the advantage of being a purely mechanical measurement and as such, more accurate and free of the personal factor which is prevalent in the present standard method.

2. The liquid limit as determined by the Casagrande mechanical device gives the water content at which a clay flows under a series of blows. Where the soil may be subject to dynamic forces this method would be the proper type of liquid limit test. For static conditions a more general definition of liquid limit would be the water content of the soil at a prescribed static shear resistance. The vane can be used to measure the shear resistance with considerable accuracy. The prescribed vane shear value might be that found at the liquid limit by the Casagrande method for non-sensitive fat clays.

3. Comparisons made between shear strengths by unconfined compression tests and vane tests showed lower shear values by the vane method, in general. This seems to be due to the relatively large zone of disturbance for small diameter vanes. This disturbance has a much greater influence on the vane shear strength at water contents below the plastic limits than at higher water contents. The data is inadequate to make any evaluation of the accuracy of the shear strengths as obtained by the two methods.

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Composition and Engineering Properties of Soil (III)

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Two natural soils, one from east Africa and the other from the western United States, composed predominantly of the clay mineral halloysite, were subjected to plasticity, compaction, permeability, strength, and frost tests. The halloysite samples exhibited low maximum densities and high optimum water contents, the extreme being a maximum density of 71 lb. per cu. ft. at an optimum water content of 47 percent. Since the sample of halloysite from east Africa was the halloysite $4H_2O$ form, dehydration studies on the hydrated form and comparative tests on the hydrated and dehydrated form were possible. These tests showed that air drying the hydrated form at room temperature caused it to lose irreversibly some of the interlayer water.

The natural fines of a sandy clay from Virginia were removed and successively replaced with nontronite made homoionic to the following ions: sodium, potassium, calcium, magnesium, and ferric iron. Plasticity, compaction, permeability, strength, and consolidation tests on the prepared soil were run. As expected, the sodium form was found to be the most plastic and compressible, and contained the highest maximum dry density and the lowest optimum moisture content.

Four chlorites (clinochlore, prochlorite, and two thuringites) were ground and subjected to plasticity and compaction tests. Two of the chlorites were non-plastic and the other two had plasticity indexes of only 4 and 10 percent even though the liquid limits were 44 and 47 percent, respectively. The prochlorite had an optimum moisture content of 12 percent even though its plastic limit was 40.

• FOR a number of years, the M.I.T. Soil Stabilization Laboratory has been conducting research in "soil technology"—the composition, geological history and structure of soil and their effect on its behavior. One phase of this research is a continuing, long-range study of the influence of the composition of soil on its engineering properties. Two approaches have been employed, namely: subject selected soil minerals to laboratory tests and make compositional analyses on soils involved in engineering projects.

Past research (Lambe and Martin, 1953, 1954) showed that three clay minerals, halloysite, nontronite and chlorite, are apparently much more abundant and important to the soil engineer than commonly thought. Samples of these minerals were obtained and tested. While the data are far too few to permit complete delineation of the properties, they do indicate the general behavior of the minerals.

Compositional analyses, along with classification test results, are presented on twelve soils. The techniques of analyses and the engineering significance of the results are discussed.

HALLOYSITE

Structure

The clay mineral halloysite exists in two forms, halloysite($4H_2O$)—"hydrated halloysite"—and halloysite($2H_2O$)—"dehydrated halloysite($2H_2O$) is identical to that of kaolinite, it is considered a kaolin mineral. Just as with kaolinite, halloysite is built of alternating gibbsite and silica sheets. Halloysite($4H_2O$) contains a monomolecular layer of water between each kaolin layer; the removal of this interlayer water results in halloysite($2H_2O$).

The a and b dimensions of the gibbsite sheet are slightly different from the corresponding dimensions of the silica sheet. When the gibbsite-silica sheets are stacked on top of each other in kaolinite, successive units are close enough together for the difference in dimensions to be taken up as a slight strain within the crystal. The interlayer water makes the sheet spacing in halloysite too large to allow the crystal strain needed for flat stacking in the *c* dimension. Thus, while kaolinite crystals are pseudohexagonal plates, halloysite crystals are hollow cylinders, resulting from the curling of the kaolin units to accommodate the differences in *a* and *b* dimensions.

Measuring particles from many halloysite samples, Bates et al. (1950) found the tubes had an average outside diameter of 700A. and an inside diameter of 400A. The tubes generally have lengths 5 to 10 times their outside diameters. Fig. 1, an electron micrograph of the Kenya halloysite described in the following section of this paper, shows the tubular shape of halloysite particles.

Properties of Kenya Halloysite

Previously reported results (Lambe and Martin, 1953) showed a soil from Nairobi, Kenya, Africa, composed entirely of halloysite. Additional samples of this borrow soil for the earth-filled Sasumua Dam were obtained.¹ Compositional analyses showed these samples to be 80% halloysite(4H₂O) and 13\% free iron oxide, mostly geothite.

Egbert and Jones (1954) subjected the Kenya soil to laboratory testing then reduced it to the dehydrated form by heating to a constant weight at 105°C and re-tested it. Their data presented in the remaining portion of this section permit a comparison between the two forms of hallovsite.

1. Dehydration. Samples of the Kenya soil

¹ The Sasumua Dam is in Aberdare Mountains, 8,000 feet above sea level, near South Kinangop, Naivasha, Kenya. The length of the dam is 1110 feet and the maximum height 112 feet. The geological formation at the site is weathered lava, underlain by a stratum of sound lava 40 to 60 feet thick. The Consulting Engineers for the Sasumua Dam are Howard Humphreys and Sons of London, Mr. E. P. Fitzgerald, the Deputy Resident Engineer, furnished the samples to the writers; Mr. Hugh Dixon, a partner of the firm, supplied information on the dam and dam site. Advisers to the Consulting Engineers included; Dr. Terzaghi, Dr. Skempton and Messrs. Scott and Wilson.

568

SOILS



Figure 1. Electron micrograph of Kenya halloysite. Magnification approx. 30,000×.

were subjected to four different drying conditions; they were periodically weighed and X-ray diffraction patterns obtained. In Fig. 2 the drying curves are plotted. If the X-ray analysis of the samples showed hallovsite (4H₂O), the weight-time point is indicated with an 0; but if the irreversible dehydration of some of the halloysite (4H₂O) was observed, the point is indicated with an X. Fig. 2 shows the transformation of mineral begins at 10% water content based on a dry weight of hal $loysite(2H_2O)$. This 10% value is in excellent agreement with the theoretical value obtained by multiplying the percentage of halloysite $(4H_2O)$ in the sample (80%) by the fraction of interlayer water computed from the formula (.139).

The results in Fig. 2 raise a most interesting question—is the interlayer water soil mineral or pore water? This water is linked to mineral surfaces so that it does not behave as free water and cannot properly be considered as pore water. On the other hand, all finegrained soils contain some water held by mineral surfaces; for convenience, this water is usually considered as pore water.

The following results include properties for hydrated halloysite(4H₂O), with the interlayer water considered as water (C = 0) and as mineral (C = .10). Since routine laboratory testing techniques define dry weight as that obtained by drying to constant weight at 105° or 110°, the interlayer water would occur as pore water (i.e., C = 0).

2. Particle Size. A portion of Kenya soil passing the #200 sieve was subjected to a hydrometer test, dehydrated, and re-tested. The data, plotted in Fig. 3, show two interesting facts. First, the dehydration from halloysite(4H₂O) to halloysite(2H₂O) caused an increase in particle size by aggregation, as one would expect. Second, the soil composed of 80% clay minerals have a small percentage of clay-size particles, 18% for halloysite (4H₂O) and 8% for halloysite(2H₂O).

The particle size curve in Fig. 3 for halloy-





TABLE 1 SPECIFIC GRAVITY

	Natural Soil	Portion Passing # 200 Sieve
$\begin{array}{l} Halloysite(2H_2O) \\ Halloysite(4H_2O) C = 0 \\ Halloysite(4H_2O) C = 0.10 \\ \end{array}$	$2.95 \\ 3.03 \\ 2.55$	2.81 3.07 2.48

TABLE 2 ATTERBERG LIMITS

	Liquid Limit	Plastic Limit	Plasti- city Index
$\begin{array}{l} Halloysite(2H_{2}O) \\ Halloysite(4H_{2}O) \ C = 0 \\ Halloysite(4H_{2}O) \ C = 0 \\ 0 \\ \end{array}$	%	%	%
	57.7	47.3	10.4
	70.4	55.7	14.7
	54.6	41.6	13.0

site(4H₂O) with C = .10 is essentially the same as that for C = 0 since the effects of this interlayer water partially cancel out in the computations.

3. Specific Gravity.² The specific gravities in Table 1 show a significant difference among the various values.

4. Atterberg Limits. The Atterberg limits in Table 2 show that: routine test techniques give a plasticity for halloysite $(4H_2O)$ which is too high; and the plasticity of the hydrated with C = .10 is not much different from the dehydrated form.

5. Strength, Permeability and Density of *Compacted Soil*. Samples of hallovsite(4H₂O) and halloysite(2H₂O) were compacted in the Wilson Miniature device;³ each specimen was equilibrated at its moisture content 24 hours prior to compaction. Some of the compacted specimens were subjected to permeability tests and others to unconfined compression tests. The results are plotted in Fig. 4.

The bottom set of curves in Fig. 4 illustrates the very high optimum water content and low maximum density characteristic of

³ A compactive effort of 25 tamps with a 40-lb spring on three layers was employed. This method of compaction was also used in the studies described in the next two sections.

halloysite. The relative flatness of the compaction curves is also an important characteristic of halloysite.

The permeabilities of the compacted samples appear surprisingly high in view of the relatively high liquid limits, but are not unreasonable when the low densities are considered. The shape of the halloysite particles, rod-like, is not one that encourages them to pack in an orderly, dense structure.

The top set of curves in Fig. 4 suggests that the hydrated form is "stronger" than the dehydrated. Considerably more data are needed, however, to determine which form of halloysite has the better strength characteristics. One would excpect hallovsite($2H_2O$) to have significantly less sensitivity to moisture, i.e., less expansion and less strength loss upon prolonged exposure to water.

6. Frost Susceptibility. Samples of halloysite $(4H_2O)$ and halloysite $(2H_2O)$ were each compacted and subjected to freezing tests by the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, Boston. Fig. 5 dramatically shows the results—the hydrated form heaved 220% of its original height and the dehydrated form, 135%. By the Corps of Engineers' frost susceptibility classification, the susceptibility of the hydrated form is "very high" (the top classification) and the dehydrated form, "high."

X-ray patterns of the samples after melting showed that the halloysite(4H₂O) was not dehydrated by the freezing. This fact suggests that halloysite(4H₂O) does not lose its interlattice water upon freezing.

7. Discussion of Results. Even though data on only one sample of halloysite have been presented and these data are not complete, they do permit several important observations. Halloysite, hydrated or dehydrated, has: low maximum compacted density, high optimum water content, high permeability and high frost susceptibility. The hydrated form can easily irreversibly dehydrate, at least partially, at room temperature and humidity. The dehydration is accompanied by a change of properties.

The engineer should know when he is working with halloysite. The proper conduct and interpretation of laboratory tests, and the intelligent handling of this clay mineral in the field almost demands that he have compositional data.

² The following properties of the Kenya soil were obtained by Dr. A. W. Skempton at Imperial College, London: Specific Gravity = 2.83 Liquid Limit = 85% Plastic Limit = 55% Standard Maximum Dry Density = 70 lb/cu.ft. Permeability = 3 × 10⁻⁷ cm/sec.
Undisturbed fill samples showed: Water Content = 51% Dry Density = 70 lb/cu.ft. Degree of Saturation = 94%
⁸ A compactive effort of 25 tamps with a 40-lb spring on



NONTRONITE

Structure

Nontronite, a member of the montmorillonoid group, is a 2:1 layer silicate in which the c axis dimension depends on the nature and amount of pore fluid. The crystal structure of nontronite and montmorillonite are essentially the same, the difference being in the nature of the isomorphous substitution which is shown by the structural formulas (Ross and Hendricks, 1945):

Montmorillonite:

SOILS



Figure 5. Frost tests on Kenya halloysite. Halloysite (2H₂O) Halloysite (4H₂O)

Nontronite:

$$\substack{ \substack{ \stackrel{\text{Na.}_{33}}{\uparrow} \\ \text{Fe}_{2.00}(\text{Al.}_{33}\text{Si}_{3.67})\text{O}_{10}(\text{OH})_2 } }$$

The iron in nontronite produces a strain in the crystal lattice that has a pronounced effect on the morphology of the individual particles. Nontronite exhibits a definite lath-shaped particle in contrast to montmorillonite in which the a and b dimensions of the particles are about equal. Measurements on one nontronite (Marshall et al. 1942) showed the dimensions of particles occurring in the 200-50 $m\mu$ equivalent spherical diameter fraction to be 567 m $\mu \times 108$ m $\mu \times 14$ m μ . Ross and Hendricks (1945) ascribed the shape of nontronite particles to a secondary cleavage parallel to b or a which, on dispersion of the clay, gives rise to the laths. This explanation is consistent with the optical continuity observed over rather large areas on undisturbed nontronite samples.

From the morphology of nontronite one would expect more broken bonds, and therefore, the higher cation exchange capacity in nontronite (145 \pm m.e./100 g) than in montmorillonite (100 \pm m.e./100 g). This secondary cleavage would also explain the reason Jackson and Truog (1939) found no increase in exchange capacity of nontronite after fine grinding whereas montmorillonite did show an increase.

Properties of Virginia Soil With Nontronite Fines

The nontronite used in these studies was the API (API, 1951) reference clay mineral H33b from Manito, Washington. The high cation exchange capacity, 145 m.e./100 g, necessitated engineering tests be run on homoionic forms of the minerals. Since not enough nontronite was available to run tests on samples of 100% nontronite, the fines of a sandy clay from Fort Belvoir were removed, and replaced with nontronite.

All particles finer than 2μ (10% by weight) were removed by successive sedimentation, replaced with nontronite, and the resulting soil then made homoionic to sodium. After the sodium form was tested, each of the following forms was prepared and tested: calcium, potassium, magnesium and ferric iron.

Fig. 6 presents the strength and density of compacted samples as a function of molding water content; Table 3 summarizes these, as well as limit, permeability and consolidation tests.

Few general statements on the effect of nontronite on soil properties can be drawn from the data in Fig. 6 and Table 3 for several reasons: the scarcity and limited nature of data; compaction samples were reused; and the incomplete replacement of clay minerals in the natural soil. While the natural clay contained only 10% finer than 2μ it was composed of 25%, by weight, of clay minerals. Over half of the clay was in the silt size portion and was, therefore, not removed by fractionation at the 2μ size.

The data showed the prepared soil made homoionic to sodium was much more plastic,



TABLE 3 SUMMARY OF PROPERTIES OF VIRGINIA WITH NONTRONITE FINES

Ionic Form of Fines	Atterb	erg Lir %	nits in	C F	ompac Permea	tion— bility
	w1	w_p	W3	γd	wopt	k at γ_d max.
Sodium Potassium Calcium Magnesium Ferric iron. Natural Va. soil.	$72.0 \\ 38.5 \\ 36.9 \\ 41.5 \\ 47.6 \\ 45$	23.7 26.8 23.5 19.2 24.8 22	$16.6 \\ 17.9 \\ 14.7 \\ 12.5 \\ 16.2$	<i>lb/cu fl</i> 117.2 104.7 114.9 114.2 109.2 106.0	% 13.5 20.0 14.8 14.2 17.2 19.0	$\begin{array}{c} cm/sec.\\ 9.3 \times 10^{-9}\\ 9.9 \times 10^{-9}\\ 9.8 \times 10^{-8}\\ 5.0 \times 10^{-8}\\ 1.1 \times 10^{-7} \end{array}$

impermeable and compressible than the other ionic forms. These results are in agreement with corresponding data on other soils (see, for example, Cornell, 1951).

The curves in Fig. 6 show that the exchangeable ions have a surprisingly large effect on the compaction and strength characteristics of the prepared soil. This effect would have probably appeared considerably larger had the samples not been reused. The results show that sodium gives a higher maximum compacted density and a lower optimum water content: potassium and ferric iron do the reverse, decrease maximum density and increase optimum water content. These effects are in agreement with theoretical concepts since sodium behaves as a "dispersing ion" and potassium and iron as "aggregating ions." The obvious implication of these results and theoretical concepts is to consider salts of these ions as trace additives to alter the compaction characteristics of soil. Such trace additive stabilization is under investigation in the Soil Stabilization Laboratory at M.I.T.

CHLORITE

Structure

Chlorite is a layer silicate composed of alternating mica-like and brucite-like layers. Substitution of Al^{3+} for Si^{4+} in the mica-like layer causes a charge deficiency which is balanced by the excess charge in the brucitelike layer caused by a substitution of trivalent for divalent ions. There is, thus, an analogy between the structure of illite and chlorite; illite being mica-like layers cemented together by K⁺, and chlorite mica-like layers bound together by the charged brucite-like layer.

No data are available on the size and shape





of chlorite particles in natural clay. Since chlorite is commonly found in association with other clay minerals, often in complex intergrown crystals, a study on the morphology of chlorite from natural clay must await considerable refinements in experimental techniques.

Chlorite must today be ranked as a common

clay mineral. The number of occurrences of chlorite in natural clays reported in the last few years has increased markedly. This increase is probably due, in large measure, to the improved testing procedures that permit positive identification of chlorite from montmorillonoid and kaolin minerals. As with the delineation of the morphology of clay-size chlorite, identification of individual species in a clay is at present extremely difficult. It is believed that chlorites rich in iron are the most common species found in clavs.

Since divisions within the chlorite group are arbitrary, the boundaries between the neighboring species are difficult to draw and thus the species designations are of little value; however, it has been found that, in general, chlorites high in ferric iron have physio-chemical properties quite different from chlorite low in ferric iron. Some engineering data for clinochlore and prochlorite, representative low-iron chlorites, and for thuringite, a representative high-iron chlorite, are reported helow

Properties of Four Chlorites

Fig. 7 presents compaction curves on four chlorites (samples ground from large crystals) and Table 4 summarizes the compaction results, as well as, giving particle size and limit data. Included in Table 4 are the corresponding properties of a silt from New Hampshire, which has a particle size distribution very close to those of the chlorites, and results obtained by Casagrande (1932) on ground mica, quartz and feldspar.

The data in Table 4 show the low-iron chlorites are much more plastic than the high-iron ones. The high-iron thuringites have properties more like those of fine-grained quartz, feldspar or other non platy mineral. The low-iron chlorites behave more as clay minerals, as does fine-grained mica.

Studies (Stephen and Mac Ewan, 1949, Lambe and Martin, 1953 and 1954) have shown that chlorites in natural clays can cause engineering problems from their high compressibility, water sensitivity and, even, lattice expansion. The chlorite species that were present in these natural clays are, unfortunately, unknown.

MINERAL ANALYSES ON NATURAL SOILS

During 1954 compositional analyses were made on many soils involved in engineering projects. The composition and some of the properties of twelve of these soils are presented in Table 5.

Test Procedures of Mineral Analyses

Test procedures, clay mineral definitions, and methods of computing mineral percent-

TA	BLF	E 4
PROPERTIES	\mathbf{OF}	CHLORITES

Mineral	Frac- tion	Atte Limi	rberg ts in %	Com	paction
	2 µ	w_1	w_p	wopt	γd
			-	%	lb/cu ft
Low iron	5	17	36	20	93
Brochlorite	6	11	40	12	100
High iron	0	77	10	12	
Thuringite A	10	Not	plastic	19	113
Thuringite B	3	Not	plastic	13	111
New Hampshire silt	7	24	22	21	99
Mica*	66	77	56	-	_
Quartz*	74	Not	plastic		-
Feldspar*	72	Not	plastic		

* From Casagrande (1932).

ages have been described previously (Lambe and Martin, 1954). The tests employed were differential thermal analysis (DTA).⁴ X-rav diffraction, electron microscopy, and total potash and glycol determinations. C. E. Hall, Associate Professor of Biophysics, M.I.T., kindly supplied the electron micrographs. The feldspar percentages given in Table 5 are rough approximations made from the relative abundance of quartz and feldspar in the fine sand and coarse silt fractions.

The mineralogical character of the -2μ fraction is the basis for the three major groupings as well as the subdivisions within each major group.

Discussion of Mineral Analyses

1. Samples with Non Clay Mineral Fines. Thermograms (Fig. 8) showed carbonate minerals, calcite and dolomite, to be the dominant component of Samples 1 and 2. The endotherm at 500°C for Sample 2 is ascribed to organic matter which is not all oxidized on the first heating cycle so that an endotherm at 500°C occurs on the re-run. Organic matter determinations on the residue after carbonate removal gave 77 % organic matter in each case, which amounts to 11 and 15% organic matter

atures are uncorrected: Calibration: 50-50 quz-BaCO2 mixture. quartz $\alpha \rightarrow \beta$ - 569 ± 3°C, amplitude = 2.9 cm BaCO3 to α - 819 ± 3°C, amplitude = 13.3 cm BaCO3 to β - 988 ± 3°C, amplitude = 3.0 cm

⁴ In accordance with the recommendation of Mackenzie and Farquharson (1952) the following information concerning the DTA equipment in the M.I.T. Soils Lab is given: Heating Rate: 12.5° /min with maximum variation of less than 1° /min. Thermocouples: Pt-Pt (10% Rh).

Sample size: 1.35 cc.

Pretreatment; 7 days over saturated Ca(NO₃): 4H₂O soln. Temperature thermocouple: in Ni steel block; peak temperatures are uncorrected:

	Remarks		The carbonates are calcite and domite No avidance	of clay minerals by DTA or X-ray.				Surface soil from the very arid (Negev) region of Is- rael.	The highly interstratified nu- ture of the clay minerals probably leads to an un- derestimation of nontro- nite.	Mineral analysis on material free of columnar aggregates of gypsum. $97\% < 50\mu$; $55\% < 5\mu$	
	Engineering Properties				<i>U_a</i> = 180 psf	<i>U</i> _{<i>u</i>} = 540 psf	$U_r^a = 460 \text{ pst}$; $U_r^a = 460 \text{ pst}$; p of 1, e = 0.85; p of 7, e = 0.70	$\gamma_{d} = 113$ $\psi_{apt} = 17$ $\zeta_{\sigma} = 64 \text{ psi}$	Consolidation test data: p of 1, $e = 1.20$. p of 10, $e = 0.69$; start of test $e = 0.03$ 1.64, end of test $e = 0.33$	Triaxial Q_e comp str = 330 psi at strain rate = 0.04% per sect σ_e = 30 psi at 700% pcr sect σ_e = 30 psi: γ_d = 92: w_0pt = 21	$\begin{array}{l} \gamma_{tt} = 125\\ w_{opt} = 11\\ w_{c} = 62 \text{ psi} \end{array}$
PROPERTIES	Atterberg Limits and Natural Water Content	% UI	$\begin{array}{l} wl = 216\\ w_p = 65\\ w_n = 213 \end{array}$	$u_{T} = 759$ $u_{P} = 136$ $u_{n} = 610$	$\begin{array}{l} wt = 27\\ w_p = 14\\ w_s = 33\\ w_s = 33\end{array}$	$ \begin{array}{lll} wt &=& 18\\ w_p &=& 18\\ w_n &=& 40\\ w_n &=& 28\\ w_p &=& 28\\ \text{ldrying} & \text{air} \end{array} $	$w_{I} = \frac{34}{2}$ $w_{P} = \frac{21}{33}$ $w_{n} = \frac{33}{23}$ $w_{n} = 21$	$w_p = \frac{49}{21}$ $w_p = 21$ $w_s = 14$	$w_P = \frac{63}{17}$	$w_p = \frac{55}{30}$ $w_n = 22$	$w_{1} = 23.3$ $w_{2} = 14.6$
TABLE 5 SOIL COMPOSITION AND	Composition of Silt and Clay Portion in % by Weight		Carbonates = 85 0.M. = 11	Carbonates = 80 0.M, = 15	Illite = 35 Quartz = 20 Foldspars = 20 Foodspars = 20 0.M, = 0.6	$ \begin{cases} \text{IIIIte} = 25\\ \text{Micas} = 6\\ \text{Quarts} = 25\\ \text{Peldsars} = 25\\ \text{O.M.} = 0.5 \end{cases} $	$ \begin{array}{l} \left \begin{array}{c} \Pi \\ \Pi $	(Montmorillonoid = 30) (Illite = 15 'uartz = 25 Carbonates = 10	Nontronite = 55 (Illite = 20 0.M. = 2	Gypsum and carbonates = 50 [Illite = 20] [Montmorillonoid = 20]	$\begin{aligned} \text{Illite} &= 30\\ \text{Vermiculite} &= 5\\ \text{Quartz} &= 3\\ \text{Quartz} &= 3\\ \text{Feldspars} &= 20\\ \text{Fe}_2 O_3 &= 2,9 \end{aligned}$
	cle Size mm	-0.002		1		42	40	10	95		
	Parti	-0.07		1	100	86	88	24	100		~~~
	Supplied by		B. Fruhauf, New York, N.Y.	B. Fruhauf, New York, N. Y.	D. W. Taylor M.I.T.	D. W. Taylor, M.I.T.	D. W. Taylor, M.I.T.	A. Gutwurcel Tel-Aviv, Is- rael	J. Mulholland, Brisbane, Australia	R. V. Whitman, M.I.T.	Mass. Dept. of Public Works
	Soil		Grey ''clay'' from New Jersey	Brown ''clay'' from New Jersey	Silty clay from Labra- dor (G-3)	Silty clay I-2 from Labrador	Silty clay E-3 from Labrador	Lais soil from Israel	Black soil from (1001- diwindi, Australia	Dugway clay from Utah	Clayey silt M21 from Massachusetts
	Sample No.		-	6	~~	4	νņ	Ŷ	1-	ж	6

576

SOILS

0	Leda elay A-11 from Canada	E. Penner, Ot- tawa, Canada	100	65	$\begin{array}{l} \text{(Illite} = 25\\ \text{(Chlorite} = 10\\ \text{Quartz} = 10\\ \text{Feldspars} = 10\\ 0.M. = 0.7\end{array}$	$u_p = \frac{w_p}{2} = \frac{27}{70}$	$U_u = 1.6 T/ft^2$ in situ pre- compression pressure = 1.9 T/ft^2	Ref. Crawford, 1953.
11	Leda clay A-25 from Canada	E. Penner, Ot- tawa, Canada	99	10	$ \begin{array}{l} \text{Illite} = 30 \\ \text{Chlorite} = 10 \\ \text{Carbonates} = 10 \\ \text{Carbonates} = 10 \\ \text{Feldspars} = 20 \\ \text{Quartz} = 15 \\ \text{Quartz} = 0.6 \end{array} $	$w_{D} = \frac{19}{w_{A}} = 35$	$U_u = 1.0 T_i f t^a$ in situ pre- compression pressure = 2.3 $T_i f t^a$	Ref. Crawford, 1953.
12	Clay from Dorena Dam, Washington	('orps of Engi- neers	15	1	$\begin{cases} \text{Kaolinite} = 40\\ \text{Montmovillonoid} = 25\\ \text{Illite} = 7\\ \text{PeD}a = 12\\ 0.M. = 2\\ 0.M. = 2\\ \text{Gibbsite} = \text{truce} \end{cases}$	$w_p = \frac{15}{64}$	$\gamma d = 88$ $w_{ij} d = 32$ $V_{c} = 52$ [sci	The sand-size fraction is mostly highly weathered basalt fragments.
MBC	DIS AND ABBREVIAT	TONS USED:				-		

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0. $U_{n} = \text{unconfined compressive strength on undisturbed sample$ $10. <math>U_{r} = \text{unconfined compressive strength on remolded sample$ $11. <math>U_{r} = U$ on sample compressive strength on remolded sample 13. $O_{rM} = \text{organic matter}$ 13. $P_{cD} = \text{free iron oxides}$ 14. $\{-\} = \text{interstratified minerals}$ 15. $Q_{r} = \text{consolidation pressure}$

577





for the whole soil of Samples 1 and 2 respectively. After treatment to remove both carbonates and organic matter, X-ray diffraction patterns on the residue showed no evidence of any crystalline components.

2. Samples with Monoclay Mineral Fines. The thermogram on the -0.07 mm fraction of Sample 3 indicates that the clay mineral is hydrous mica. X-ray diffraction and DTA on the -2μ fraction show that the hydrous mica is illite.

3. Samples with Mixtures of Clay Mineral Fines. Hydrous mica to varying degrees is indicated by the thermograms for Samples 4 through 11. Carbonate minerals are evident on the thermograms of Samples 6 and 8. The high potash content and low glycol retention of Samples 4 and 5 suggest a hydrous mica toward the mica end; therefore, the amount of mica required to account for the deficiency in glycol retention was added to the illite component.

Samples 6, 7, and 8 are hydrous micas of the illite-montmorillonoid type. The interstratified nature of Sample 8 is shown by the X-ray pattern following glycerol treatment which gave a strong line at 24A. and the next line at 4.45A.; heat treatment gave a strong 10A. line. The X-ray pattern of Sample 7 was similar to Sample 8 but the higher glycol retention and lower potash content indicate more montmorillonoid than Sample 8. The hydrous mica clay in Sample 6 is very randomly interstratified because, following glycerol treatment, no basal spacing was observed on the X-ray pattern but after heat treatment a moderately strong 10A. line appeared. The vermiculite in Sample 9 was identified from the behavior of the 14A. X-ray reflection following NH₄Cl treatment.

The clay mineral in Samples 10 and 11 was identified as an interstratified illite-chlorite which apparently has considerable order to the stacking of the illite and chlorite layers. X-ray patterns following glycerol, heat, and NH₄Cl treatments permitted identification of chlorite, illite, quartz and plagioclase feldspars⁵ but there were still strong reflections at 8.4 and 2.7A. which could not be identified. On all patterns the 14A. chlorite reflection was very weak while the reflections at 10.0, 8.4, 7.0A. were strong with the 10.0A. line being somewhat stronger than those at 8.4 and 7.0A.

A more drastic heat treatment, 750°C for 30 minutes, produced the expected changes in the chlorite component, namely: (a) a slight contraction of, and a marked intensity increase of the 14A. spacing, and (b) disapperance of the 7.0A. line. The treatment did not, however, affect the 8.4 or 2.70A. reflections. The 8.4A. reflection is ascribed to the 4th order reflection of an interstratified illitechlorite mixture composed of 2 illite layers per chlorite layer. It is likely that the 2.70A. reflection is associated with the complex illite-chlorite structure. Levinson⁶ has observed similar X-ray patterns on clay sediments from Lake Superior.

The thermogram of Sample 12 suggests a kaolin mineral; however, the large absorbed water reaction is not compatible with either kaolinite or hallovsite so that a hydrous mica of illite-montmorillonoid type is suspected. X-ray examination of glycerol treated clav gave diffuse bands at 24 and 11.5A., a fairly strong line at 7.2A. which trailed off to larger d, and other d values and intensities attributable to kaolin and hydrous mica. Based only on the reflections that can be assigned to a kaolin, the kaolin appears to be hallovsite because the 001 and 002 reflections are much weaker than 020 reflection and 001 reflection trails off to higher d. After heat treatment, however, the X-ray pattern still had a very strong reflection of 4.45A. as well as lines at 24 and 10.5A. indicating that hydrous mica is a prominent constitutent of this clay. From these data it is concluded that the clay is an interstratified kaolinite and hydrous mica and the reason the kaolin lines appeared more like hallovsite than kaolinite was due to the hydrous mica present.

As a check, electron micrographs were obtained in which fairly well defined kaolinite particles were observed but no halloysite tubes. A typical electron micrograph is given in Fig. 9. Since neither Mg or K acetate treatment produced appreciable difference in the X-ray pattern the hydrous mica is called an illite-montmorillonoid type.

Even large fragments 0.5–1.0 cm diameter of Sample 12 have a slippery feel and when rubbed with the fingernail become very shiny. The fragments contain pockets of α Fe₂O₃, magnetite, and clay. X-ray examination

⁵ Plagioclase feldspars still present in -1μ fraction.

⁶ Private communication, Prof. A. A. Levinson, Mineralogy Department, Ohio State University.

SOILS



Figure 9. Electron micrograph of Dorena Dam clay. Magnification approx. 30,900×.

showed that the clay in some pockets is identical to the clay in the -2μ fraction, while other pockets contain hydrous mica much higher in montmorillonoid and no kaolinite. The matrix seems to be a mixture of clay and iron oxides. These weathered rock fragments have a remarkable water stability because several grams of particles 0.2-0.4 mm were allowed to soak in water for three days then wet sieved on a sieve with 0.074 mm openings and about 34 of the material remained on the sieve. However, when this material was rubbed between the fingers, it became very sticky and plastic. After a few times of rubbing between the fingers and wet sieving only about 5% of the original sample remained on the sieve.

Engineering Significance of Results

Samples 1 and 2 were termed "clays" yet contained no clay minerals. The samples contain nearly the same kind and amount of carbonates and approximately the same amount of organic matter; however, the plasticity index of Sample 2 is more than four times that of Sample 1. This fact emphasizes the importance of the nature of organic matter. So little is known on the composition of soil organic matter that it can merely be reported in percentage.

All other Samples, i.e. 3–12 contained clay minerals with illite the most common. Samples 3, 4, and 5, three silty clays from Goose Bay, Labrador, are similar in composition and properties, except for the lower plasticity of Sample 4. The plasticity of an air-dried portion of Sample 4 is, however, much closer to those of Samples 3 and 5. The increase in plasticity resulting from air-drying Sample 4 could be due to the breakup of aggregation by drying. Why Sample 4 should have more stable aggregates than Samples 3 and 5 is not known.

The measurable remolded strength (460 psf.) of Sample 5 when the water content is equal to the liquid limit again suggests these Labrador clays have fairly stable aggregates. The remolding action given the compression test specimens apparently was not as thorough

as that given the soil used in the limit and particle size tests.

Samples 6 and 7 are both known as expansive soils from their field behavior: the low shrinkage limit of Sample 6 and high consolidation of Sample 7 also indicate moisture sensitivity. This characteristic of these samples is expected since both contain a montmorillonoid.

Samples 10 and 11 are from the glacial, marine "leda" clay underlying the National Museum Building, Ottawa, Canada. Consolidation of the clay caused differential settlements as large as 1.48 feet and, as one would expect, serious cracks in the Museum. Crawford (1953) has given detailed engineering properties of these samples; they are in line with what one would expect from the composition of the soils.

Sample 12. from the Kern slide area of the Dorena Dam, was obtained and studied since it was reported to be composed of halloysite. As pointed out in the preceding section, extensive tests proved that this sample contained a complex interstratified mixture of clay minerals. The relatively low plasticity is probably due to the relatively stable aggregates.

SUMMARY AND CONCLUSIONS

This paper describes the results of engineering tests on three selected clay minerals. Both hydrated and dehydrated halloysite were found to have: low maximum compacted density, high optimum water content, high permeability and high frost susceptibility. The hydrated form can easily irreversibly dehydrate, at least partially, at a typical room temperature and humidity. The dehydration is accompanied by a change in properties.

Tests on a sandy clay with homoionic nontronite fines were too limited in nature and number to permit broad conclusions. As one would expect from theoretical considerations, the sodium form was found to have the highest plasticity, permeability and compacted density and lowest optimum water content of the various ionic forms tested.

Two species of low-iron chlorites were found to be plastic when ground to silt and clay sizes; two samples of thuringite, a high-iron chlorite, were found to be non plastic. Compositional analyses are reported for twelve soils made by the following tests: X-ray diffraction, differential thermal, glycol retention, potash and

organic matter contents and electron microscopy. Most of the soils contained mixtures of clay minerals, usually existing in complex interstratifications. Hydrous mica was found in all soils containing clay minerals. Those soils expansive in behavior were found to contain montmorillonoids.

Further evidence was found of the importance of the quantity and stability of aggregates of soil fines.

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Distributed Loads on Elastic Foundations: The Uniform Circular Load

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FORMULAS are presented for computing the stresses, strains, and deflections produced at a point within a semi-infinite, homogeneous, elastically isotropic body by a uniform circular load applied to its surface. The expressions presented are obtained principally by extending and developing the work of A. E. H. Love. Reference is made also to an earlier work by Kwan-ichi Terazawa who obtained a solution by a method different from Love's. Some discussion is also included on the relation between the two methods. It is suggested that the formulas may be useful in developing theoretical concepts relating to the design of airfield pavements.

• THIS paper presents the results of certain mathematical studies (1) made in connection with projects for improving the present methods for the design of airfield pavements. In computing the theoretical values of the stresses, strains, and deflections produced in the pavement or subgrade by the loads on the airplane wheels, it was found convenient to assume the tire contact area as circular and to employ formulas for a uniform circular load

from the theory of elasticity. Where the point at which such values are to be computed is taken directly beneath the center of the circular area, the computations may be made from relatively simple formulas. However, for points not under the center, the formulas are much more complex and in some cases had not been completely developed.

Values at such "offset" points can be obtained graphically by means of charts de-