SOIL COMPOSITION AND ITS INFLUENCE ON THE ENGINEERING BEHAVIOUR OF FINE-GRAINED SOILS

By R. TORRENCE MARTIN and T. WILLIAM LAMBE
Soil Stabilization Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

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ABSTRACT

Fifty per cent. of the soils studied came from the United States and represent samples from sites in which engineering difficulties were encountered; therefore, it is significant that the clay in 50% of all soils examined was an illite-smectite type, while illite-chlorite comprised 15% of the total. For illite-smectite clays, quantitative estimation of the illite and smectite percentages is obtained from the total potash and glycol retention data. The agreement between measured and calculated cation exchange capacities is taken as supporting evidence of the reliability of the methods used. The chlorite component in the illite-chlorite clays was a high-iron chlorite. Regular and random stratification of illite and chlorite components was observed. The most important influence of composition on behaviour is the very high water sensitivity of the expansive minerals. Most of the soils studied which had caused stability or volume change problems in the field contained expansive minerals. For soils with fines of a single mineral species or a simple mixture of minerals, predictions of behaviour can be made with fair accuracy from a knowledge of soil composition. Where the soil fines are interstratified minerals or cemented crystals, predictions can seldom be made with accuracy. Interstratification or cementation usually inhibits the water sensitivity of normally expansive minerals. This fact seriously limits the value of soil compositional data to the engineer.

INTRODUCTION

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 behaviour. One phase of this research is a continuing, long-range study on the influence of the composition of soil on its engineering properties; this paper summarizes some of the results of this phase.

The research at M.I.T. and elsewhere has clearly shown that, not only is the nature of the components of a fine-grained soil important, but also the manner in which these components are arranged, and the geological history of the soil can have considerable influence on the
properties of the soil. These three factors are, however, usually interrelated so that sometimes knowledge of the composition alone will permit some estimate of the other factors, and thus the engineering behaviour of the soil. While such facets of soil technology as exchangeable ions, pore fluid, precompression, etc., can have significant effects on the engineering behaviour of fine-grained soils, the mineralogical composition is usually the most important factor. The present discussion is, therefore, confined to mineralogical composition and its bearing on engineering properties.

Compositional data on fine-grained soils are of importance to both the researcher and practitioner in soil engineering. The pioneers in soil mechanics made considerable progress in explaining the properties of cohesionless soils by considering them composed of discrete particles of unknown composition. This method has, however, been less successful in explaining such complex phenomena in fine-grained soils as secondary compression, loss of shear strength on remoulding, strength-density-moisture-content relationships of compacted soils, and soil swelling. The correct explanation of these confusing phenomena must consider in detail the composition of the soil involved.

Compositional data help the practicing soil engineer by serving as a means of classifying the soil, aiding in planning his engineering tests, and often permitting the prediction of unusual behaviour which might not otherwise have been expected. Compositional data also help the engineer predict possible alterations in soil properties caused by changes in environmental conditions. There are a number of reasons why compositional data are not of more immediate practical importance to the soil engineer. Making compositional analyses, especially assigning percentages to the various components, can be a most difficult and, in fact, sometimes arbitrary process requiring techniques and equipment rarely found in a soil engineering laboratory. Interactions among soil components and the effects of impurities or trace components in soil can be predicted only with difficulty. The problems presented by interactions of components are discussed later in this paper.

**Distribution of Soils and Mineral Species**

While the soils examined came from many parts of the world, these soils do not represent a true cross section of the soils of the world because there was an uneven geographical distribution and the majority of soils were investigated because of unusual or troublesome engineering behaviour. The geographical distribution of the
100 odd soils studied (expressed as a percentage of the total) is as follows:

Western hemisphere 80% (70% of these were from N. America—50% from U.S.A.—and 10% from S. America): Eastern hemisphere 20% (Africa 8%, Europe 7%, Far East 5%).

Since the majority of samples came from the temperate regions of North America, the preponderance of three-layer phyllosilicates is believed to be a fair representation of the soils that most frequently exhibit unusual or troublesome engineering behaviour for the temperate region of North America. In view of the fact that illite-smectite and illite-chlorite are the two largest composition groups encountered, the discussion in this paper will be largely restricted to these two groups.

The illite-smectite group includes soils where the mineral species are simple mixtures, randomly stratified clays and/or some of both. Fig. 1 shows the frequency of various illite to smectite ratios (I : S) in the illite-smectite group. The observed abnormal distribution may indicate that compositions with an I : S of approximately 1 : 10 or 10 : 1 are either (a) unstable, (b) hard to identify or (c) satisfactory soils for engineering purposes. The relative importance that these three factors have in determining the distribution as revealed in Fig. 1 is at present an unsolved problem.

**MINERAL ANALYSIS**

A. Method.—Equipment used to identify minerals in fine grained soils includes differential thermal analysis,* X-ray diffraction and petrographic and electron microscopes. Chemical and physical measurements to aid in quantitative mineral analysis include glycol retention, total potash, cation exchange capacity, free iron oxides, and organic matter. Details of these methods and procedures are described elsewhere (T. William Lambe and R. Torrence Martin, 1954; T. William Lambe and R. Torrence Martin, 1956); there is one item, sampling, which deserves further comment.

Any investigator who studies soils recognizes the importance of sampling because the results of any investigation are limited by the

*(DTA) Thermograms given in this paper were obtained under the following experimental conditions:—Heating rate—12.5°C/min with a maximum variation of less than 1°C/min. Thermocouples—Pt-Pt (10% Rh). Sample pretreatment—No pretreatment. Temperature Thermocouple—in Ni steel block; peak temperatures uncorrected. Calibration—50-50 quartz: BaCO₃ mixture. Quartz at 573 ± 3°C. BaCO₃ to α at 819 ± 3°C. BaCO₃ to β at 988 ± 3°C.
reliability of the samples taken. Since for mineralogical analysis only a few grams of soil are often required, it is especially important to ensure that these few grams represent the whole mass. For example, samples of Bearpaw shale from Saskatchewan, Canada, were sent to three different laboratories for mineral analysis. Each laboratory reported the clay as something different—kaolinite, illite, and montmorillonite. Admittedly, methods for clay mineralogical investigations are far from perfect; however, it also seems inconceivable that the methods could be so poor. Upon examination of additional samples it was found that all three analyses were entirely possible because of the variability in the natural deposit.

B. Illite-Smectite Clays.—X-ray diffraction of glycerol treated illite-smectite type clay gives a 17-18 Å reflection for the montmorillonitic component and a 10 Å line for the illite component. Clays are occasionally encountered in which no 18 Å line is observed and in which the 10 Å reflection is very broad; such a clay is called illite-smectite if upon heat treatment, 550°C for 30 minutes, the 10 Å line becomes fairly sharp and strong without the appearance of any new lines to indicate vermiculite or chlorite components. After heat treatment, a typical illite-montmorillonitic clay gives a strong 10 Å line and no 18 Å reflection. A variable basal reflection with a maximum \( d \) of 14-15 Å is called vermiculite.

After the presence of illite and smectite has been established, determination of glycol retention and total potash content on the minus 2 microns fraction permits calculation of the percentage illite and smectite. The percentage illite is calculated from the potash content on the assumption that ideal illite contains 6% \( K_2O \). Glycol
retention required for the calculated illite percentage is subtracted from the measured glycol retention of the clay and this excess attributed to smectite. To compute the percentage of illite and smectite in the minus 74 microns fraction, the ratio of the amplitude of the 600°C endotherm for the minus 74 microns fraction to that for the minus 2 microns fraction is used. Although this is an arbitrary method of computation, the mineral percentages so obtained are thought to be as reasonable a quantitative estimate of clay components as can be obtained. As a check on the validity of the calculated mineral percentages, the observed and computed cation exchange capacities for the minus 74 microns fraction of a large number of illite-montmorillonitic type soils have been compared. The extent of agreement is illustrated by the data in Table 1 in which the average percentage deviation from the mean of calculated and observed exchange capacity is ±7%. This variation is believed to be satisfactory, because for routine exchange capacity determinations reproducibility to ±5% is considered good.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Cation exch. cap. (meq/100g)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>575</td>
<td>38</td>
</tr>
<tr>
<td>590</td>
<td>14</td>
</tr>
<tr>
<td>592</td>
<td>17</td>
</tr>
<tr>
<td>594</td>
<td>26</td>
</tr>
<tr>
<td>595</td>
<td>29</td>
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<td>35</td>
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<tr>
<td>599</td>
<td>46</td>
</tr>
<tr>
<td>600</td>
<td>35</td>
</tr>
<tr>
<td>672</td>
<td>47</td>
</tr>
</tbody>
</table>

Average deviation from mean ±7%.

Upon differential thermal analysis, the illite-smectite clays investigated almost universally give an endothermic reaction about 600°C. This peak temperature is characteristic of the smectites nontronite and beidellite; however, the shape of the 600°C endotherm for nontronite and beidellite is a broad shallow peak. Very frequently illite-smectite type clays are encountered in which the 600°C endotherm is very narrow and similar to that of a kaolin mineral. For the hydroxyl water loss reaction, extremes in peak sharpness for different illite to smectite ratios are shown. The X-ray diffraction
patterns of the clays which gave a sharp 600°C endotherm did not indicate the presence of a kaolin mineral.

In order to ascertain, if possible, whether or not the 600°C endotherm for the illite-smectite clays was indicative of the composition of the smectite component, sixteen samples were subjected to the Greene-Kelly (1953) test for the identification of montmorillonite. Samples were chosen to cover all the different types of differential thermal curves as well as a range of illite to smectite ratios. Since all the clays tested were dioctahedral, a positive test—collapse to 10 Å of the glycerol-solvated, lithium-saturated, oven-dried specimen—confirms that the clay is montmorillonite, while a negative test indicates nontronite or beidellite.

Table 2 shows that the smectite component in two-thirds of the clays was montmorillonite. Table 2 also contains an amplitude to width ratio for the 600°C endotherms. The width “b” was measured at the mid-point of the peak amplitude or a/2. Generally the clays with the sharpest 600°C endotherms were negative to the Greene-Kelly test. These results suggest that the shape of the 600°C peak is related to the composition of the smectite component. However, data in Table 2 further indicate that montmorillonite is generally confined to illite-

<table>
<thead>
<tr>
<th>Illite: smectite</th>
<th>Soil</th>
<th>Amplitude: width* for 600°C peak (a/b)</th>
<th>Greene-Kelly Test**</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:5:1</td>
<td>478</td>
<td>4.5</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>5.3</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>594</td>
<td>5.8</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>590</td>
<td>14.4</td>
<td>+</td>
</tr>
<tr>
<td>1:1</td>
<td>600</td>
<td>2.9</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>592</td>
<td>4.6</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>449</td>
<td>3.7</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>4.5</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>568</td>
<td>3.8</td>
<td>—</td>
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<td></td>
<td>599</td>
<td>7.5</td>
<td>—</td>
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<tr>
<td>1:25</td>
<td>575</td>
<td>4.5</td>
<td>+</td>
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<tr>
<td></td>
<td>436</td>
<td>7.3</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>598</td>
<td>10.4</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>14.4</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>559</td>
<td>15.0</td>
<td>—</td>
</tr>
</tbody>
</table>

*Amplitude (a) to width (b) at a/2. Kaolinite a/b = 17.0 ± 0.5, illite a/b = 5.0 ± 0.5.

**Greene-Kelly (1953); + indicates montmorillonite, —nontronite or beidellite; refer to text for explanation.
smectite clays that are illite rich. Such a conclusion makes it very
difficult to explain normal degradation and aggradation of clays.
Where interstratification occurs, as for most of the clays examined
here, the general lack of expansion for illite-smectite of less than
1 : 2.5 may mean that in interstratified clays a certain minimum
number of nontronite or beidellite layers are necessary before the
lithium-saturated, oven-dried clay will expand.

Another factor that has not been considered in the foregoing dis-
cussion is the effect that the illite component may impose upon the
differential thermal behaviour and upon the X-ray diffraction pattern
of the lithium-treated sample. Further research is believed to be
necessary in order to define the limits of application of the Greene-
Kelly test for the identification of montmorillonite in stratified clays.

C. Illite-Chlorite.—The qualitative identification of illite and chlorite
in clays containing these two minerals has proved to be relatively
simple by the use of X-ray diffraction in conjunction with heat treat-
ment to various temperatures. The presence of kaolin minerals is
unlikely in the illite-chlorite clays examined, because even if the total
differential thermal peak were ascribed to kaolinite the amount would
generally be less than 5%. In addition, the changes that take place
in the intensities of the 14 Å and 7 Å reflections following heat treat-
ment strongly favour chlorite over kaolinite. The chlorite species
encountered is predominantly thuringite, high in ferric iron, because
the 7 Å reflection is two to four times as strong as the 14 Å line before
heat treatment.

Regular and random stratification of illite and chlorite components
are common in illite-chlorite clays. Evidence for regular stratifi-
cation is based on reflections at 8.5 Å and 2.7 Å that maintain the
same intensity relative to other chlorite reflections from silt size
(minus 74 microns) to fine clay (minus 1 micron) and in oriented
aggregate patterns as well as normal powder patterns. The randomly
stratified illite-chlorite clays vary considerably in the temperature
stability range of the pseudo-chlorite that results from heat treatment.
In some instances the chlorite component has disappeared completely
from the X-ray pattern of a specimen heated to 550°C while for other
illite-chlorite clays the pseudo-chlorite is still present after heating to
850°C.

While qualitative identification of chlorite in clays is fairly easy,
the quantitative estimation of chlorite has proved to be exceedingly
difficult for clays comprised of several phyllosilicate members. The
complexity of the situation may be illustrated by an example. From
the illite-chlorite clays investigated, four samples were chosen that
(1) had essentially the same potash content, 4.5 ± 0.2%, (2) had very
nearly the same intensities for the 14 Å and 7 Å chlorite reflections,
and (3) had the same breakdown temperature for the psuedo-chlorite,
750°C. The similarity in potash content was taken as an indication
that the illite content was fairly constant. On the X-ray patterns
the intensity of the chlorite reflections on heated and unheated
specimens were, within the limits of visual observation, constant.
Therefore, one might expect the differential thermal curves of these
four illite-chlorite clays would be quite similar. Thermograms for
the above illite-chlorite clays shown in Fig. 2, are to say the least,
quite variable. The quantitative estimation of chlorite in illite-
chlorite clays remains an unsolved problem of clay mineralogy.

![Thermograms for illite-chlorite clays.](image)

**ENGINEERING BEHAVIOUR**

*A. Influence of Composition on Engineering Behaviour.*—Both labor-
atory and field tests have clearly shown that monomineralic clays
possess properties which vary markedly with composition. Research
at Cornell (Cornell University 1951) measured, for example, the fol-
lowing properties of sodium montmorillonite and sodium kaolinite:

<table>
<thead>
<tr>
<th>Property</th>
<th>Sodium montmorillonite</th>
<th>Sodium kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity index, in %</td>
<td>650</td>
<td>21</td>
</tr>
<tr>
<td>Coef. of consolidation</td>
<td>2.6</td>
<td>0.26</td>
</tr>
<tr>
<td>Permeability at plastic limit, in ft/yr</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Cation exchange capacity, in meq/100g</td>
<td>100</td>
<td>3</td>
</tr>
</tbody>
</table>

These test data show that the differences in properties between pure sodium montmorillonite and pure kaolinite are considerable.

The significant effect of composition on behaviour has also been measured on many natural soils (T. William Lambe and R. Torrence Martin, 1953; T. William Lambe and R. Torrence Martin, 1954; T. William Lambe and R. Torrence Martin, 1955; and T. William Lambe and R. Torrence Martin, 1956). The most important influence of composition on behaviour is the very high water sensitivity of the expansive minerals, particularly the smectites. In fact, most soils encountered in this study which caused stability or settlement—expansion problems contained smectite or organic matter. These soils are characterized by their low permeability, slow compression under load, relatively large secondary compression, high rebound on load removal, and loss of strength in the presence of moisture.

In natural soils containing monomineralic fines, a reasonable estimation of engineering behaviour can nearly always be made from knowledge of composition. A soil, for example, containing montmorillonite would be expected to slough in an open cut or cause undesirable movement of shallow footings when subjected to seasonal moisture changes. On the other hand, prediction of other properties based on composition can not always be made with soils containing multimineralic fines. If the fines are simple mixtures, approximate predictions can be made; if the fines are interstratified or cemented, predictions are far from dependable.

Mixtures of “clay minerals” with coarse particles may or may not have properties which would be expected from the proportion of each component in the mixture. Plasticity is usually as expected, e.g., the plasticity index of 50% clay plus 50% sand is approximately half of the sum of the individual plasticity indices. Other properties are, however, sharply influenced by particle size distribution. Fig. 3 shows, for example, that the maximum compacted density of kaolinite-sand mixtures occurs at a mixture of 70% sand—30% clay and this maximum density exceeds that of the pure components.
Much more unpredictable and complex than the effect coarse particles have on the composition—property relation, are the effects of the interactions of the fines. Fines can become firmly cemented or flocculated together; different species of minerals in clays commonly occur as interstratified sheets. The resulting soil particles may be quite unlike either of the components which make-up the particles.

**B. Cementation and Flocculation.**—The authors have noted with concern the extensive cementation of clay fines which occurs in natural soil (T. William Lambe and R. Torrence Martin, 1954; T. William Lambe and R. Torrence Martin, 1955). This cementation is illustrated in Fig. 4 in which clay size (percent. minus 2 microns) is plotted against clay content as determined by mineralogical analysis. Soils with all particles finer than 2 microns plot on the straight line in Fig. 4 which is at 45 degrees. Soils having particles finer than 2 microns which are not composed of “clay minerals” plot above the line, while soils having clay particles larger than 2 microns plot below the diagonal line. The data in Fig. 4 shows that the majority of the soils studied contain clay particles larger than 2 microns—this fact indicates cementation or flocculation of particles which was strong enough to resist the chemical and mechanical dispersion given in the normal hydrometer analysis for particle size distribution. Both the illite-smectite and illite-chlorite mixtures showed the cementation or flocculation. The extreme case of flocculation occurred with the montmorillonitic soil which had 85% clay by composition but only 2% by weight of particles finer than 2 microns.

The aggregation of fines illustrated by Fig. 4 has been found to be
very common with all types of fine-grained soils. This fact raises the question as to the meaning of particle size distribution in clays—especially when chemical and physical means of non-standard intensity are employed to disaggregate the clay for particle size analyses. When clay particles are strongly cemented, one can justifiably ask whether the resulting particles are still clay. Cementation usually results in a sharp loss of properties—plasticity, water sensitivity, etc.—usually associated with fine clay particles. This tendency suggests that a particle size analysis on soils which had been given some standard minimum or no particle disaggregation might be more meaningful than the standard hydrometer test. Cementation or flocculation does not, however, necessarily destroy properties such as plasticity. For example the extreme case noted in Fig. 4 had a plasticity index of 66% but only 2% by weight particles finer than 2 microns.
C. Properties of Illite-Smectite Mixtures.—As pointed out previously, illite-smectite mixtures of minerals occurred in half of the soils which were analysed in this study. A study of the properties of soils containing these mixtures is, therefore, of importance. In Fig. 5 are plotted the relative composition of smectite and illite against plasticity, where the plasticity has been divided by the percentage of soil minus 2 microns to allow for the fact that the soil is not completely of clay size. Fig. 6 presents the same data where clay composition has been used to correct the plasticity rather than clay size. The ratio of plasticity index to clay size has been termed “activity”; the ratio based on clay composition has no special name. In both Figs. are plotted the plasticities of the pure minerals and a hatched zone is shown between the two extremes. If the principle of proportionality held, all of the measured data would fall within the hatched zone. A glance at the two figures shows that actually only one point falls within the hatched zone. The plotted points show no trend other than that the ratio of smectite to illite has no apparent effect on plasticity for a given amount of clay. These plots suggest that in these mixtures, the less plastic mineral has more influence on the plasticity of the mixture than the more plastic. A broader inference is that foreign materials can reduce the high water sensitivity usually associated with expansive minerals.

The following fact illustrated by Figs. 5 and 6 has been generally
noted on natural soils with multimineralic fines. The prediction of engineering behaviour from composition in these soils is hazardous. The water sensitivity of expansive minerals is usually reduced more than would be expected from the principles of proportionality. Soils with only a small percentage of expansive minerals can, however, be influenced by the expansive minerals far out of proportion to the percentage of their composition. This possibility is particularly true with permeability, thus a mixture of 80% kaolinite and 20% montmorillonite will have a permeability much nearer that of a 100% montmorillonite than that of a 100% kaolinite.

The preceding discussion clearly indicates a serious limitation to the engineers' use of compositional data on multi-mineral soils to predict behaviour.

REFERENCES
Final report soil solidification research, Cornell University, Ithaca, N.Y., 1951, 2, 11-53.

DISCUSSION
Dr R. Greene-Kelly drew attention to the fact that the depressed endothermic peaks observed in the d.t.a. graphs could be explained otherwise than by beidellite which was in fact the rare end-member of a series. It was possible to obtain peaks as low as 550°C with normal material. Furthermore, although perhaps not pertinent to the present discussion, decomposition and subsequent re-hydration lowered the low temperature endothermic peak.

Dr R. C. Mackenzie elaborated on the remarks by Greene-Kelly and stated that there were apparently three different types of montmorillonitic endothermic peak with peaks at 600°C, viz., 550°-600°C, 550°-650°C and 650°-700°C, the latter being the most common, but all were normal montmorillonites. Intermediates between these types did not seem to exist. He also drew attention to the occurrence in soils of the Scottish Highlands of a chlorite which showed 20%-30% quantitatively by X-rays and yet which gave no large endothermic on d.t.a. The authors, in reply to the two previous speakers, expressed great interest in their findings on montmorillonite and stated that they also had observed the type of chlorite described by Mackenzie.
Mr I. L. Freeman pointed out the great difficulties involved in particle size measurements when organic matter was present especially in, for example, bituminous shales, where the result obtained was usually found to be that of the original size resulting from grinding.

Dr B. H. Knight asked Dr Martin whether he thought that the standard method of dispersion using a high speed rotating blade gave reliable results. Grain-size measurements could not be relied upon to give an exact record of the clay present. He continued to say that he was surprised to find such a test still specified in British Standard 1377 (methods of testing soils). The authors agreed with both the previous speakers on the need for better and more reliable methods, and enlarged on their own difficulties in this regard.

Dr I. Havenaar asked if any correlation had been attempted between exchangeable ions and plasticity. In reply Dr Martin stated that this latter property had been measured on soil as it occurred in the field. He then enlarged on the considerable effects soluble salts could have on this property, especially in the case of illite.