

## Composition and Engineering Properties of Soil (II)

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THIS paper, a continuation of the authors' paper of last year, describes research on the composition and properties of soil. Analyses of over 40 soils from widely scattered parts of the world are discussed in relation to their properties. Several general relationships between soil composition and behavior are drawn.

The difficulties of making complete soil-composition analyses are discussed by the use of specific examples taken from the soils studied. A pattern of tests is presented.

The test results show the presence of vermiculite, halloysite, attapulgite, and carbonate minerals.

● THE engineering behavior of a soil is more dependent on the composition of the soil than on any other characteristic. The reasons this important fact is not exploited more by the soil engineer are twofold: (1) the difficulty of making compositional analyses and (2) the lack of knowledge of the relationships between properties and composition. While the complete mineral analysis of many soils requires little effort, the analysis of some of the plastic soils can be troublesome and time consuming. In general, compositional data on fine-grain soils are of more value to the engineer than are data on coarse-grain soils; unfortunately the analysis of these fine-grain soils is usually more difficult than the analysis of the coarse-grain ones.

The prediction of the engineering behavior of a soil from its composition is based on the principle that the contribution to a given property of any given soil component is in proportion to the percentage of that component in the soil mass (or that the deviations from proportionality are known). For example, the liquid limit of a soil composed of 50 percent montmorillonite and 50 percent kaolinite would be 0.5 times the liquid limit of montmorillonite plus 0.5 times the liquid limit of kaolinite. This fundamental principle involves several assumptions which are met to varying degrees in different soils. The most important of these assumptions are that: (1) the interactions among the soil components are known; (2) the minerals in the soil are similar to standard minerals which are used to determine

the basic properties; and (3) the effect of impurities or trace components in the soil can be determined.

There can be both chemical and physical effects of one component on another. For example, we can mix a sand which has a compacted maximum dry density of 100 pcf. with a clay which has a maximum compacted dry density of 100 pcf. and get a mixture which has a compacted dry density of 120 pcf. The clay particles are small enough to fit into the voids of the sand to an amount which could hardly be predicted from the mineralogical composition of the sand and the clay. Colloidal principles and ion-exchange fundamentals suggest many possible chemical reactions between soil components. For example, if calcite is added to a sodium montmorillonite, there may well be an exchange of calcium, furnished by the calcite, for sodium on the montmorillonite as well as cementation of the clay particles by the calcite.

Winterkorn (16) has presented dry-tensile-strength data on various mixtures of two soils. The dry strength of Putnam clay was 90 psi. and the strength of Cecil clay was 50 psi., but a mixture of 90 percent Putnam and 10 percent Cecil clay did not have a tensile strength of 86 psi. but a strength of 167 psi.

Studies on the engineering properties of single minerals usually employ pure, highly crystalline minerals; however, there is an increasing amount of evidence that the minerals in soils are often poorly crystallized. The engineering properties of the pure, well-

crystallized minerals used as standards may be only approximately equal to the corresponding properties of the same minerals when in a low crystalline form.

Free iron oxides and organic matter are two materials which can have effects on the engineering properties of soil far out of proportion to their percentage of the composition. The effects of these two and other soil trace components depend on the soil in which they are present. For example, a certain percentage of organic matter may have a minor effect on a sand, (see Sample 1) while the same percentage could have a considerable effect on the properties of halloysite.

The preceding paragraphs indicate that it is unreasonable to expect that the soil engineer will be able to delineate completely the engineering behavior of a soil knowing its composition. On the other hand, the present state of knowledge of soil technology is such that the average engineer could employ compositional data considerably more than he now does. The value of compositional data to the engineer will naturally increase as this young science advances. At the present time a complete compositional analysis seems justified on a soil involved in a major construction job, since such information serves as an excellent means of classifying the soil, aids in planning other engineering tests, and often permits the prediction of unusual behavior which might not otherwise have been expected. On even small jobs the engineer might be wise to have compositional studies made on the soil if the standard engineering tests indicate some unusual behavior.

Data on the relationships between mineralogical composition and soil properties can be obtained by one of two approaches. The first approach consists of determining the engineering properties of known clay minerals alone or as added components to soils. The second approach consists of making mineralogical analyses on soils of known properties and drawing correlations between composition and properties. The most-complete study involving the first approach was made at Cornell University under the sponsorship of the Engineer Corps (17). Employing the second approach, this paper presents mineral analyses on 40 soils from all over the world. These and similar studies contribute to knowledge by: (1) giving information on the

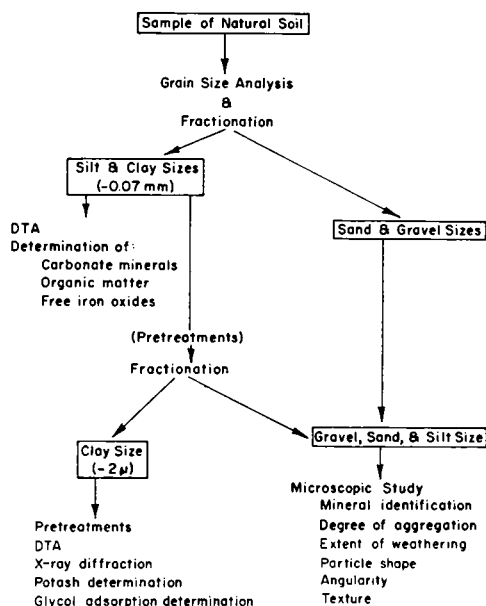


Figure 1. Flow sheet for mineral analysis.

occurrence of different minerals in soils; (2) permitting general correlations between compositions and behavior to be drawn; and (3) indicating those minerals which should be subjected to tests to determine their engineering behavior alone or as soil components.

## MINERAL ANALYSIS

### Test Procedures

The flow sheet in Figure 1 indicates the general analysis scheme. A thermogram<sup>1</sup> on the  $-0.07$ -mm. fraction is obtained as the first step in analysis, because there are instances where this thermogram indicates the complete composition (see, for example, thermograms of Samples 6 and 14). In any case, the thermogram on the silt and clay portion is a valuable guide as to what additional tests and special treatments might be most useful. Determination of carbonate minerals is generally made from the carbonate peaks on the thermogram. Where carbonate minerals are poorly crystallized or a mixture of carbonates occurs making interpretation of

<sup>1</sup> A thermogram is the plot of  $\Delta T$  versus  $T$  obtained by differential thermal analysis (DTA). Details of this procedure have been previously described by Lambe (7).

the thermal peaks difficult, the loss in sample weight which results when the soil is treated with 2N acetic acid is ascribed to carbonate minerals. Although not as accurate as Scholtenburger's method (15), the acetic-acid method has been found to be accurate to  $\pm 10$  percent on inorganic soils, which is considered satisfactory.

Organic matter is determined by Peech's method (12). A solution of potassium dichromate and sulfuric acid oxidizes the organic matter and the unreacted dichromate is then titrated with ferrous sulfate solution. Free iron oxides are brought into solution by the use of Mackenzie's (9) extraction procedure and the iron determined by the use of the o-phenanthroline color reaction recommended by Peech (11). Results of the determinations of organic matter and of free iron oxide are expressed in percent of the dry soil weight ( $-0.07$ -mm. fraction).

Determinations of carbonate minerals, organic matter, and free iron oxides are performed prior to preparation of the clay fraction for analysis, because these determinations dictate what pretreatments will be required.

Whether pretreatments are performed prior to, or after, fractionation of the clay, is determined by how much organic matter, carbonate minerals, or free iron oxide are present. For example, separation of the clay minerals from Sample 11 would be rather difficult if the major portion of the calcite had not been first removed. Pretreatments used are: (1) removal of carbonate minerals by the use of acetic acid, (2) removal of organic matter by the use of 15 percent  $H_2O_2$ , (3) removal of free iron oxides by the use of the Mackenzie extraction procedure. After pretreatment the fractionated  $-2\text{-}\mu$  clay is made homoionic with respect to calcium by the use of calcium acetate; the excess salt is removed by alcohol washing.

Tests made on the clay fraction include DTA, x-ray diffraction, potash determination, and glycol retention. The x-ray patterns were obtained with an evacuated powder camera of 114.6-mm. diameter and unfiltered chromium radiation. Treatments used in conjunction with x ray for positive identification of mineral species are those of Brindley (2). The method for potash determination is essentially like that of Gammon (6). Glycol

retention measurements are made following Dyal and Hendricks' procedure (5) except that a free glycol surface is included with each batch because tests have shown that a definite equilibrium value can be obtained by this procedure.<sup>2</sup> Methods of calculating the percentages of the various clay minerals are discussed in Section C.

Results of the clay-fraction analysis are reported in Table 3 in terms of the combined silt and clay fractions. For example, if DTA on the combined silt and clay, and clay fractions gave an endothermic peak about 600 C. with an amplitude of 3 and 5 cm., respectively, and the detailed study of the clay fraction revealed it to be 80 percent illite, then by the use of the DTA data for the combined silt and clay the illite percentage for the  $-0.07$ -mm. portion of the soil would be 50.

#### Definition of Terms

Since the identification of minerals in fine-grained soils involves the assumption that the properties of the soil minerals are identical with those of a set of reference minerals, it is imperative that the reference minerals be defined and their properties given.

*Kaolin* is the mineral group which includes kaolinite, halloysite, dickite, and nacrite. Kaolinite and halloysite are the commonest species of this group and their identification has been thoroughly discussed by Bramao, et al, (1) and Sand and Bates (14).

*Montmorillonoid* is the mineral group which includes montmorillonite, nontronite, hectorite, and saponite. Nontronite and montmorillonite are the commonest species of this group.

*Hydrous mica* is the mineral group which includes all forms of clay mica, both with and without interstratification.

*Illite* is the mineral group within the hydrous mica group for which the x-ray patterns show no changes with either mild chemical or heat treatment.

*Chlorite* is the mineral group which includes clinochlore, prochlorite, penninite, ripidolite, thuringite, and leuchtenbergite.

*Vermiculite* and *attapulgite* are specific minerals about which there is likely to be little ambiguity.

<sup>2</sup> Unpublished data of M.I.T. Soil Stabilization Laboratory.

TABLE 1  
GLYCOL RETENTION AND POTASH DATA FOR  
REFERENCE MINERALS<sup>a</sup>

Mineral	Source	Glycol Retention		K <sub>2</sub> O
		mg./g.	%	
Kaolinite	Bath, S. C. <sup>b</sup>	20	0	
Halloysite	API H-12 <sup>c</sup>	50	0	
Montmorillonoid (average)	API H-33a, H-25 <sup>c</sup>	280	0	
Illite	API H-35 <sup>c</sup>	80	6.0	
Attapulgite	Attapulcus, Ga. <sup>b</sup>	150	0	
Vermiculite	M.I.T. Geology Dept.	170	0	
Chlorite	Wards Natural Science Estab.	35	0	

<sup>a</sup> Data obtained on  $-2\mu$ , organic matter, free calcium-saturated material.

<sup>b</sup> Samples from API type localities but the actual API number is not known.

<sup>c</sup> API number refers to Reference 20.

Criteria for positive identification of the above minerals and groups are largely based on the procedures recommended by Brindley (2). Specific cases will be considered in Section C.

Glycol retention and potash data for the reference minerals are given in Table 1. Thermograms obtained on the thermal analyzer of this Laboratory have been published for the reference minerals (7). The *d*-value tables of Brindley (2) and standard patterns of this laboratory were used for the interpretation of the x-ray patterns.

#### Discussion of Mineral Analyses

There is little question that clay minerals play an important role in determining soil properties. For this reason, the 40 samples analyzed are divided into three major groups depending on the nature of the  $-2\mu$  fraction. Within each major division the soils are further separated into groups of similar mineralogical character. The clay mineral percentages given in Table 3 in many instances indicate the relative proportion of the minerals present as determined on the clay fraction and should not be construed as an indication of high accuracy.

*Non-Clay-Mineral Fines.* The thermogram of Sample 1 (Fig. 2) showed no clay minerals and when the  $-2\mu$  fraction was x-rayed only reflections of quartz and feldspars were observed. Both the x-ray data on the clay size material and the petrographic data on the silt indicated quartz and feldspars in about equal abundance. Since the DTA indicates 35 percent quartz, the percentage of

feldspar must be about 35. The clay content of Sample 1 is so low that even with an organic matter content of 3.8 percent the soil is nonplastic.

Samples 2 and 3 are classed as organic soils; thermograms of the organic matter free portion of these soils indicate no clay minerals. Petrographic examination of the clay size material from Sample 3 showed it to be diatomaceous earth. X-ray diffraction of the clay size from Sample 2 gave poorly defined reflections attributable to boehmite and goethite. From the thermogram of Sample 2 the percentage of hydrous iron and aluminum oxides was estimated.

Sample 4 is predominately iron oxides as evidenced by the chemical analyses and the strong  $\alpha\text{Fe}_2\text{O}_3$  and magnetite reflections on the x-ray-diffraction patterns. It might be mentioned that a free-iron-oxide determination on Sample 4 showed 60 percent  $\text{Fe}_2\text{O}_3$  as free iron oxides.

*Monoclay-Mineral Fines.* The monoclay-mineral soils are about equally divided among the three major clay minerals, kaolinite, illite, and montmorillonoid.

Thermograms of Samples 6 and 8 are clearly those of a kaolin mineral. The slope ratio of the 600-C. peak and the x-ray patterns both indicated that the kaolin mineral is kaolinite. By the use of DTA and x-ray data, Sample 7 was clearly identified as kaolin and boehmite; however, whether the kaolin is halloysite or kaolinite is difficult to ascertain, because the near superposition of thermal peaks makes it impossible to measure the slope ratio of the 600-C. kaolin peak and, while a glycol retention of 62 mg. per g. is nearer that for halloysite than kaolinite, the contribution that boehmite makes to the glycol value is unknown. The x-ray pattern tends toward halloysite but is not considered sufficiently clear cut to warrant the elimination of kaolinite. Therefore, the clay mineral in Sample 7 is called simply kaolin.

Illite is the only clay mineral in the clay fractions of Samples 9 and 10; but based on the  $-0.07\text{-mm.}$  material, the amount of illite is low.

Thermograms on Samples 13 and 14 reveal the mineral montmorillonite; this conclusion is substantiated by the x-ray and glycol data. The clay mineral in Sample 11 is wholly montmorillonoid probably nontronite, but this comprises a mere 5 percent of the total

TEMPERATURE IN 100° C

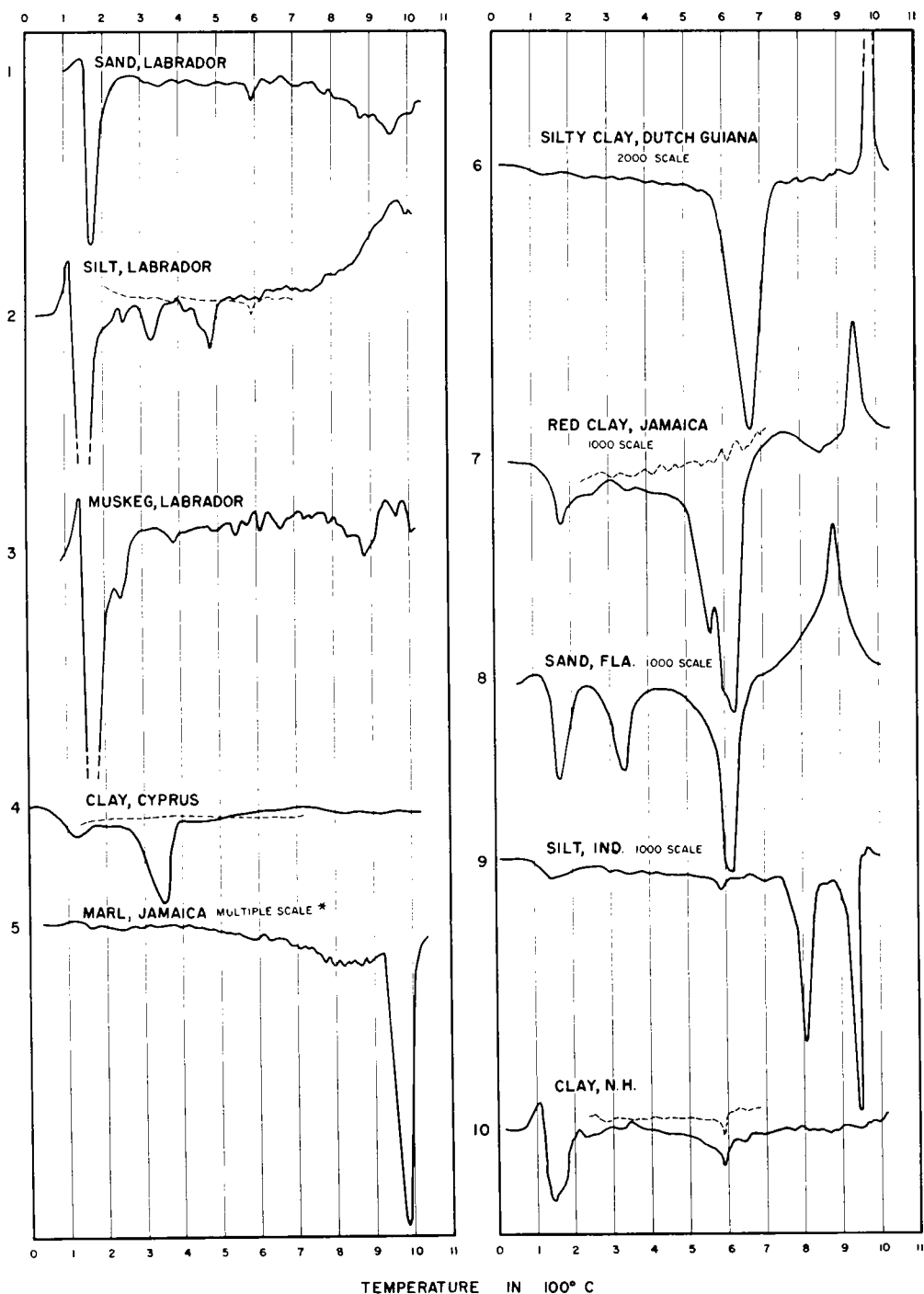


Figure 2. Thermograms for natural soils. All samples are  $-0.07$  mm. and 50 percent R.H. Asterisk on the ordinate scale means 500 unless otherwise noted.

TABLE 2  
DISTRIBUTION OF ILLITE-MONTMORILLONOID  
MIXTURES IN HYDROUS MICA

Frequency (# of samples observed)		Ideal (I:M) ratio <sup>a</sup>
for a given (I:M) ratio	for interstratification	
1	0	5:1
2	2	3:1
4	4	1:1
2	1	1:2
1	1	1:5
2	0	1:15

<sup>a</sup> See text for method of calculation.

sample. The thermogram of Sample 12 indicates illite or nontronite in addition to dolomite. X-ray diffraction shows strong montmorillonoid lines and moderate feldspar lines. Petrographic examination of the fine sand of Sample 12 revealed that feldspars were much more abundant than quartz. The fact that many of the feldspar grains showed extreme weathering probably accounts for the presence of feldspars in the clay size material.

*Mixtures of Clay Mineral Fines.* Over half of all the samples studied contain mixtures of clay minerals. X-ray data on these mixtures indicate that they vary from apparently simple mixtures to highly interstratified complexes. Where interstratification is indicated by the x-ray data it is so shown in Table 3. Then on the assumption that the interstratified layers are ideal illite, montmorillonoid, chlorite, or vermiculite, the percentage of the minerals is calculated.

Hydrous mica occurs in 28 of the 40 samples examined, and in 16 of these 28 the only clay minerals are in the hydrous mica group. Samples 9 and 10, which are clearly illite, have already been discussed.

Thermograms on Samples 15 through 28 generally suggest hydrous mica with various degrees of montmorillonoid as evidenced by the adsorbed H<sub>2</sub>O peak. X-ray data on this group indicate (1) illite and montmorillonoid minerals to varying degrees and (2) interstratification from nil to very marked. Just where a certain sample falls within the hydrous mica group was estimated from the potash and glycol data. The amount of illite was calculated from the potash data by the use of 6 percent K<sub>2</sub>O for the reference illite. The amount of montmorillonoid was calculated from the glycol data after subtraction of

the illite contribution. Admittedly this calculation procedure is somewhat arbitrary because two samples, one interstratified and the other a simple mixture having the same proportion of calculated illite and montmorillonoid, would probably behave differently. The calculation, however, of ideal illite-montmorillonoid for these hydrous micas does provide a basis of comparison. Further, as shown in Table 2, the interstratified samples dominate the mid illite-montmorillonoid region and as the proportion of illite or montmorillonoid becomes large the clay is apparently a simple mixture.

The occurrence of simple mixtures near the ends of the illite-montmorillonoid range may be more apparent than real, because as the amount of a given component becomes low, its x-ray reflections weaken and the evidence for interstratification will also weaken or disappear. Sample 23 was the only sample where illite and montmorillonoid x-ray reflections were strong that no evidence of interstratification was observed.

The high-potash-and-low-glycol value of Sample 28 strongly suggest a hydrous mica toward the mica end. By the use of 11 percent K<sub>2</sub>O and 20 mg. of glycol per g. for mica, the amount of mica required to account for the apparent deficiency in glycol retention was calculated. Since the x-ray and DTA data indicate strong illitic character, the proportioning of the potash and glycol values to illite and mica appears to be justified.

The second largest group of mixtures are those composed of hydrous mica and chlorite or vermiculite. This group is considered as a unit because the identification of the mixture as hydrous mica-chlorite or hydrous mica-vermiculite is based on differences produced in the x-ray reflections following various treatments. Samples 29 through 33 have been identified as hydrous mica-chlorite mixtures; Samples 35 and 36 as illite-vermiculite mixtures; and Sample 34 as an illite-swelling chlorite mixture.

Almost identical x-ray patterns were obtained on Sample 32 for both glycerol and NH<sub>4</sub>Cl treatments.<sup>3</sup> Following heat treatment<sup>3</sup> the 14Å reflections became very strong, the

<sup>3</sup> Glycerol treatment, the clay is mixed with glycerol, allowed to stand for 30 minutes and the product X-rayed.

NH<sub>4</sub>Cl treatment, the clay is boiled 5 minutes with 2N NH<sub>4</sub>Cl and the product X-rayed.

Heat treatment, the clay is heated at 550°C. for 30 minutes and the product X-rayed.

TABLE 3  
SOIL COMPOSITION AND PROPERTIES

Sample No.	Soil	Supplied By	Particle Size in MM		Composition of Silt and Clay Portion in % By Weight	Atterberg Limits and Natural Water Content in %	Engineering Properties	Remarks
			-0.075	-0.002				
1	<i>Nonclay Minerals</i> Brown silty sand from Labrador, Canada (Ontario Northland Railway)	Hanna Company, Cleveland, Ohio	22	2	Quartz = 35 Feldspars = 35 O.M. = 3.8	Not plastic		No clay minerals
2	Organic silts from Labrador, Canada (Ontario Northland Railway)	Hanna Company, Cleveland, Ohio	55	0	O.M. = 25 Quartz = 20 Hydrous Fe and Al oxides = 20-40	$w_1 = 388$		Quartz very abundant; diatoms and mica abundant in the silt sizes
3	Black Muskeg from Labrador, Canada (Ontario Northland Railway)	Hanna Company, Cleveland, Ohio	57	0	O.M. = 76 Diatoms = $\pm 5$	$w_1 = 302$		Diatoms dominant in the clay size
4	Reddish brown clay	D. D. Dimitrius, Cyprus			Chemical Analysis: $\text{Fe}_2\text{O}_3 = 65$ $\text{SiO}_2 = 10.9$ $\text{Al}_2\text{O}_3 = 8.0$ + $\text{H}_2\text{O}$ , O.M. etc. = 15.2 $\text{Fe}_2\text{O}_3 = 60$	Cation exchange capacity = 6 m.e./100 g		This earth used as paint pigment. Mineral species present are $\alpha\text{Fe}_2\text{O}_3$ and magnetite (Ref. 4)
5	<i>Monoclay Minerals</i> Marl from near Kingston, Jamaica, B.W.I.	E. E. Fraser, Water Commission, Jamaica, B.W.I.	45	7	Calcite = 75 Montmorillonoid = 10	$w_1 = 28$ $w_p = 20$		
6	Grayish white silty clay from Suriname Dutch Guiana	Moran, Proctor, Mueser and Rutledge, New York City	97	77	Kaolinite = 90	$w_1 = 57$ $w_p = 35$ $w_n = 28$	Void ratio at pressure of 1 = 0.83, at p of 10, e = 0.82, U = 11.5 T/ft <sup>2</sup>	Very strong pre-compressed clay (Ref. 10)
7	Bright red clay from near Kingston Jamaica, B.W.I.	E. E. Fraser, Water Commission, Jamaica, B.W.I.			Kaolin = 65 Boehmite = 25 Illite = trace Quartz = trace $\text{Fe}_2\text{O}_3 = 12$ O.M. = 3.1	$w_1 = 60$ $w_p = 37$		
8	Red silty sand from Lake Wales, Florida	Mt. Lake Corporation Lake Wales			Quartz = 35 Kaolinite = 60 $\text{Fe}_2\text{O}_3 = 6.5$ O.M. = 1.2			
9	Brown silt from Valparaiso, Indiana	ACAFEL, Corps of Engineers	97	8	Dolomite = 35 Quartz = 30 Illite = 15 O.M. = 1.3 $\text{Fe}_2\text{O}_3 = 1.5$	$w_1 = 24$ $w_p = 20$	$\gamma_d = 116$ $w_{opt} = 13.5$ } std. Proctor: CEFSC of "very high"	Angular grains of quartz, feldspars and pyroxenes in about equal proportion in the silt and fine sand
10	Stratified clay from Portsmouth, N.H.	ACAFEL, Corps of Engineers	85	15	Quartz = 35 Illite = 5-15 $\text{Fe}_2\text{O}_3 = 1.5$	$w_1 = 26$ to 30 $w_p = 18$	$\gamma_d = 97$ to 104 and $w_{opt} = 24$ to 28 CEFSC of "High" for undisturbed and remolded	Very angular mineral grains in silt and fine sand
11	Yellowish tan silt from French Morocco	R. R. Philipe, Corps of Engineers	73	13	Quartz = 5 Calcite = 90 Montmorillonoid = 5	$w_1 = 31$ $w_p = 23$	Std. Proctor Compaction test Data: $\gamma_d = 97$ $w_{opt} = 19.5$	
12	Dark gray shale from Panama Canal Zone	W. J. Turnbull, WES Corps of Engineers	70	20	Feldspar (clay sizes) = 10 Dolomite = 10 Montmorillonoid = 25 O.M. = 2.0 $\text{Fe}_2\text{O}_3 = 1.7$	$w_1 = 75$ $w_p = 46$ $w_n = 37$	Consolidation test data: start of test e = 1.065 p of 1, e = 1.054 p of 10, e = 1.033 end of test e = 1.060	High rebound; Swells in presence of water. Very highly weathered plagioclase feldspars dominant in the fine sand and coarse silt
13	Dark gray bentonite from Oahe Damsite, Pierre, S. D.	S. J. Wilson, Harvard University			Montmorillonite = 85		U = 13.5 psi	
14	Bentonitic clay from Cyprus	D. D. Dimitrius, Cyprus	100		Montmorillonite = 100			

TABLE 3—Continued

Sample No.	Soil	Supplied By	Particle Size in MM		Composition of Silt and Clay Portion in % By Weight	Atterberg Limits and Natural Water Content in %	Engineering Properties	Remarks
			0.075	0.0025				
15	<i>Clay Mineral Mixtures</i> Hydrous Micas Dark gray clay from Tomari Harbor, Okinawa	Moran, Proctor, Mueser and Rutledge, New York City			Quartz = 15 Illite = 40 Montmorillonoid = 7 O.M. = 3.7 Fe <sub>2</sub> O <sub>3</sub> = 3.7 (Illite = 50) (Montmorillonoid = 15) Fe <sub>2</sub> O <sub>3</sub> = 3.8 Gibbsite = 5 (Illite = 40) (Montmorillonoid = 12) Quartz = trace	w <sub>n</sub> = 58	Consolidation Test Data: p of 1, e = 1.54 p of 10, e = 1.34 U = 0.43 T/ft <sup>2</sup>	(Ref. 10)
16	Red clay from near Kingston, Jamaica, B.W.I.	E. E. Fraser, Water Commission, Jamaica	86	29		w <sub>l</sub> = 66 w <sub>p</sub> = 24		
17	Bentonite from Westmoreland, Jamaica, B.W.I.	E. E. Fraser, Water Commission, Jamaica				w <sub>l</sub> = 130±	Non-swelling bentonite	Silt and sand fraction almost 100% volcanic glass. Grains very angular and irregularly shaped
18	Clay from WASHO test road, Malad, Idaho	ACAFEL Corps of Engineers	92	23	Carbonate minerals = 15 (Illite = 13) (Montmorillonoid = 12) O.M. = 2.7 Fe <sub>2</sub> O <sub>3</sub> = 1.4 Quartz = trace	w <sub>l</sub> = 37 w <sub>p</sub> = 24	CEFSC of "medium" $\gamma_d$ = 100 w <sub>opt</sub> = 21	
19	Clay from Municipal Airport, Fargo, N. D.	ACAFEL Corps of Engineers	97	45	Quartz = 15 Carbonate minerals = 10 (Illite = 26) (Montmorillonoid = 29) Fe <sub>2</sub> O <sub>3</sub> = 4.0 O.M. = 0.9 Quartz = 20 Calcite = 10 O.M. = 1.2 (Illite = 15) (Montmorillonoid = 15) Fe <sub>2</sub> O <sub>3</sub> = 0.6	w <sub>l</sub> = 68 w <sub>p</sub> = 46 w <sub>n</sub> = 29 to 32	CEFSC of "Low" Natural dry density of 86 to 89 lb./cu. ft.	
20	Black sandy silt from Texas		68	2	Quartz = 20 Calcite = 10 O.M. = 1.2 (Illite = 15) (Montmorillonoid = 15) Fe <sub>2</sub> O <sub>3</sub> = 0.6	Not plastic		Mica abundant in silt and fine sand
21	Red Periman clay from Tinker Air Base, Okla.	Ohio River Div. Corps of Engineers	83	38	Quartz = 40 (Illite = 30) (Montmorillonoid = 30) Fe <sub>2</sub> O <sub>3</sub> = 2.3 Quartz = 10 O.M. = 2 (Illite = 25) (Montmorillonite = 50)	w <sub>l</sub> = 58 w <sub>p</sub> = 20 w <sub>s</sub> = 11		Highly weathered sand composed of quartz and feldspar
22	Gray brown clay from Jackson, Mississippi	W. J. Turnbull, WES Corps of Engineers	98	75	Quartz = 10 O.M. = 2 (Illite = 25) (Montmorillonite = 50)			Exhibits excessive swelling
23	Gray clay from Brookley Air Base, Mobile, Ala.	Ohio River Division, Corps of Engineers	95	55	Montmorillonoid = 45 Illite = 25 O.M. = 5.6	w <sub>l</sub> = 106 w <sub>p</sub> = 40 w <sub>l</sub> = 62* w <sub>p</sub> = 37* w <sub>n</sub> = 80 w <sub>l</sub> = 30 w <sub>p</sub> = 20	Natural $\gamma_d$ = 52 U = 23 psi, R = 4 psi. Highly compressible and expansive clay.	
24	Brown sandy silt from Nile Valley, near Cairo, Egypt	A. D. Little Company, Cambridge, Mass.	55	11	Quartz = 25 (Montmorillonoid = 50) (Illite = 10) Dolomite = 8 Fe <sub>2</sub> O <sub>3</sub> = 3.1 Montmorillonoid = 80 Illite = 5			Micas very common and amphiboles and pyroxenes abundant in silt and fine sand
25	Gray-green, slickensided shale (Cucarache) from Panama Canal Zone	S. J. Wilson, Harvard University	89	64				
26	Dark brown clay Bombay, India	Dames and Moore	79	24	Magnesite = 5 Fe <sub>2</sub> O <sub>3</sub> = 4.5 O.M. = 0.7 (Illite = trace) (Montmorillonoid = 70)	w <sub>l</sub> = 69 w <sub>p</sub> = 30 w <sub>n</sub> = 38	Natural dry density = 87 lb./cu. ft.	This soil undergoes excessive shrinkage and cracking upon drying. Amphiboles and pyroxenes more abundant than quartz and feldspars in the fine sand.
27	Yellow clay from near Kingston, Jamaica, B.W.I.	E. E. Fraser, Water Commission, Jamaica, B.W.I.	81	20	Montmorillonoid = 70 Illite = 5 Fe <sub>2</sub> O <sub>3</sub> = 2.3 Quartz = trace	w <sub>l</sub> = 99 w <sub>p</sub> = 28		
28	Gray boulder clay from Townsend Pit, Bernardson, Mass.	Mass. Dept. of Public Works	44	4	Quartz = 20 (Illite = 60) (Mica = 25) Fe <sub>2</sub> O <sub>3</sub> = 0.5 O.M. = 1.7	w <sub>l</sub> = 34 w <sub>p</sub> = 19	$\gamma_d$ = 116 w <sub>opt</sub> = 16 U at w <sub>opt</sub> = 2200 lb./sq. ft.	Sand and silt mostly angular quartz and mica. (Soil M17 Ref. 21)



TABLE 3—Continued

Sample No.	Soil	Supplied By	Particle Size in MM		Composition of Silt and Clay Portion in % By Weight	Atterberg Limits and Natural Water Content in %	Engineering Properties	Remarks
			— 0.075 —	— 0.002 —				
29	Clay Mineral Mixtures—Continued Illite-Chlorite or Vermiculite Gray clay from Livermore Falls, Maine	International Paper Company	82	19	Quartz = 30 (Illite = 30) (Chlorite = 5±) Fe <sub>2</sub> O <sub>3</sub> = 1.9 O.M. = 0.4	w <sub>l</sub> = 33 w <sub>p</sub> = 18		
30	Brown boulder clay from Fall River Expressway, Mass.	Mass. Dept. of Public Works	28	3	Quartz = 45 (Illite = 40) (Chlorite = 10±) Fe <sub>2</sub> O <sub>3</sub> = 0.6	w <sub>l</sub> = 19 w <sub>p</sub> = 12	γ <sub>d</sub> = 119 w <sub>opt</sub> = 13, U at w <sub>opt</sub> = 1900 lb./sq. ft.	Sand and silt mostly sub-angular quartz and feldspars (Soil M2 Ref. 21)
31	Gray clay from Searsport, Maine	ACAFEL Corps of Engineers	95	30	Quartz = 35 Illite = 45 Chlorite = 15± O.M. = 0.7 Fe <sub>2</sub> O <sub>3</sub> = 1.6	w <sub>l</sub> = 37 w <sub>p</sub> = 19 w <sub>n</sub> = 26 to 30	Natural dry density = 95 to 99 CEFSC of "High to very High" for undisturbed and "medium" for remolded.	Feldspars more abundant than quartz; mica very common in silt and fine sand
32	Gravelly sandy clay from Thule, Greenland	ACAFEL Corps of Engineers	43	12	Carbonate minerals = 45 (Illite = 20) (Mica = 3) Chlorite = 30 Fe <sub>2</sub> O <sub>3</sub> = 0.7 (Illite = 55) (Mica = 15) (Chlorite = 20±) O.M. = 0.9 Fe <sub>2</sub> O <sub>3</sub> = 2.1	w <sub>l</sub> = 19 w <sub>p</sub> = 10	γ <sub>d</sub> = 140† w <sub>opt</sub> = 7.0† CEFSC of "Low"	
33	Gray clay from Sweden	Swedish Geotechnical Institute	70					The clay minerals of this sample may be interstratified. Suspension of this clay used to lubricate sides of tunnel built above ground surface then slide into place.
34	Gray silt from Whitehorse, Yukon Territory, Canada	ACAFEL Corps of Engineers	95	—	Quartz = 30 Calcite = 10 Fe <sub>2</sub> O <sub>3</sub> = 0.9 (Illite = 25) (Swelling Chlorite = 15)	w <sub>l</sub> = 25 w <sub>p</sub> = 19	γ <sub>d</sub> = 124.5 w <sub>opt</sub> = 11.5 CEFSC of "Medium"	Estimation of percent of clay minerals in total soil difficult for this sample. Mica very common in silt and fine sand.
35	Brown silt from Fairbanks, Alaska	ACAFEL Corps of Engineers	90	5	Quartz = 35 (Vermiculite = 27) (Illite = 20) O.M. = 1.2 Fe <sub>2</sub> O <sub>3</sub> = 1.3	w <sub>l</sub> = 32 w <sub>p</sub> = 26	γ <sub>d</sub> = 107† w <sub>opt</sub> = 17.1† γ <sub>d</sub> = 97 to 104§ w = 24 to 28§ CEFSC of "High" for undisturbed and "Very High" for remolded.	All mineral grains very angular; mica very common in silt and fine sand.
36	Red sandy clay from White Pine, Michigan	Moran, Proctor, Mueser and Rutledge, New York City	65	22	Quartz = 50 Dolomite = 15 (Illite = 20) (Vermiculite = 5) O.M. = 2 Fe <sub>2</sub> O <sub>3</sub> = 0.9	w <sub>l</sub> = 23 w <sub>p</sub> = 13 w <sub>n</sub> = 14	Consolidation test data; p of 1, e = 0.38; p of 10, e = 0.33; U = 2.3 T/ft <sup>2</sup> ; Natural dry density = 138	Low strength for the very high density (Ref. 10)
37	Illite-Kaolin Red and Gray clay from foundation of Delaware Memorial Bridge	Moran, Proctor, Mueser and Rutledge, New York City	78	52	Quartz = 50 Kaolinite = 25 Illite = 25 Fe <sub>2</sub> O <sub>3</sub> = 4.2	w <sub>l</sub> = 35 w <sub>p</sub> = 20 w <sub>n</sub> = 20	Consolidation test data; start of test e = 0.54, p of 1 e = 0.53, p of 10 e = 0.45; end of test, e = 0.60, U = 22.9 T/ft <sup>2</sup>	Very high strength: sample swelled more on rebound than it compressed on loading (Ref. 10)
38	Tan silty clay from Baker Pit, Wellfleet, Mass.	Mass. Dept. of Public Works	41	13	Quartz = 50 Illite = 20 Kaolinite = 15 Gibbsite = trace O.M. = 0.5	w <sub>l</sub> = 29 w <sub>p</sub> = 18	γ <sub>d</sub> = 107 w <sub>opt</sub> = 18 U at w <sub>opt</sub> = 1600 lb./sq. ft.	Sand and silt mostly sharp angular quartz and mica. Prominence of micas and sillimanite grains make deviations from sphericity large (Soil M 10 Ref. 21)
39	Attapulgite-Hydrous Mica Light brown clay from French Morocco	W. J. Turnbull, WES, Corps of Engineers	55	18	Quartz = 15 Calcite = 60 Illite = 12 Attapulgite = 12 O.M. = 0.9	w <sub>l</sub> = 100 w <sub>p</sub> = 34 w <sub>n</sub> = 30	Consolidation test data; start of test e = 1.15, p of 1, e = 1.10, p of 10, e = 0.96, end of test, e = 1.15, compaction test data: γ <sub>d</sub> = 81	Complete rebound: Very low compacted dry density

TABLE 3—Continued

Sample No.	Soil	Supplied By	Particle Size in MM		Composition of Silt and Clay Portion in % By Weight	Atterberg Limits and Natural Water Content in %	Engineering Properties	Remarks
			0.075	0.002				
40	Clay Mineral Mixtures—Continued Attapulgite-Hydrous Mica—Continued Tan sandy silt from French Morocco	R. R. Philippe, Corps of Engineers	86	0	Quartz = trace Calcite = 50 Dolomite = 20 Attapulgite = 13 (Illite = 4) (Montmorillonoid = 6)	w <sub>l</sub> = 44 w <sub>p</sub> = 29	Std. Proctor Compaction Data: $\gamma_d = 102$ w <sub>opt</sub> = 19.4	

## Symbols and Abbreviations Used in Table

1. O.M. = organic matter
  2. w<sub>l</sub> = Liquid limit
  3. FeO<sub>3</sub> = free iron oxides
  4. w<sub>p</sub> = plastic limit
  5. w<sub>n</sub> = natural water content
  6. ACAFEL = Arctic Construction and Frost Effect Laboratory, Corps of Engineers, Boston, Massachusetts
  7.  $\gamma_d$  = optimum dry density in lb./cu. ft.
  8. w<sub>opt</sub> = optimum water content in %
  9. CEFSC = Corps of Engineers, Frost Susceptibility Classification
  10. e = void ratio
  11. U = unconfined compressive strength
  12. R = unconfined compressive strength on remolded sample
  13. p = applied pressure in tons per square ft
  14. ( ) = interstratified minerals
  15.  $\pm$  on chlorite percentages indicates uncertainty, see text for explanation.
- \* Oven dried.  
† Mod. AASHO.  
‡ Std. Proctor.  
§ Natural.

10Å reflection remained unchanged and the 7Å reflection became very weak. The  $d$  values for larger values of  $2\theta$  also matched those of illite or chlorite reflections. Therefore, Sample 32 is clearly a hydrous mica-chlorite mixture and since no evidence of interstratification was observed, it is apparently a simple mixture.

For sample 32 the amount of chlorite was estimated from the thermogram but for the other samples containing chlorite the thermal peaks are small and not sufficiently resolved to permit estimation from DTA. The percentage chlorite reported for Samples 31, 33, 29, and 30 were made by a comparison of the intensities of x-ray reflections and on the assumption that the chlorite in these samples is the same species as in Sample 32. The pitfalls of using x-ray reflection intensities for estimation of percentages are recognized, but were resorted to for the chlorites because no other method was available. For Samples 30, 31 and 33 the estimation of the chlorite percentage cannot be far in error, because such a large proportion of the clay fraction of these samples is hydrous mica.

Glycol retention values for Samples 32 and 33 are slightly low for the illite percentages indicated by the percent K<sub>2</sub>O.

This fact is generally interpreted as indicating a hydrous mica toward the mica end of the hydrous-mica group. The amount of mica required to account for the apparent deficiency in glycol retention was calculated in a manner similar to that used for Sample 28. This calculation produces an idealized condition just as the percentage calculation of illite and montmorillonoid for hydrous mica toward the montmorillonoid end of the hydrous-mica range. Samples 31 and 32 appeared to be simple mixtures while Samples 36, 33, 29, and 30 gave evidence of being interstratified.

The clay fraction of Sample 34 has been analyzed as illite and swelling chlorite. X-ray patterns of this clay with no treatment and NH<sub>4</sub>Cl treatment were similar, producing sharp reflections at 14, 10, and 7Å as well as smaller  $d$  values indicative of chlorite and illite. Treatment of the sample with glycerol gave a strong 18Å reflection, no apparent change in the 10Å reflection and a somewhat weakened and broadened 7Å reflection. After heat treatment the 10Å line remained unchanged, the 7Å line was weak, and the 14Å line was strong. On the assumption that a swelling chlorite will retain the same amount of glycol as vermiculite, which from structural

considerations would be a good first approximation, the glycol excess after calculating the illite percentage was ascribed to swelling chlorite.

Illite and vermiculite were the clay minerals found in the  $-2\ \mu$  material of Samples 35 and 36. Both samples gave evidence of being interstratified but Sample 36 was more-randomly stratified than Sample 35. After  $\text{NH}_4\text{Cl}$  treatment the  $10.5\text{\AA}$  reflection was much stronger on Sample 35 than on 36. Percentages were again estimated from the potash and glycol data.

The hydrous mica in six of the eight samples in the hydrous-mica-chlorite-vermiculite group was illite, and the percentage of illite in seven of the eight was greater than or equal to the percentage of the other components.

Illite, along with kaolinite, is again a major component in the clay fraction of Samples 37 and 38. The DTA, x-ray, glycol, and potash data indicate that these two samples are straightforward mixtures of illite and kaolinite. The percentage kaolinite was estimated from the amplitude of the DTA peak, because it has been found from the study of known mixtures that in mixtures containing as much as two thirds of illite and one third of kaolinite, the illite does not affect significantly the amplitude of the kaolinite peak. Illite was calculated in the usual way. The glycol data closely check these calculations.

Although illite was a component of Samples 39 and 40, attapulgite was also present and was the dominant mineral in the clay fraction of Sample 40. X-ray diffraction patterns of Sample 40 show it to be a mixture of attapulgite and hydrous mica of the illite-montmorillonoid type. Estimation of percentages in this mixture is rather difficult. Illite was calculated from the potash data; division of the remaining glycol between montmorillonoid and attapulgite is not as difficult as first appears, because from a comparison of x-ray reflections on Sample 40 with those of reference minerals, certain facts are clear. Attapulgite reflections are strong, montmorillonoid reflections are weak, and although many illite and attapulgite reflections reinforce each other, illite appears to be weak. A small amount of illite is also indicated by the potash data (15 percent); since x-ray data indicate montmorillonoid stronger than illite, the

percentage montmorillonoid must be greater than 15. In order to account for the measured glycol retention for a minimal montmorillonoid percentage of 15, there will be a maximal attapulgite percentage of 70. Since the x-ray data indicate attapulgite strong and montmorillonoid weak, another limiting case can be calculated when the percentage montmorillonoid and attapulgite are equal. The stipulation imposed by the glycol data makes the percentage montmorillonoid equal to the percentage attapulgite at 35 percent. Therefore, the percentage attapulgite is between 35 and 70, and the percentage montmorillonoid is between 15 and 35. The values reported for the clay fraction were taken about midway, i.e., attapulgite 50 percent and montmorillonoid 25 percent. Sample 39 appeared to be a simple mixture of illite and attapulgite.

#### ENGINEERING SIGNIFICANCE OF RESULTS

Table 3 summarizes the compositional data and properties of the soils analyzed; much of the engineering data were furnished by the supplier of the soil. Some of the grain-size and plasticity data were obtained in the MIT Soil Stabilization Laboratory. From the data in Table 3 several significant and interesting observations can be made on the occurrence and properties of soil minerals.

#### *Nature of Soil Fines*

The soils presented in Table 3 are too few and their geographical sources not randomly enough selected for quantitative information on the distribution of soil components to be presented. Since all of the soils presented were involved in engineering projects, a cursory study of the occurrence of the various soil components, however, is valuable.

While nearly all of the soils studied had clay minerals in their clay-size fraction, only 25 percent had monoclay mineral fines. The other 75 percent of the soils had fines composed of mixtures of clay minerals; 75 percent of the soils contained illite, 50 percent montmorillonoid, and 15 percent kaolin. This high percentage of illitic soils is not surprising in view of the many glacial soils in Table 3.

Six of the samples contained chlorite, two attapulgite, and two vermiculite. These three minerals are considered by some as clay min-

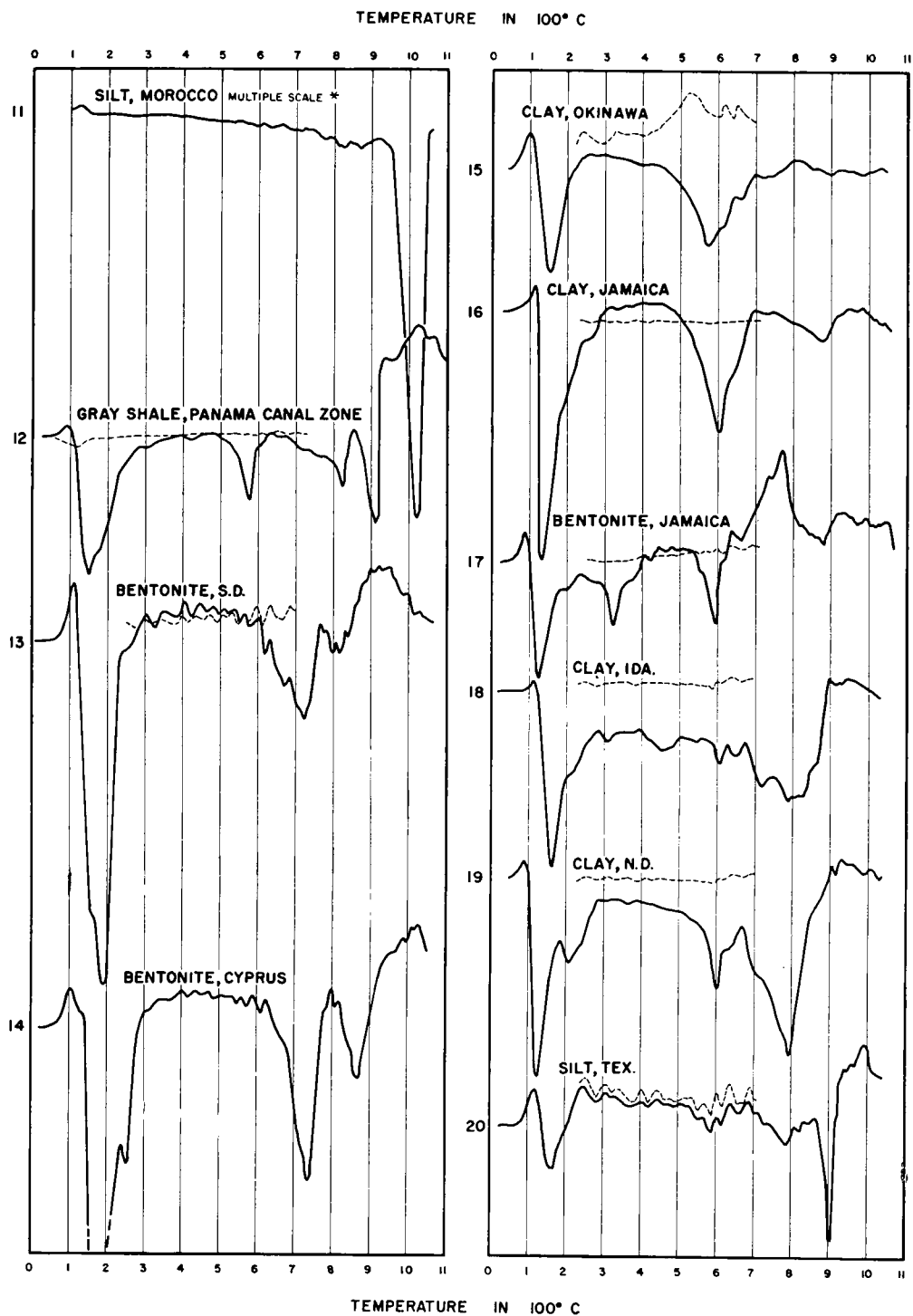


Figure 3.

TEMPERATURE IN 100° C

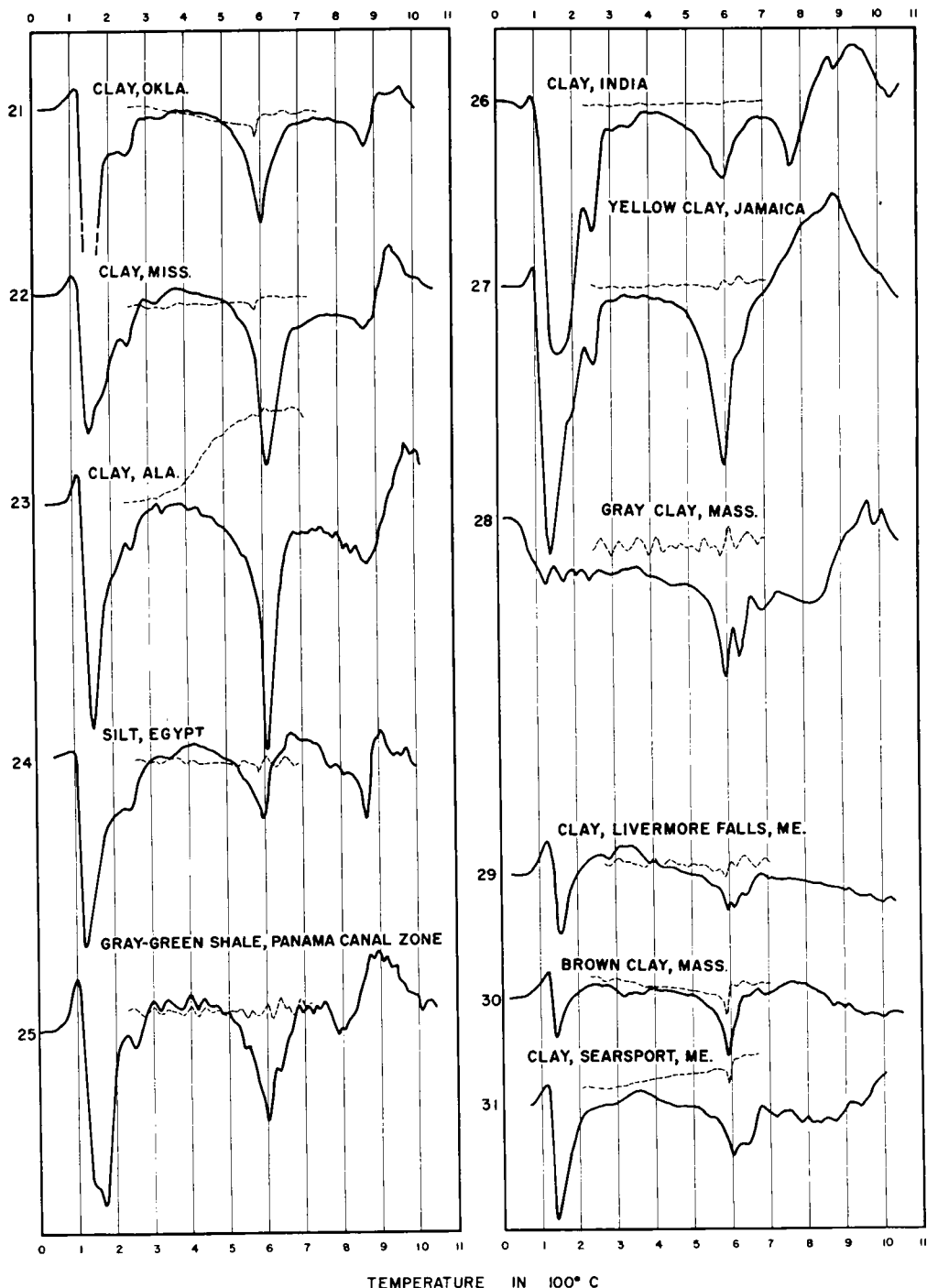


Figure 4.

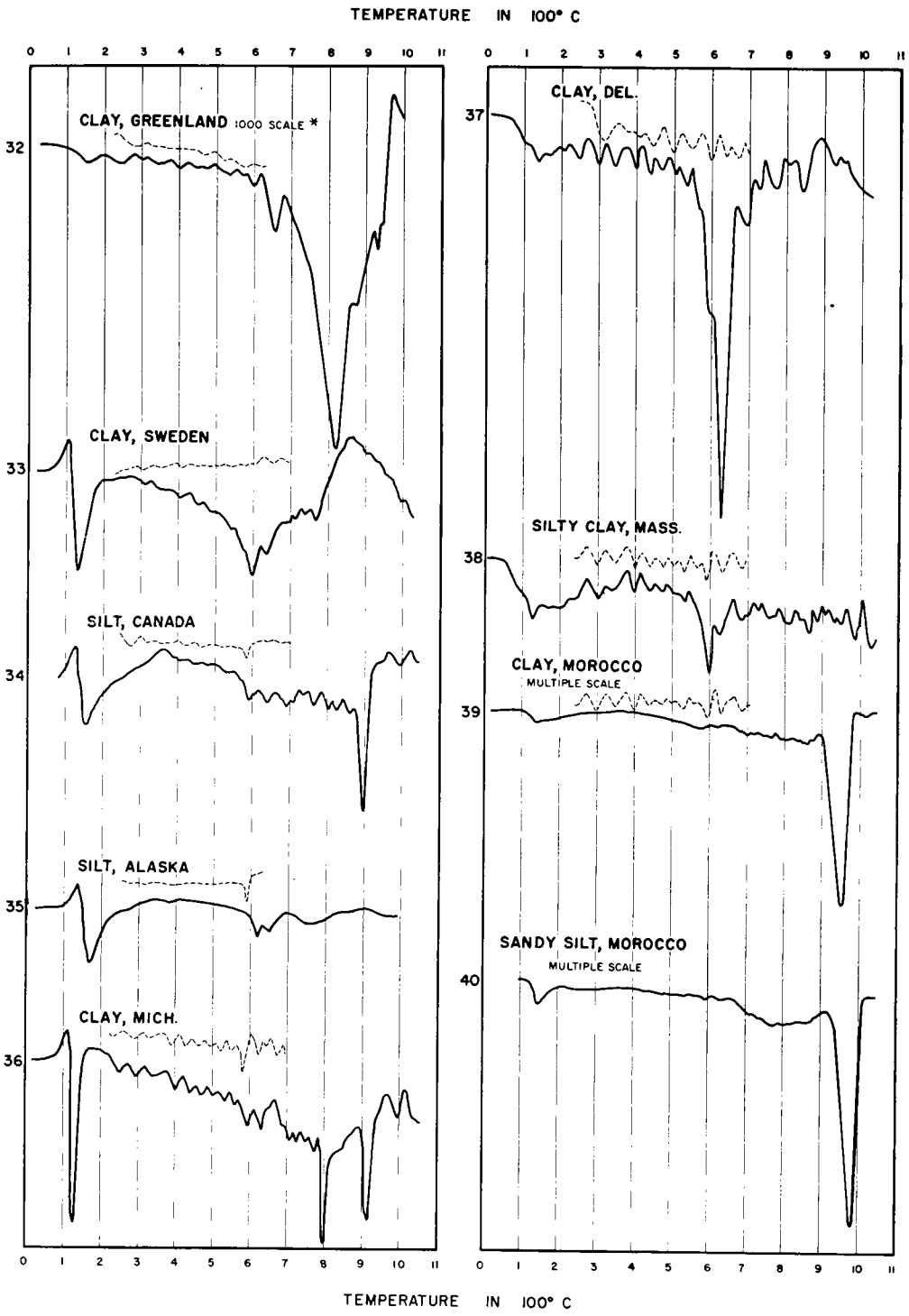


Figure 5.

erals and by others as not. More of the soils had chlorite than kaolinite.

Calcite, dolomite, quartz, and feldspars accounted for nearly all of the non clay mineral portion of the soil samples. The feldspar in Sample 12 existed in particles finer than two microns.

The prevalence of small quantities of organic matter and free iron oxides (each was in over 60 percent of the soils) may be surprising.

### *Cementation of Fines*

The stable aggregates formed by the clay mineral fines for many of the soils in Table 3 gives the soil engineer an item worthy of thought and investigation. The vast difference between the percentage clay size and the percentage clay mineral is illustrated in Figure 6. The percentage clay size was determined by standard hydrometer method using a deflocculating agent and mechanical dispersion.<sup>4</sup> Mineral analysis gave the percentage clay mineral. Percentages for both clay size and clay mineral were computed on the  $-0.07$ -mm. fraction. In Figure 6 the number by each point indicates the sample number and the diagonal line represents the ideal condition where the material less than  $2 \mu$  is all clay minerals and the material larger than  $2 \mu$  is all nonclay minerals. To the right of the diagonal indicates cementation or aggregation of fines and to the left indicates nonclay material in the clay size.

While it is possible for clay mineral particles to be larger than  $2 \mu$ , as has been recently shown by Carr (3), such occurrences are apparently rare. Samples 28 and 30, which showed severe cementation, were pretreated to remove organic matter and free iron oxides. Then the resultant sample was fractionated to remove  $-2 \mu$  material. The remaining silt showed no clay minerals either by DTA or x ray. While samples to the left contain nonclay minerals, the deviations from the diagonal are insignificant because of the 10-percent experimental error in determining the clay mineral percentages.

Much more striking is the severe aggregation or cementation shown by many of the samples, i.e., samples to the right of the diagonal. Common cementing or aggregating

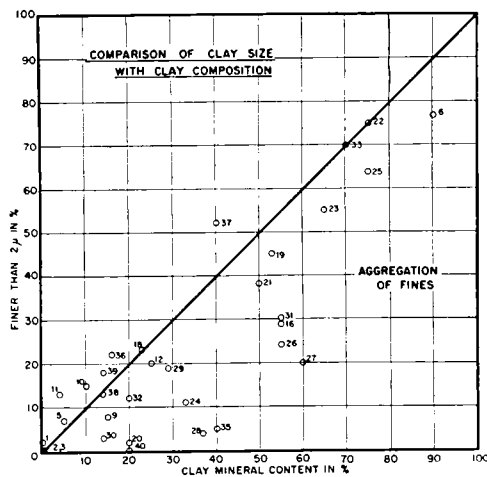


Figure 6. Comparison of clay mineral and clay sizes.

agents are carbonates, free iron oxides, and organic matter; these are present in varying amounts and in various combinations in the samples to the right of the diagonal, but some of the samples to the left also contain these cementing agents.

The effect a given percentage of a cementing agent will have on soil properties is difficult to predict. The clay mineral in Samples 28 and 36 is hydrous mica. Since Sample 36 contains more free iron and organic matter and less clay mineral than Sample 28, one would expect a pronounced cementation in Sample 36. Figure 6 reveals, however, that Sample 36 has no cementation, while Sample 28 is highly cemented or aggregated. From the high carbonate content of Sample 40, it is not surprising that the clay size and clay mineral percentages do not agree; however, in Sample 39, which has the same kind of clay mineral and about the same carbonate content as Sample 40, the percentage clay mineral and clay size show substantial agreement. These examples illustrate that the percentage of cementing component is not necessarily an indication of the effect it will have on the soil properties.

We can question whether such highly cemented clay material is more clay-like or silt-like in behavior. The relatively low liquid limit of 69 for Sample 26 would certainly suggest that the montmorillonoid in its cemented state is not as plastic as montmorillonoid usually is. A similar example of fine aggregation is presented by Sample 27,

<sup>4</sup> More thorough dispersion might be obtained had the most-effective deflocculating agent been at optimum concentration rather than a standard treatment being employed.

which shows only 20 percent of its mass finer than 2 microns but over 70 percent of its mass composed of montmorillonoid and illite. While its liquid limit of 99 is higher than that of Sample 26, it is still lower than would normally be expected of a soil having almost 70 percent of its mass composed of montmorillonoid.

#### *Relationships Between Composition and Properties*

Experience has generally shown that the kaolin soils are relatively low in plasticity and high in strength, while the montmorillonoids are high in plasticity and low in strength and the illitic soils fall between these other two. Halloysite is an exception to this rule, since it is a kaolin that is highly plastic and can be a treacherous soil to the engineer. The Kenya soil (8), which was composed of almost pure halloysite, had a liquid limit of 90 and a compacted dry density of 65.5 pcf. at an optimum water content of 55 percent.

The data in Table 3 show that the soils that are highly plastic or cause trouble from swelling have either montmorillonoid or attapulgite in their fine fractions. While the engineer may be well aware of the troubles that the expanding lattice montmorillonoids can cause him, he may be surprised to learn that attapulgite too must be considered with caution. While the research at Cornell (17) did not consider attapulgite to the extent that it did montmorillonite, illite, and kaolinite, the tests showed that attapulgite was a highly plastic and compressible soil mineral.

Attapulgite, sometimes called a member of the "fibrous clay group," consists essentially of chains of the montmorillonite type lattice which are stacked at every other layer and are only about six octahedral groups wide. Adsorbed water and exchangeable ions, usually calcium, are held in the tunnels formed by the alternate stacking. The fibrous structure of attapulgite gives it a high plasticity (liquid limit over 100), low maximum dry density (around 55 pcf.) high optimum water content (between 60 and 70). Tests performed at the Arctic Construction and Frost Effects Laboratory of the Corps of Engineers in Boston (19) showed that attapulgite as a soil fine could make the soil highly frost susceptible. The properties

(maximum compacted density of 81 pcf. and complete rebound of consolidation test specimen) of the Moroccan clay (Sample 39) are in line with what would be expected from its attapulgite content.

Several soils in Table 3 have unusual properties which cannot definitely be explained in terms of their composition. The plasticity of Sample 26 is considerably lower than its composition implies. The aggregation of fines, brought about in this case by 5 percent magnesite, 4.5 percent free iron oxides, and 0.7 percent organic matter, is apparently the cause of the montmorillonitic clay behaving so noncharacteristically.

The low strength yet high density of Sample 36 may be caused by the small quantities of organic matter and vermiculite present.

The high strength and high consolidation rebound of Sample 37 cannot be readily explained in terms of its composition. Aggregation of fines by the iron oxide may contribute to the strength; destruction of the interparticle linkage during consolidation could aid the rebound tendency.

While the extent of attapulgite and vermiculite as soil components is yet to be determined, the limited data available indicate the desirability of engineering studies on these soil minerals. The roles of small quantities of free iron oxides and organic matter, other than their aggregating tendencies, should be studied. While there have been suggestions that carbonates are conducive to high frost heave (18), the contribution of carbonates to the engineering properties of soil is not understood. Here too research appears justified.

#### *Bentonites*

The definition of bentonites suggested by Ross and Shannon (13) as a material produced in situ from volcanic ash has considerable merit for the engineer's use. The engineer who thinks of bentonite as a sodium montmorillonite such as Wyoming bentonite, will be interested in the bentonite from Westmoreland in Jamaica (Sample 17), which contained only 12 percent montmorillonoid and exhibited no swelling properties. On the other hand, the bentonites from South Dakota (Sample 13) and Cyprus (Sample 14)



were composed almost entirely of montmorillonite.

#### SUMMARY AND CONCLUSIONS

This paper presents the compositional analyses on 40 soils from scattered parts of the world. The most-common soil components were quartz, illite, and small amounts of organic matter and free iron oxides.

Many of the soils contained clay mineral fines which were aggregated or cemented by carbonates, organic matter or free iron oxides. The apparent effect of this cementation was to reduce plasticity and compressibility.

A comparison of soil composition and properties suggests that the studies be conducted on vermiculite, attapulgite, organic matter, and free oxides to determine their effect on the properties of soils in which they are components.

#### ACKNOWLEDGMENTS

Those listed in Table 3 who supplied soil samples and engineering data have made the studies described by this paper possible. Many of the laboratory tests were performed by William Mueser in connection with his master's thesis.

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