Composition and Engineering Properties of Soil

T. WILLIAM LAMBE, Associate Professor and Director, and

R. TORRENCE MARTIN. Head of Soil Analysis Section

Soil Stabilization Laboratory. Massachusetts Institute of Technology

• SINCE the development of soil mechanics the engineer has devoted considerable effort to improving techniques for measuring the engineering properties of soil but has given little attention to the composition of soil. This unbalanced emphasis is explained by several facts: (1) soil mineralogy is a relatively new science; (2) the identification of soil components requires special techniques and equipment; (3) natural soils usually consist of more than one mineral. While these factors have been and will continue to be major obstacles to the soil engineer, they are not entirely unsurmountable, and they should not obscure the fact that composition is the most fundamental soil characteristic.

For several years the M.I.T. Soil Stabilization Laboratory has been making mineral analyses on soils from many parts of the world. This paper presents the composition and a summary of the properties of 26 of the hundreds of soils studied. The soils selected are representative of those analyzed and the observations made on the few soils discussed in this paper have been substantiated on others. The influence that exchangeable ions, specific surface, and trace impurities (especially organic matter in the form of colloids or exchangeable ions) can have on soil properties is fully appreciated; these characteristics are not discussed here in detail since they are usually of less importance than composition and because the lack of space in this paper necessitated this limitation of scope.

MINERAL ANALYSIS

Test Procedures

The tools available for clay-mineral identification today are many. Differential thermal analysis, X-ray, electron microscopy, and electron diffraction are among the more recent additions that have rightfully earned their place among such old standbys as the petrographic microscope and chemical analysis. The tests employed depend not only on the equipment available, but also, to a consider-

able degree, on the ultimate use that is to be made of the data. A routine procedure is not used in the M.I.T. Soil Stabilization Laboratory, because the results of one test usually indicate which additional tests should be made. For example, if differential thermal analysis shows the sample to be kaolin, a total potash determination would be of no value; however, tests for differentiating between kaolinite and halloysite are essential to obtain a reliable analysis. Because this flexible approach is employed at M.I.T., the initial sample preparation and the tools used are described first; details of procedures are discussed along with the specific mineral analysis.

The sample analyzed was that portion which, having passed a No. 140 sieve, was brought to moisture equilibrium at 50 percent relative humidity. A No. 140 sieve was used to avoid the difficulty of getting soil through smaller openings, and to give a maximum particle size which is small in relation to the sample size. While such a sample is designated as -140, it may actually be all clay size. Moisture equilibrium permitted an approximation of specific surface from the low temperature endotherm. Fifty percent relative humidity was chosen because it has been shown to be an index of specific surface (23), which in turn has been correlated with soil properties.

Tests used for the mineral analysis reported here were differential thermal analysis¹ and X-ray. Differential thermal analysis was used as the first step in mineral analysis because (1) the thermogram gives the simplest overall characterization of the sample (whereas an X-ray pattern is sometimes only a profusion of detail); (2) it usually permits the determination of the dominant clay group; (3) it gives a good approximation of specific surface; and (4) it detects as little as 5 percent quartz. Although the montmorillonoid² clays have a

¹ Details of differential thermal analysis techniques at this laboratory have been described previously $(i\bar{s})$. ² Montmorillonoid is used as the name of the mineral group which includes montmorillonite, nontronite, nec-torite and saponite, and kaolin is used for the mineral group which includes kaolinite, halloysite, dickite and nacrite.

very large specific surface compared to the other groups, a large endothermic peak at 150 C. can also be produced by organic matter or hydrous oxides of iron and aluminum (7); therefore, while the presence of a large 150 C. endothermic peak is suggestive of a montmorillonoid, it is not conclusive. Early estimation of quartz is desirable because this is usually the key to the amount of nonclay minerals and therefore the clue to the practicality of fractionation as a pretreatment. The presence of quartz in soils is indicated by the α to β phase transition occurring at 573 C. on the rerun thermogram. X-ray powder patterns were obtained with and without glycerol solvation using copper K_{α} radiation and a camera of radius 57.3 mm. Glycerol, used to change the hydration state of clay, changes the basal spacing of montmorillonoids. The sample was mixed with collodion, rolled into a thin pencil about 0.5 mm. in diameter and 5 mm. long, and then mounted in the camera. The reference mineral X-ray patterns of this laboratory were supplemented with data from Brindley (2) and van der Marel (17) for the interpretation of the powder photographs. Where initial tests showed it to be advantageous, fractionation and various chemical and heat treatments were used prior to differential thermal analysis or X-ray diffraction.

It was recognized that there are instances where chemical analysis, particularly total potash (S), and a measure of internal swelling such as described by Dyal and Hendricks (5)are highly desirable. Unfortunately, the samples reported here were tested before this equipment was available.

Assumption in Mineral Analysis

The basic assumption made in the identification of minerals in fine-grained soils is that the properties of those minerals are identical with those of a set of reference minerals. If such an equivalence of properties exists, the magnitude of any measured property represents a certain quantity of a given reference material. In view of the variability within the clay mineral groups, this assumption appears unwarranted; however, reliable mineral analyses can be made when the results of a group of tests establish a specific trend.

Monoclay Mineral Soils

Thermograms 1 to 8, given in Figure 1, are easily resolved and show these samples to be monoclay mineral soils. Although Samples 1 to 4 are definitely in the kaolin group, a more detailed analysis is required to distinguish between kaolinite and halloysite. Bramao (1) successfully differentiated between kaolinite and halloysite by applying the slope ratio test to the 600 C. endotherm. The slope ratio is defined as the ratio of angles between the vertical and the ascent and descent of the endotherm. By the use of the criteria given in Table 1, Sample 3 contains halloysite, while the other three contain kaolinite. Because a single distinguishing criterion is not always conclusive, these samples were checked by two other methods. X-ray data of Bramao (1) indicated the following criteria as reliable for differentiating between kaolinite and halloysite when the sample was predominately kaolin: (1) Kaolinite, a sharp (001) reflection at 7.15–7.20 Å; a strong (002) reflection. (2) Halloysite, a broad weak (001 reflection at 7.25–7.50 Å; (020) reflection much stronger than (002).

Application of this test is justified, as the samples under study are clearly kaolin. The results listed in Table 1 indicate that Samples 3 and 4 are halloysite, and 1 and 2 are kaolinite. Another technique for distinguishing halloysite, that of treating the sample with glycol and subjecting it to differential thermal analysis (22), which produces an endothermic peak about 500 C., gave positive results for Samples 3 and 4. Why Sample 3 failed to give a slope ratio indicative of halloysite remains unanswered.

Since differential thermal analysis gives a composite of all heat reactions, it is only monoclay mineral soils that can be easily identified solely by this method. Illitic soils are notably absent from this group, where differential thermal analysis usually suffices for mineralogical characterization. Confusion in their identification arises from the fact that the montmorillonoid minerals, beidellite and nontronite, as well as kaolins, have endothermic reactions at about 600 C. Thermogram 9 appears to be a good illite curve, but the possibility of a small amount of kaolinite cannot be eliminated by thermal analysis alone. However, subsequent X-ray data on Sample 9 indicated that illite was the only



clay mineral present. The possible ambiguity of a large absorbed water neak for the montmorillonoid minerals, which would separate them from illite, has already been mentioned. The complexity produced by the composite thermal reactions can in some instances be significantly reduced by chemical or physical pretreatment.

Pretreatment—Carbonate Removal

The effect of hydrochloric acid treatment³ on samples containing carbonate minerals is illustrated by Samples 10, 11, and 12. At first glance, Thermogram 10b, after acid treatment, seems to be only quartz, but the 580 C. peak is actually considerably larger than one attributable to the quartz reaction,

TABLE 1 SLOPE RATIO, X-RAY, AND GLYCOL TESTS FOR KAOLIN SAMPLES

- <u> </u>	Slope Ratio	X-Ray ^a	Glycol ^a
$ \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} $	$ \begin{array}{c} 1.4 \\ 1.2 \\ 1.7 \\ 2.5 \end{array} $	K K H H	
kaolinite (K) halloysite (H)	0.78-2.39 2.50-3.80	K H	+

^a Criteria given in text.

and X-ray diffraction showed several fairly strong kaolinite lines. Acid treatment undoubtedly destroyed some of the clay present, as well as decomposed the carbonates, producing colloidal material to account for the medium 150 C. endothermic peak. Thermogram 11b bears little resemblance to that of the untreated material; however, it must be remembered that Curve 11b represents only 15 percent of the original sample. This remaining clay could be nontronite, beidellite, or even illite plus amorphous material. X-ray examination indicated that the clay was an expanding lattice type, i.e., a montmorillonoid. After carbonate removal Curve 12b was found to be illite and quartz, by both differential thermal analysis and X-ray.

Pretreatment, Fractionation

The effect of fractionation is well illustrated by Sample 13. Before fractionation (Curve

13b), the sample is 50 percent quartz. and from the thermogram the clay seems to be kaolinite, except that the large adsorbed water reaction is not in harmony with that of kaolinite. Quartz has disappeared from the thermogram after fractionation, leaving only clay. The large 150 C. peak suggests a montmorillonoid, and the 580 C. endothermic peaks suggest nontronite as the most likely species. The rather abrupt change in slope on the 580 C. reaction and the exothermic peak at 900 C. are interpreted as being due to kaolinite. X-ray patterns obtained by Havens (11) and in this laboratory confirm this conclusion. The small endothermic reaction at about 325 C. is gibbsite.

Illite-Montmorillonoid Soils

Thermograms of Samples 14-19 are characterized by a large adsorbed water reaction and endothermic peaks in the range of 600 to 800 C. Such a combination suggests either a mixture, or more probably, interstratification of illite and montmorillonoid. Because of the variability in thermal behavior of the montmorillonoids as well as the illites these samples are difficult to analyze. Therefore, the qualitative statement illite-montmorillonoid is all that is warranted on the basis of differential thermal analysis alone.

X-ray examination of true mixtures of illite and montmorillonoids gives the 10 Å line characteristic of illite and the 14 to 17 Å line of montmorillonoids that varies with hydration. Regular interstratification gives a high spacing reflection⁴ and a series of higher order reflections which are precise submultiples of this. As interstratification becomes random. several changes take place in the X-ray pattern. The (001) spacing, although still sharp, shifts to a position between that of the (001) reflections of the pure components and the extent of the shift depends upon the relative proportion of the two components. Higher order reflections do not form an integral series of (001), and there is also a marked rise in scattering near the primary beam.⁵

X-ray patterns on Samples 14, 15, and 16 showed lines of illite and montmorillonoid but no lines attributable to regular or random interstratification; accordingly, these samples

³ Treat with 0.5 N acid until further additions give no effervescence, then increase the strength to 1.0 N and finally treat with 2.0 N. A small portion of sample is then tested with concentrated HCl to see that all carbonates have been removed. On rare occasions, stronger than 2.0 N acid is needed.

For example, illite (10 Å) interstratified with mont-morilonoid (17.5 Å glycerol solvated), in the proportion 1 to 1 will give a high spacing of 27.5 Å.
 See Chapter XI (2) for extensive treatment of inter-

stratification.

are considered to be mixtures of illite and montmorillonoid. The montmorillonoid ie probably montmorillonite in Samples 14 and 16. and nontronite in Sample 15. Only Sample 14 has sufficient resolution of the illite and montmorillonoid peaks to make a quantitative estimation from the thermal data. In view of Dval and Hendricks' recent paper (6), the authors are hesitant to use X-ray data for quantitative estimation of montmorillonoids. A total potash determination on the clay fraction of Samples 15 and 16 would enable one to assign a specific portion of the sample to illite, because illite is the only clay mineral that contains potassium as an integral part of the crystal structure. Since this assumes illite to be the only mineral present containing potassium, it is essential that the sample be fractionated to remove feldspars. Feldspar removal can be checked by X-ray

diffraction. Sample 17 has previously been called beidellite, and this name is used here. Grim and Rowland (10) have called beidellite a mixture of montmorillonoid and kaolinite, which is also consistent with the X-ray and thermal data of this particular sample.

The Bearpaw Shale is an illite-montmorillonoid that displays great heterogeneity. Previous analyses (20) were contradictory; the shale was reported to be predominately montmorillonite in one case and predominately kaolinite in another case. The first sample analyzed in this laboratory (18a) was predominately illite, with some montmorillonite and kaolinite. Because all three of the major clay mineral groups had been reported in the same soil, it was decided that additional samples should be examined. One of these, Sample 18b, gave a typical illite thermal curve, and X-ray examination showed predominately illite with some montmorillonoid. By the use of differential thermal analysis and X-ray, Sample 18c, while definitely dominated by montmorillonite, contained some illite. In view of the variability between Samples 18b and 18c, which were taken a mere 24 ft. apart in the same hole, it is not surprising that Sample 18a and the results of previous analyses were so divergent.

On the basis of differential thermal analysis, Sample 19 was included in the illite-montmorillonoid type materials, but X-ray examination proved it to be a mixture of illite and chlorite.

A comparison of chlorite thermograms with Sample 19 showed a sequence of peaks in general accord, except that the adsorbed water reaction of Sample 19 is larger. Since illite is known to be present, it will account for part of the 150 C. peak. The remainder is attributed to completely random interstratification of montmorillonoid on such a fine scale that it appears amorphous to X-rays. A part of the 150 C. endothermic peak is assigned to interstratification, because after heating to 550 C. for 1/2 hr., the intensity of the 10 Å line was considerably enhanced indicating completely random interstratification. Whether one attributes such phenomena to interstratification or to amorphous material is not important. It is believed that the best solution of this dilemma would be simply to report the extent of internal swelling as measured by glycol retention, because whether caused by completely random interstratification or by colloidal amorphous material, an increase in internal surface results.

Chloritic Soils

Thermograms of Samples 20 to 23 all have a medium-sized adsorbed-water reaction and a medium 600 C. peak, although above 700 C. there is considerable divergence among the group. The magnitude of the 150 C. peak is small when compared to the 600 C. reaction. if illite is the mineral responsible for both peaks. Chlorite minerals, when subjected to differential thermal analysis (19) give a small peak about 150 C. and a peak similar to illite about 600 C., followed by other exothermic and endothermic peaks of lesser importance. The exact nature of these higher temperature reactions depends on the particular chlorite species present; the presence of chlorite is, therefore, suspected in Soils 20 to 23.

The X-ray lines of chlorite minerals can be easily confused with those of kaolinite, especially if the particular chlorite is rich in iron. In such a case, the first and third order reflections are weak, while the second and fourth are strong, resulting in a pattern very difficult to distinguish from that of kaolinite. Heat treatment⁶, which decomposes minerals of the kaolinite group and enhances the 14 Å line of all chlorites, is very useful for resolving this problem. By the use of this procedure,

⁶ 550–600 C. for ½ hour (2).

Sam- ple No.	Soil	Supplied by:	Composition	Atterberg Limits, Natural Water Content	Remarks
1.	Sandy silt, Buggs Island Reservoir near Norfolk, Va.	Ohio River Divi- sion, Corps of Engineers	% Kaolinite, 90 Quartz, 10	$w_1 = 52.3$	
2.	Soapstone, Asia Minor	Dr. Karl Terzaghi, Harvard Univer- sity	Kaolinite, 100		Sold in market of a small village west of Ankara to natives, to be used as soap
3.	Brown clay, Nai- robi, Kenya, South Africa	Mr. E. P. Fitzger- ald, City Engi- neer's Office, Kenya	Halloysite, 100	$w_1 = 90$ $w_p = 45$ $w_n = 50$ to 105%	This soil used for fill ma- terial for dam; air-dry soil wets very slowly on immersion-i.e., possesses a degree of water repellency. Diffi- cult to compact. Nat- ural void ratio 1.4 to 2.0. Std. Protetor void ratio 1.2 to 1.4
4.	Silty elay, Cavinti, Laguna, P. I.	Mr. F. R. Lozada, Nat. Power Corp. Manila	Halloysite, 90 Limonite	$w_1 = 106 \text{ undried}$ $w_p = 74$ $w_1 = 82 \text{ oven dried}$ $w_p = 56$	Very plastic, sticky (sticky limit 86 per- cent) soil from borrow area near Lumot dam site. Residual deposit from weathering of lava flows
5.	Very soft clay, Northern Idaho	Mr. R. O. Hill, Boise, Idaho	Montmorillonite, 70 Goethite	$w_1 = 160 \\ w_p = 56$	This material of volcanic origin has caused se- vere stability prob- lems in Idaho-e.g., 12 slides in 232 mi. of road
6.	Bentonite, Alberta, Canada	Dr. A. Casagrande, Harvard Univer- sity	Montmorillonite, 100	$w_1 = 720 \\ w_p = 39$	
7.	Marl, Montezuma Swamp, Cayuga Lake, New York	Dr. A. Casagrande (Mr. A. H. Emery, New York High- way Dept.)	Dolomite and Cal- cite, 90 Hydrous aluminum oxides Organic Matter	$w_1 = 90 \text{ undried}$ $w_p = 45$ $w_1 = 83 \text{ air dried}$ $w_p = 49$ $w_1 = 63 \text{ oven dried}$ $w_p = 49$	Fresh water marl; car- bonate from both plants and animals; soil firm in natural state but very sensi- tive to remolding
8.	Serpentine, Yanco Tunnel, S.W. Puerto Rico	Dr. Karl Terzaghi, Harvard Univer- sity	Serpentine, 100		The serpentine squeezed into the tunnel and exerted heavy pressure on the temporary sup- ports
9.	Brown clay, Dogue Creek, Va.	Engineer Research and Development Lab. Fort Bel- voir, Va.	Illite, 70 Quartz, 30	$\begin{array}{c} w_1 = 30\\ w_p = 21 \end{array}$	This soil becomes sticky and untrafficable when wet
10.	Loess, Vicksburg, Miss.	Waterways Experi- ment Station (WES), Vicks- burg, Miss.	Quartz, 40 Dolomite, 20 Calcite, 20 Kaolinite, 20	$w_1 = 27 \\ w_p = 25$	Unweathered loess from hills in the immediate vicinity of WES. Soil has very high undis- turbed strength
11.	Clay, Israel	Mr. L. Zetlin, Israel, via Prof. Hough, Cornell Univer- sity	Dolomite, 85 Beidellite or Non- tronite, 15		This soil undergoes ex- cessive periodic vol- ume change, resulting in as much as 12 in. of swell during wet winter and 6 to 10-ft. deep cracks during dry summer. Struc- tures on this soil crack severely
12.	Silty gravelly sand, Truax AFB, Madison, Wis.	Frost Effects Lab. U. S. Corps of Engineers, Bos- ton, Mass.	Dolomite and Cal- cite, 40 Illite, 50 Quartz, 10	$w_1 = 14$ $w_p = 12$	This soil used in frost studies (Ref. 24); has a frost susceptibility classification of me- dium

TABLE 2 SOIL COMPOSITION AND PROPERTIES

Sam-	-			Atterberg Limits	
ple No.	Soil	Supplied by:	Composition	Natural Water Content	Remarks
13a.	Clay fraction of Red clay, near Eliza- bethtown, Ky.	Mr. J. H. Havens, Kentucky High- way Dept.	% Nontronite, 40 Kaolinite, 40 Gibbsite	$\frac{\%}{w_1 = 136 \text{ undried}}$ $\frac{w_1 = 36 \text{ undried}}{w_1 = 97 \text{ air}}$ $\frac{w_1 = 97 \text{ air}}{w_p = 41 \text{ dried}}$	This expanding soil was used in stabilization studies by the Ken- tucky Highway De- partment (Ref. 11)
13b.	Red clay, near Elizabethtown, Ky.	Mr. J. H. Havens, Kentucky High- way Dept.	Quartz, 50 Kaolinite, 10 Nontronite, 20	$w_1 = 34 w_p = 20$	This expanding soil was used in stabilization studies by the Ken- tucky Highway De- partment (Ref. 11)
14.	Buckshot clay, Mound, La.	Waterways Experi- ment Station, Vicksburg, Miss.	Illite, 60 Montmorillonite, 25 Quartz, 15	$w_1 = 67 w_p = 22$	Alluvial backswamp de- posit of Miss. River; it has high plasticity and low sensitivity
15.	Openwork-Gravel Clay, Chief Joseph Dam, Washington	Dr. A. Cusagrande, Harvard Univer- sity	Illite, 30± Nontronite, 60± Quartz, 5	$w_1 = 154$ $w_p = 28$	This clay is from the voids in the openwork gravel at the Chief Joseph dam site; it contains many shrink- age cracks. The origin of this cracked clay in the gravel has been discussed in Ref. 3
16.	Surface clay, Orange Free State Gold- fields, S. A.	Dr. E. J. Hamlin, via Mr. B. S. Berg- man, Johannes- burg, South Africa	Illite, 40 Quartz, 10 Montmorillonite, 20±	$w_4 = 34 w_p = 17$	This residual clay from Ecca shales has given much trouble from heaving associated with moisture changes (Ref. 14)
17.	Porterville Clay, Friant-Kern Canal, 2 mi South-East of Orosi, Cal.	Mr. W. G. Holtz, Bureau of Reela- mation	Beidellite, 100	$w_1 = 58$ $w_p = 23$ $w_n = 30$	This expanding clay has caused severe cracking of canal lin- ing because of its ex- pansive characteris- tics (see Ref. 12). Base exchange capacity 57 me./100 g., predom- inately Ca and Mg
18a.	Bearpaw Shale, near Saskatche- wan River, south of Saskatoon, Canada	Dr. Karl Terzaghi, Harvard Univer- sity	Illite, 70 Montmorillonite, 20 Kaolinite, 10		Slopes of this shale 5 to 1 or flatter and con- tain scars from vast slides, probably caused by gravity creep (Ref 20)
18b.	Bearpaw Shale, near Saskatche- wan River, south of Saskatoon, Canada	Mr. Peterson, Dept. of Agriculture, Saskatchewan	Illite, 70 Montmorillonoid	$w_1 = 69 \\ w_p = 22 \\ w_n = 18$	
18c.	Bearpaw Shale, near Saskatche- wan River, south of Saskatoon, Canada	Mr. Peterson, Dept. of Agriculture, Saskatchewan	Montmorillonite, 70 Illite, 15	$w_1 = 260$ $w_p = 38$ $w_n = 29$	
19.	Mud, San Fran- cisco Bay, Cal.	Dames and Moore, Cal.	Illite, 80 Chlorite	$w_1 = 74 w_p = 36$	This weak and com- pressible clay has caused many water- front and foundation problems
20.	Blue clay, Cam- bridge, Mass.	:	Illite, 50 Quartz, 25 Chlorite	$w_1 = 40$ $w_p = 25$	Probably the most tested clay in the world; moderately compressible, sensi- tive, low undisturbed strength
21.	Grey, silty quick- clay, Solbakken, Drammen, Nor- way	Mr. R. C. Vold, Geotechnical In- stitute, Norway	Illite, 60 Quartz, 20 Chlorite	$w_1 = 18.7$ $w_p = 16.5$ $w_n = 28.3$	This soil is a typical Norwegian quick- clay; i.e., it has a natural water content greater than its liquid limit; it is extraordi- narily sensitive, since its remolded strength is zero

TABLE 2-Continued

Sam- ple No.	Soil	Supplied by:	Composition	Atterberg Limits, Natural Water Content	Remarks
				~ ~ %	
22.	Fat Blue clay, On- soy, Southeastern Norway	Mr. R. C. Vold, Geotechnical In- stitute, Norway	Illite, 40 Quartz, 10 Chlorite	$w_1 = 67$ $w_p = 32$ $w_n = 55$	Post glacial deposit, base exchange capac- ity 14 me./100 g.
23.	Sandy clay, Dow AFB, Bangor, Maine	Frost Effect Lab. U.S. Corps of Engineers, Bos- ton, Mass.	Illite, 50 Quartz, 40	$w_1 = 30 w_p = 18$	This soil used in frost studies (Ref. 24); has a frost susceptibility classification of high
24.	Sandy silt, airport site near Arcata, Cal.	Mr. R. C. Mainfort, C.A.A.	Gibbsite, 30 Quartz, 30 Chlorite Disspore	$w_1 = 27$	This soil would not respond to stabiliza- tion with Portland cement (up to 20 per- cent tried) alone. Treated samples dis- integrated, probably due to swelling (Ref. 16)
25.	Clay, Mexico City, Mexico	Mr. Pedro Albin, Mexico City	Hydrous aluminum oxides, predomi- nately amorphous	$w_1 = 388$ $w_p = 226$	This clay (volcanic ori- gin) is world famous for its extremely high compressibility and sensitivity
26.	Sandy clay, Fort Belvoir, Va.	Engineer Research and Development Lab., Fort Belvoir, Va.	Quartz, 40 Kaolinite, 25 Hydrous Oxides of Iron and Alu- minum	$\begin{vmatrix} w_1 &= 49 \\ w_p &= 25 \end{vmatrix}$	Typical soil from Vir- ginia area; becomes very sticky, almost untrafficable, when wet

TABLE 2-Concluded

Samples 20–22 were found to contain appreciable chlorite, and although chlorite lines did not appear in the X-ray pattern of Sample 23, this does not preclude completely random interstratification of illite and chlorite, which would influence the thermogram but not the X-ray pattern. Quantitative estimation of chlorite from X-ray data was not made because of unknown variation in reflected intensities arising from isomorphous substitution.

Hydrous Oxide Soils

Although they contained no clay minerals, Soils 24 and 25 had considerable plasticity. Thermal analysis of Sample 24 showed mostly hydrous aluminum oxides, including the minerals gibbsite and diaspore, with possibly some illite or chlorite. X-ray diffraction gave strong lines of chlorite and diffuse lines attributable to gibbsite and diaspore.

Sample 25 contained only hydrous aluminum oxides, as evidenced by differential thermal analysis and X-ray. In fact, this material must be largely amorphous, as only very weak diffuse lines of the hydrous aluminum oxide bayerite appeared on the X-ray pattern.

A summary of the mineral analyses based on evidence presented is given in Table 2.

It is believed that by the use of total potash or by glycol retention, most of the vague cases would be eliminated.

ENGINEERING SIGNIFICANCE OF RESULTS

Table 2 summarizes the compositional data and properties of 26 soils; in nearly all cases the properties and field behavior presented were furnished by the supplier of the soil. The authors were unable to determine the Atterberg limits needed to complete the table because they did not have the required soil. From the data in Table 2 several interesting and significant observations can be made on the occurrence and properties of soil minerals.

Mixture of Minerals in Soils

Nearly all of the 26 soils analyzed contained more than one mineral; however, about 65 percent of the soils contained only one clay mineral. Since the clay minerals dominate the properties of cohesive soils, the relatively high percentage of soils with monoclay mineral portions is very encouraging. If all soils were as variable and heterogeneous in composition as the Bearpaw Shale, the use of compositional data to the engineer would be limited.



The prevalence of soils like Samples 1 to 6 means that the soil engineer can expect compositional data on many soils to be of considerable value to him.

Prevalence of Chlorite and Nontronite

The widespread occurrence of chlorite (Samples 19, 20, 21, 22, and 24) and of nontronite (Samples 11, 13, and 15) will surprise many engineers. Because recent research (2, 13, 18) suggests that chlorite may be a common mineral in fine grained soils, considerably more work on the identification and the properties of chlorite is needed.

Nontronite, a montmorillonoid containing large amounts of ferric iron, is certainly not, as was once thought, a rare mineral; in fact, it appears to be common as predicted by Ross and Hendricks (21). The undesirable properties—high plasticity, high compressibility, expandability—associated with montmorillonite are found to be characteristic of nontronite; for example, Sample 13a. The apparent prevalence of nontronite and its sensitivity to disturbance should emphasize the need for additional engineering data on this mineral.

Lack of Amorphous Soil Components

Some years ago it was commonly accepted that the fine-grained portion of soil consisted entirely of amorphous material. The inquiring eyes of the X-ray and electron microscope enabled the mineralogist to discover that the clays were composed predominately of crystalline material. In spite of this discovery, many engineers still think that clays contain an abundance of amorphous material.

It is interesting that only one soil, the notorious Mexico City clay, contains significant quantities of amorphous material. In fact, the sample of this clay analyzed revealed practically no crystalline material; analyses on other samples of Mexico City clay, by the authors, as well as by other experimentors (25), have shown this clay to be montmorillonitic. It may be that, as with the Bearpaw Shale, the composition of the Mexico City clay is quite variable. The high limits $w_1 =$ 388 and $w_p = 226$ suggests the presence of a montmorillonoid or a very large specific surface for the amorphous samples.

Heterogeneity and Variability of Soil

The soil engineer is aware that soil may be a mixture of several minerals and that this mixture can vary in composition within a single deposit. He should certainly hope that he is seldom, if ever, faced with a soil that has the extreme heterogeneity and variability of the Bearpaw Shale! The first sample (18a) of this shale analyzed showed it to be predominately illite. X-ray data were necessary to detect the relatively small amounts of kaolinite and montmorillonite.

Samples 18b and 18c are entirely different from each other and from 18a. The much larger adsorbed water deflection (see Fig. 3) on 18c than on 18b would lead one to expect the large difference in liquid limits, 260 percent compared to 69 percent. Viewing the compositions given in Table 2 for the three samples of Bearpaw Shale, one can easily see why such unlike compositions had been reported for the shale.

A stratified material like the marine deposited Bearpaw Shale can have a behavior typical of the most unstable layers. The vast slides which have occurred (Ref. 20 and correspondence from Terzaghi) in the Bearpaw Shales could not have been predicted as readily from the analysis of samples 18a and 18b as from that of Sample 18c.

Experience with the Bearpaw Shale points out an inherent weakness of using test data on a single small sample of soil to predict the behavior of a large mass of heterogeneous material and emphasizes the need for a thorough test program on such soils.

Properties of Kaolin Soils

The most common minerals in the kaolin group are kaolinite and halloysite, with kaolinite the more prevalent. While kaolinite, with a liquid limit of approximately 50 percent and a plastic limit of approximately 30 percent, is the least plastic of the common clay minerals, it is slippery when wet and can, therefore, cause engineering problems. It is used for soap (Sample 2) because of its slipperiness and is often employed as a cosmetic or patent medicine base, e.g. "Peptokaolin." Kaolinite can present trafficability problems (Sample 26) when wet.

Halloysite, which is about twice as plastic as kaolinite, can be a very treacherous soil.



Grim (9) has already pointed out that at temperatures under 60 C. the hydrated form, halloysite $(4H_2O)$, can change to the more plastic form, halloysite $(2H_2O)$. Unlike the illites or other kaolin minerals, halloysite adsorbs certain organic materials. The adsorption of organic colloids may be the cause of the water repellency which Sample 3 exhibits.

High *in situ* and compacted void ratios are typical of halloysite (Sample 3) according to the experience of the Bureau of Reclamation (correspondence from Dr. Mielenz, head of the Bureau's Petrographic Laboratory). Difficulties in working and compacting halloysite should be expected.

Properties of Illitic Soils

It is not always realized that illite is the name of a mineral group about which so little is known that the individual minerals in the group have not been identified and named. While a liquid limit of 100 percent and a plastic limit of 55 percent are typical of the illites, the limits and other properties can vary considerably. Illite is the most common clay mineral group in the marine clays and usually occurs with other clay minerals as either a mixture or interstratified minerals.

Soils containing illites are more compressible and plastic than those containing kaolinite. While experience has shown illitic soils can cause the engineering problems characteristic of any fat clay (Samples 19, 20, and 22), they are not as treacherous as halloysite or the montmorillonoids.

Properties of Soils Containing Montmorillonoids

Since the attractive forces between the individual sheets in a montmorillonoid crystal are relatively weak, the sheets can be easily separated. Because water can separate the sheets with a resultant expansion of the crystal, the montmorillonoids are termed "expanding lattice" minerals. The very high specific surface caused by sheet separation and the relatively large electrostatic charge resulting from isomorphous substitution make the montmorillonoids the most active of the clay minerals.

The properties of a montmorillonoid depend to a marked extent on the nature of its exchangeable ions, e.g., sodium montmorillonite has a liquid limit of approximately 700 percent while iron montmorillonite has one of approximately 200 percent. The effect of exchangeable organic ions may be even larger.

The engineer has rightly become wary of soils containing montmorillonoid. He can be faced with severe problems in stability (Samples 5 and 18) and volume change (Samples 11, 16, and 17) that tax his ingenuity in dealing with these soils. A soil may contain only a small amount of a montmorillonoid and yet have its undesirable characteristics (Sample 11).

Alteration of Soil Properties

Casagrande pointed out as early as 1932 (4) that drying could alter the plasticity of a soil; experience has confirmed his original data. Drving reduced the plasticity of the marl (Sample 7) as it usually does with soils containing organic matter. The 43 percent reduction in the plasticity index of the Kentucky red clay (Sample 13a) caused by air drying is particularly interesting in view of the apparently widespread occurrence of the expanding mineral, nontronite. Ross and Hendricks (21) state that thorough dispersion of nontronite produces ribbonlike particles which were not apparent in the undisturbed clay. It would appear, therefore, that nontronite can be sensitive both to drying and to partial dispersion by remolding.

Much more care is required in the performance and interpretation of laboratory tests on soils containing halloysite and the montmorillonoids, especially nontronite, than on soils containing kaolin and illite.

Apparent Anomalies

Considerable data have shown the Atterberg limits to be usually very indicative of soil behavior. Since the liquid limit measures the amount of water a soil can imbibe before losing its strength, a high limit normally warns that expanding minerals may be present. The acceptance and use of limits has rightfully grown steadily and will most likely continue to do so. They have been used to identify, in a qualitative manner, the highly compressive and expansive soils. It is important, therefore, to point out the occasional soil wherein the limits apparently fail to indicate accurately its composition and be-





havior. The values of the limits appear to be much too small for Samples 9, 16, 17, and $21.^7$

The limits for these four soils, Samples 9, 16, 17, and 21, should be approximately double the measured values given in Table 2 to be consistent with the compositional analyses. The field behavior of these soils appear much more consistent with the compositional analyses than with the limit values.

CONCLUSIONS

This paper clearly shows the importance of compositional data on soils. Mineral analyses of soils are excellent for soil description and are usually reliable indicators of soil behavior. For soils containing such minerals as montmorillonoid and halloysite, a mineral analysis can be more valuable than the results of routine laboratory tests. On large engineering projects, mineral analyses of the soils involved should be made, not only as an aid in design, but also for determining the size and scope of the engineering test program needed.

The value of compositional data will become more important as identification techniques are improved and the behavior of the various minerals is more fully investigated.

ACKNOWLEDGEMENT

The studies described in this paper were made possible by the coöperation of many people and organizations. The authors are grateful to those (listed in Table 2) who generously supplied the soils and usually extensive engineering data; the interpretations of the data are entirely the authors' and they accept full responsibility for them.

All of the mineral analyses were made at M. I. T.; the thermal analyses in the Soil Stabilization Laboratory and the X-ray analyses in the M. I. T. Mineralogy Laboratory. The studies reported were partially supported by the Engineer Research and Development Laboratories, Fort Belvoir, Virginia, and partially from funds given to

the Soil Stabilization Laboratory by various industrial organizations.

For aid in performing the mineral analyses, James K. Mitchell, research assistant, and Fred Flanders, technician, of the Soil Stabilization Laboratory, deserve the appreciation of the authors.

REFERENCES

- BRAMAO, L. et al; 1952. "Criteria for the Characterization of Kaolinite, Halloysite, and a Related Mineral in Clays and Soils." Soil Science 73: 273-287.
- 2. BRINDLEY, G. W. (editor); 1951. X-ray Identification and Crystal Structures of Clay Minerals. The Mineralogical Society, London.
- CARY, ALLEN S.; May 1950. "Origin and Significance of Openwork Gravel." ASCE Proceedings 76, Separate No. 17.
- 4. CASAGRANDE, A.; October 1932. "Research on the Atterberg Limits of Soils." Public Roads.
- DYAL, R. S. AND HENDRICKS, S. B.; 1950. "Total Surface of Clays in Polar Liquids as a Characteristic Index." Soil Science 69:.421-432.
- DYAL, R. S. AND HENDRICKS, S. B.; 1952. "Formation of Mixed Layer Minerals by Potassium Fixation in Montmorillonite." Soil Science Society of America Proceedings 16: 45-48.
- FIELDES, M. et al; 1952. "Relation of Colloidal Hydrous Oxides to High Cation Exchange Capacity of Some Tropical Soils of the Cook Islands." Soil Science 74: 197-205.
- GAMMON, N. JR.; 1951. "Determination of Total Potassium and Sodium in Sandy Soils by Flame Photometer." Soil Science 71: 211-214.
- 9. GRIM, RALPH E.; June 1949. "Mineralogical Composition in Relation to the Properties of Certain Soils." *Geotechnique 1* No. 3.
- GRIM, R. E. AND ROWLAND, R. A.; 1942.
 "D. T. A. of Clay Minerals and Other Hydrous Oxides." American Mineralogist 27: 801-818.
- 11. HAVENS, JAMES H. AND GOODWIN, WILLIAM A.; November 1951. "Clay Mineralogy and Soil Stabilization." Highway Materials Research Laboratory, Kentucky Department of Highways, Lexington, Kentucky.
- HOLTZ, W. G. AND GIBBS, H. J.; June 1952. "Engineering Properties of Expansive Clays." Meeting of the ASCE, Denver, Colorado.

⁷ Atterberg limits are usually measured on that portion of the soil passing a No. 40 sieve; as pointed out, the minueral analyses reported in Table 2 were made on the minus-140-sieve portion of a sample. This difference in test procedure can partially account for the limits appearing too low on soils containing much material finer than a No. 40 sieve and coarser than a No. 140. Sample 17 had less than 5 per cent material in this range; Sample 16 had 25 precent (the data are not available for 9 and 21). The difference of procedure would not explain the low limits for Samples 17 and 16; it is felt that the same holds for Samples 9 and 21. Using that portion of a soil finer than a No. 140 or 200 sieve erities of a soil.

- JEFFRIES, C. D. et al; "Mica Weathering Sequence in the High Field and Chester Soil Profiles." Presented at Section II of the Annual Meeting of the American Society of Agronomy, Cincinnati, November 1952.
- JENNINGS, J. E.; October 1950. "Foundations for Buildings in the Orange Free State Goldfields." South African Council for Scientific and Industrial Research.
- LAMBE, T. W.; 1952. "Differential Thermal Analysis." PROCEEDINGS, 31st Annual Meeting, Highway Research Board, pp. 621-641.
- MAINFORT, R. C.; February 1951. "A Summary Report on Soil Stabilization by the Use of Chemical Admixtures." *Technical Development Report No. 136*, Civil Aeronautics Administration.
- VAN DER MAREL, H. W.; 1950. "Identification of Minerals in Soil Clay by X-ray Diffraction Patterns." Soil Science 70: 109-136.
- MARTIN, R. TORRENCE AND RUSSELL, M. B.; October 1952. "Clay Minerals for Four Southern New York Soils." Soil Science 74: 267-279.
- ORCEL, J. M.; 1927. "L'Eau des Chlorites". Bulletin de la Societé Francaise de la Minéralogie 50: 278-322.

- 20. PETERSON, ROBERT; September 1952. "Studies—Bearpaw Shale at Damsite in Saskatchewan". Convention Preprint Paper No. 52, ASCE Centennial Convocation, Chicago, Illinois.
- Ross, C. S. AND HENDRICKS, S. B.; 1945. "Minerals of the Montmorillonite Group." U. S. Geological Survey Professional Paper 205-B.
- 22. SAND, L. B. AND BATES, T. F.; 1952. "Mineralogy of the Residual Kaolins of the Southern Appalachians." Presented at Geological Society of America, Annual Meetings, Boston, Massachusetts.
- 23. "Final Report, Soil Solidification Research, Vol. 1, Summarization, Fundamental and Applied Research." Cornell University, Ithaca, New York, September 1951.
- 24. "Frost Investigations, Fiscal Year 1951." Second Interim Report of Investigations, Corps of Engineers, New England Division, Boston, Massachusetts.
- "Identificacion y Estudio de la Estructura," 1951. Arcillas del Valle de Mexico, No. 4. ICA, Mexico City.
- "Variacion de Propiedades Mecanicas con la Profundidad," 1952. Arcillas del Valle de Mexico, No. 9. ICA, Mexico City.