ (\text{undisturbed})\\ w_s = 14.8 \ (\text{remolded}) \end{array}$	$w_1 = 58$ $w_2 = 24$ $w_3 = 15$ $w_3 = 15$ to 25		$w_p = 49$ $w_p = 40$	
	.Composition, by Weight, of	Portion Finer than 0.074 mm.	$ \begin{cases} IIlite &= 35 \\ Vermiculite &= 7 \\ Kaolinite &= 25 \\ Quartz &= 15 \\ PeO3 \\ PeO3 \\ Organic matter &= 1.4 \end{cases} $	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	[II]lite15Montmorillonoid20Kaolinite20Kaolinite20Uartz10Feldspars6Organic matter3	Halloysite $(2H_2O) = 20$ Wenthered mica = 25 Gibbsite = 10 Quartz = 50	Halloysite $(2H_2O) = 35$ Hydrous mice $= 10$ Weathered mice $= 35$ Ouartz $= 15$ Gibbsite $= 5$ Fe2Oa	Halloysite $(2H_{2}O) = 20$ Weathered mica = 15 Weathered mica = 30 Quartz = 30 Gibbsite = 3 FeeOa = 2 FeeOa
	it Particles er than:	0.002 mm.	=	16	37	52		m	
-	Fin	0.074 mm.	32	47	8	62	22	17	
	Supplied Bv		Arctic Construc- tion and Frost Effects Labo- ratory, Corps of Engineers, Boston, Mas- sachusetts	Creole Petro- leum Corpora- tion, Venezu- ela	Creele Petro- leum Corpora- tion, Venezu- ela	Creole Petro- leum Corpora- tion, Venezu- ela	W. V. Conn. Corps of Engi- neers, Atlanta, Georgia	W. V. Conn, Corps of Engi- neers, Atlanta, Georgia	W. V. Conr, Corps of Engi- neers, Atlanta, Georgia
	Soil		Clayey gravelly sand from Greenland (TP-244)	Red sandy clay from Amuay, Venezuela	Blue clay from Amuay, Vene- zuela,	Brown sandy clay from Si- burua, Vene- zuela	Partially weath- ered granite gness from South Pied- mont	Red clay from South Pied- mont	Red clay from South Pied- mont
	Sam-	Ňo.	18	19	20	21	53	33	24

TABLE 7-Continued

	$\gamma d = 97 \text{ lb./ft.3}$ $w_{\text{opt}} = 23\%$
	Not plastic
Halloysite $(2H_2O) = 30$ Hydrous mica = 10 Hydro biotite = 25 Quartz = 25 Fe $_2O_3$ = 15	Very poorly crystallized kaolin. Hydrous mica de- veloped on volcanic ash. Gibbsite = 15 Fe ₃ O ₃ = 12 Organic matter = 2
9	
40	
G. A. Sowers, Georgia Tech.	
Silty sand from near Atlanta, Georgia	Red clay from Tokyo, Japan
25	26

() = Minerals enclosed are interstratified. $V_u = Undisturbed shear strength by vane test. <math>V_r$ = Remolded shear strength by vane test. k_u/k_r = Ratio of undisturbed to remolded permeability. γ_c = Maximum composition pressure of sample in nature. k_x/k_r = Ratio of horizontal to vertical permeability in undisturbed sample. U = U monitors is trength γ_c max = Maximum composition results. $V_i = 0$ monitors in nature. k_x/k_r = Ratio of horizontal to vertical permeability in undisturbed sample. U = U monitors is trength γ_c max = Maximum composition values. $V_i = 0.1$, 10 ± 1 V_{real} is interval. $V_{real} = 0$ point mode to $V_i = 0$ point -3 layers. $w_{opt} = 0$ ptimum water content. V = U monitors in the function rates $V_i = 0.1$, 10 ± 1 $V_{real} = 0.1$, 10 ± 5 , 90 ± 5 $V_{real} = 0.1$, 10 ± 5 , 90 ± 5 $V_{real} = 0.1$ $V_{real} =$

100 NON CLAY FINES 80 16 •8 L. 60 21 13 × z II. ₹ ∾40 FINER THAN AGGREGATION OF FINES 20 19 indicates sample 10₊₁₈ listed in table .25 40 60 80 20 īnn CLAY MINERAL CONTENT IN %

Figure 6. Comparison of clay composition and clay size.

and 25, where a large percentage of the halloysite appears in the sand size, because the halloysite is firmly cemented to sand-size mica flakes.

The samples studied in this paper exhibited considerably less aggregation than those in the 1954 study (1). This fact is explainable by the composition and geological history of the various soils. Aggregation or cementation is generally present in marine sediments and residual soils, especially those which have been subjected to high consolidation pressures and/or have been leached by ground water. Soils of glacial origin, such as Sample 16 often have particles finer than 2 microns which are not composed of phyllosilicate clay. Sample 16, a clay from the St. Lawrence River, contains carbonates, quartz, and feldspars in the -2micron size portion.

The degree of fine aggregation and the strength of these aggregates must, of course, be considered when interpreting particle size and compositional data. For example, Soil 25 contains considerable "clay mineral" but is not plastic; on the other hand. Sample 16 is more plastic than would be expected from its compositional analysis. A comparison of a particle size analysis on a clay, in which the clay was given no chemical or mechanical dispersion with a corresponding analysis on the same clay in which complete dispersion was obtained, might be useful to the engineer. An intelligent interpretation of the conventional particle size analysis of a clay, where the degree of mechanical and chemical dispersion is unknown, is certainly difficult.

Relations Between Composition and Properties

The data presented in Table 7 show that the soil engineer's general suspicion of montmorillonoid is justified. The very high sensitivity of montmorillonoids to water presents the soil engineer problems associated with stability and volume change. Soils 7 and 8, for example, which were involved in dam failures, both contained significant percentages of montmorillonoid. Sample 7 flocculated so severely in the hydrometer analysis that the Prairie Farm Rehabilitation Administration was unable to obtain a particle size analysis below the silt size. Samples 11 and 12 from South Africa, both containing significant quantities of montmorillonoid, are known locally as expansive clavs and cause severe problems because of volume changes due to changes in climate. Both of these soils have very low shrinkage limits which suggest that the soils would undergo marked volume changes with changes in moisture.

Samples 23 and 25 both contain dehydrated halloysite. [The samples were dry when received, so they could have been hallovsite (4H₂O) at natural water content.] The relatively low compacted density of these two soils is expected in view of this hallovsite content (3). Hallovsite soils usually have low maximum compacted densities; their permeabilities at maximum density are lower than would be expected from their Atterberg limits. The strength of compacted hallovsite is not as high as occurs with many soils of equal plasticity. These facts do not mean, however, that hallovsite is necessarily a poor material for an engineering use, such as dam fill. No evidence has yet been presented to the authors of a case where halloysite had unusual field performance or was the cause of an engineering failure. Density is not a fundamental soil property, but is usually a reliable indicator of such fundamental properties as strength, permeability, and compressibility. Hallovsite is an example of a soil which can have a low density but not have the undesirable fundamental properties that would be expected from this low density.

As already noted, organic matter occurred in a surprisingly large percentage of the soils; however, only two soils, Numbers 1 and 2, contained enough organic matter to be called "organic soils." The data on Soil 1 illustrate the well known fact that drying can have a



tremendous influence on the properties of an organic soil. The liquid limit of Sample 1 on the undried material was 537 percent and the corresponding value on the dried soil was 228 percent. The organic content determination made by chemical analysis and ignition loss are in good agreement on Sample 1. This good agreement is explained by the fact that the nonorganic parts of Sample 1, quartz, and feldspars, are not decomposed by the heat used for the ignition loss determination and do not contain significant quantities of adsorbed moisture. Ignition loss is a very poor measure of organic matter in soils which have minerals such as carbonates that can be decomposed by heat or minerals such as montmorillonoids that have large quantities of adsorbed moisture which are driven off by the heat. The influence of carbonate minerals on the percentage organic matter determined by ignition loss is shown by Sample 2 where ignition loss indicates 63 percent organic matter whereas the organic matter content is 36 percent.

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