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LABORATORY STUDIES RELATING TO THE CLAY FRACTION OF COHESIVE SOILS [x)]

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SUMMARY.

This paper outlines the effect of the clay fraction on such engineering properties of cohesive soils as the strength, compactibility and permeability, and refers to the physico-chemical properties of individual clay particles which are important in this connexion.

Experimental results and data obtained at the Road Research Laboratory relating to the properties of the clay fraction are presented. These include results of Liquid and Plastic Limit tests, which have been grouped according to the general geological areas from which the soils were taken. When the Liquid Limits were plotted against the Plasticity Indices for particular groups, it was found that there were two relationships corresponding to the equations $PI = 0.75(LL - 15)$ and $PI = 0.8(LL - 15)$.

Tests are also described in which samples of soil free from organic matter and carbonates were ignited to about 800°C. and the loss in weight expressed as a percentage of the total soil and of the clay fraction. With British soils most of the loss appears to take place in the clay fraction, the values falling into two distinct groups which are thoughtto correspond to different chemical and mineralogical groups. The loss during ignition of some of the other soils studied, particularly those of morainic origin from Scandinavia appears to be uniformly distributed throughout the soil fraction, from which it is inferred that the clay fractions of these soils contain particles derived from the primary weathering of rocks. The minerals in the clay fractions of British soils, however, presumably contain the more hydrated products of secondary weathering.

Data are included that were obtained with a method for determining the particle size distribution of the coarser clay particles, involving the use of a hypodermic syringe for sampling sedimenting clay suspensions, and some preparatory work in this investigation indicates the effect of the variation of the dispersing agent concentration on the deflocculation of suspensions of kaolin and montmorillonite clays.

Finally electron micrographs taken at the National Physical Laboratory of various types of clay particles are shown.

INTRODUCTION.

This paper outlines the effects of the clay fraction (particles smaller than 0.002 mm equivalent diameter) on the engineering properties of cohesive soils, and indicates how these effects depend on the physico-chemical characteristics of the individual clay particles. The results of some preliminary investigations undertaken at the Road Research Laboratory and having a bearing on this subject are presented.

EFFECT OF THE CLAY FRACTION ON THE ENGINEERING PROPERTIES OF COHESIVE SOILS.

From a consideration of the results of measurements of the engineering properties of cohesive soils in relation to their particle size analyses, it is possible to draw certain general inferences as to the effect of the clay fraction on these properties.

Thus, the major part of the mechanical strength of cohesive soils is derived from films of water surrounding the clay particles. When such soils are relatively dry, these films are thin and impart a high strength to the soil structure. An increase in moisture content, increases the film thickness resulting in a loss in strength, and the stability is therefore considerably dependent on the moisture content. This component of the stability is referred to as the cohesion, and is almost entirely a function of the clay fraction.

In the case of compaction, the results obtained with the standard compaction test indicate that soils having a high clay content cannot be compacted to such high densities as soils containing less clay, presumably due to the increased cohesion between the particles.

The average pore size in cohesive soils is less than that in granular soils, and their permeability is therefore less. The consolidation properties and the susceptibility of such soils to damage by frost, as well as their drainage characteristics are dependent on the permeability, and therefore indirectly on the clay content.

The water films surrounding the clay particles have a tendency to grow at the expense of free, capillary water and therefore contribute considerably to the soil suction (pF), differences between which cause moisture movements in unsaturated soil. When the films grow, the volume of the particles, and hence the bulk volume of the soil, increases, and when they diminish due to the drying of the soil, the particle volumes decrease. The phenomena of swelling and shrinkage are thus intimately bound up with the clay fraction.

PHYSICO-CHEMICAL CHARACTERISTICS OF CLAY PARTICLES.

The behaviour of the clay fraction in relation to the properties indicated above is determined by the physico-chemical characteristics of the individual clay particles. Amongst the more important of these is the surface area, which is dependent on the size and shape of the particles. Both these factors may alter in certain types of clay mineral, owing to an expansion or contraction of the particles, depending on the composition of the surrounding solution. Further, many of the effects of the clay fraction on the behaviour of the soil mass may be explained by the existence of a thin film of adsorbed water on the surfaces of the clay particles. The properties

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of these adsorbed films will depend upon the mineralogical and chemical composition of the clay particles as well as the quantity and nature of any ions adsorbed on their surfaces.

RESULTS OF INVESTIGATIONS HAVING A BEARING ON THE CLAY PROBLEM.

In the course of soil investigations at the Road Research Laboratory, results have been obtained having a bearing on the clay problem, and relevant data have also been collected during the routine examinations of soils at the Laboratory. A review of these results and data are given below.

1. ANALYSIS OF LIQUID AND PLASTIC LIMIT DATA.

These test were performed according to the A.S.T.M. procedure. 1) 2)

Both the Liquid and Plastic Limit are known to be dependent on the amount and type of the clay fraction in a soil, but the difference between them, the Plasticity Index is a function of the amount of clay only xa). Therefore, if the Liquid Limits of a number of different soils are plotted against their Plasticity Indices, any variation in the relationship between these factors will be due to the presence of different types of clay mineral in the soils. This forms the basis for some of the soil classification systems used in Soil Mechanics, the most widely known being that due to A. Casagrande. 3)

Figs. 1a, 1b and 1c show the results of Plasticity tests on a large number of British soils plotted in this way, and grouped according to the general geological areas from which they were taken. The equations corresponding to the relationships for a number of such groups are given in Table 1.

Table 1.

Equations to the Plasticity Index/Liquid Limit relationships obtained for some groups of British Soils.

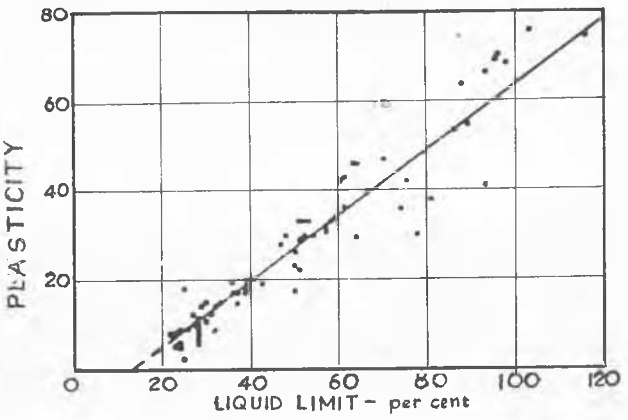
Recent and Pleistocene	PI = 0.74(LL-17)
Oligocene and Eocene	PI = 0.74(LL-13)
Upper and Lower Greensand and Gault	PI = 0.82(LL-17)
Chalk and Wealden	PI = 0.80(LL-16)
Oolitic and Liassic	PI = 0.75(LL-15)
Marl and Sandstone	PI = 0.72(LL-15)

PI = Plasticity Index
LL = Liquid Limit

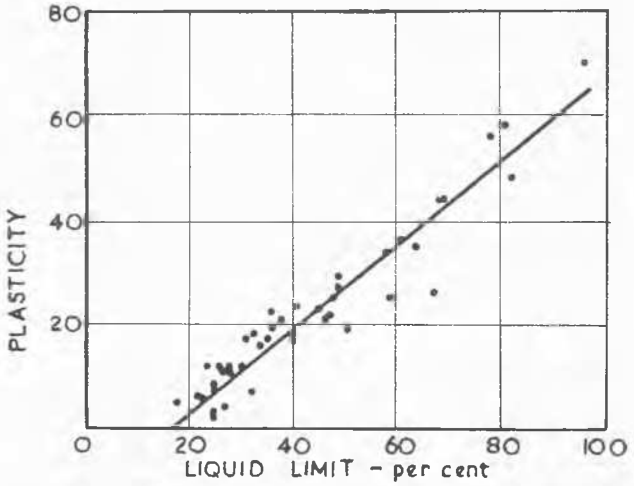
It will be noted that although all the equations are similar, there appear to be two relationships corresponding to PI = 0.75(LL-15) and PI = 0.80(LL - 15) approximately, but it is difficult to say whether these differences are significant, bearing in mind the possible experimental errors in simple tests of this type and the considerable scatter of the points. This variation in relation to the clay content, is brought out in Fig. 2, which shows the Liquid and Plastic Limits of the Oolitic and Liassic group plotted against the clay contents.

2. ANALYSIS OF LOSS ON IGNITION DATA.

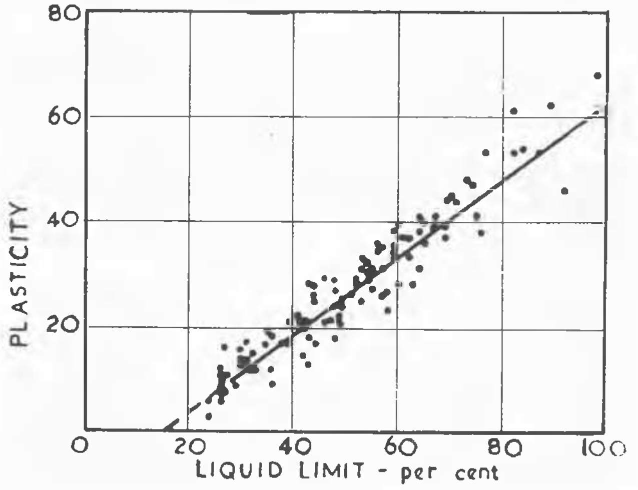
Data obtained from loss on ignition determinations have also been examined in an at-



a Oligocene and Eocene



b Upper and Lower Creensand and Gault



c Oolitic and Liassic

Relations between Atterberg plasticity index and liquid limit for three groups of English clays.

FIG. 1

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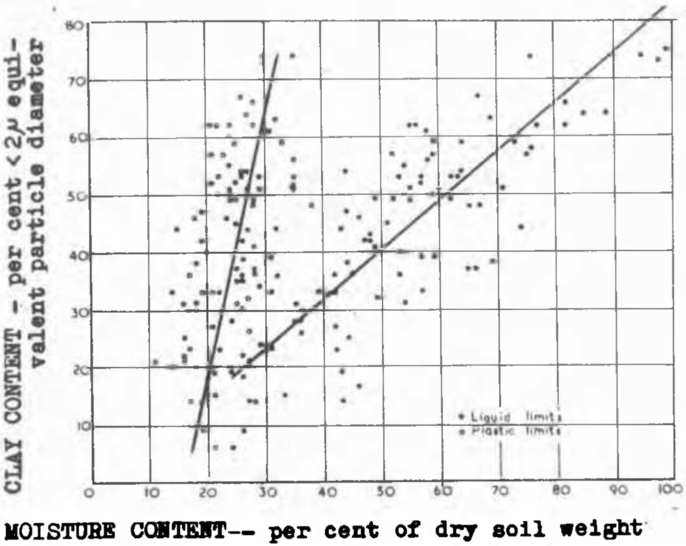
xa) L.F. Cooling and A.W. Skempton have correlated the liquid limit and the clay fraction. (L.F. Cooling "The development and scope of soil mechanics" Instn. Civ. Eng. 1946).



Relation between clay content and Atterberg liquid and plastic limits for soils in oolitic and liassic areas.

FIG. 2

tempt to classify clays. Samples of soil, dried at 105°C., from which carbonates and organic material had been removed, were heated to temperatures between 700°C. - 800°C. in an electric furnace, and the loss in weight determined. Since the silt and sand fractions of most British soils are believed to contain only particles of silica or primary silicates derived from igneous rocks, it was assumed that all the loss on ignition would be from secondary hydrated alumine-silicates of the types found among the clay minerals. The loss in weight was therefore calculated as a percentage of the fraction having equivalent particle diameters less than two microns the proportion of which had previously been obtained from a particle size analysis. The results of these calculations are given in Table 2.

Table 2.

Ignition losses of some British cohesive soils.

Geological Group	Number of Samples tested	Loss at a percentage of the clay content
Recent and Pleistocene	3	13
Oligocene and Eocene	2	14
Wealden	3	21
Lower Greensand and Gault	2	14
Oolitic and Liassic	2 (1)	20 (13)

Three other soils from Marl and Magnesian Limestone areas gave values of 13%, 14% and 16% respectively.

The results suggest that again there may be two main groups, one giving a loss of about 14% and the other about 20% on ignition, comparable to the two Liquid Limit/Plasticity Index relationships. However, if the geological grouping used is accepted and the results compared with those given in Table 1, it will be noted that there are certain differences. Thus, while soils from Recent and Pleistocene, Oligocene and Eocene, and Marl areas and one soil from the Oolitic and Liassic areas gave ignition losses of approximately 14% corresponding to a slope of 0.75 on the LL/PI line, the two soils from the Greensand and Gault area gave the same loss but had a slope of 0.80. The Wealden soils appeared to have entirely different characteristics in both respects, i.e., a loss on ignition of 21% and a slope of 0.80. These discrepancies may be due to incorrect geological classification, or to the fact that this classification was not made with the use of the detailed drift map, but was based on the geological type of the underlying strata.

A second, rather more extensive, series of experiments was made with soils of known mineral content from Britain, and with soils from Europe, Asia and Africa. The results, shown in Table 3, are given as the total loss on ignition of the whole soil, and the ignition loss as a percentage of the clay content.

It will be seen that the total loss of the kaolin clays from St. Austell was constant at about 13 - 14%, whereas the losses in terms of the clay contents were variable. This suggests that the whole soil and not merely the clay fraction contains kaolinite. Similarly, the moraine soils from Scandinavia gave a constant, rather low, total loss of 3 - 4%, which was also variable when expressed as a percentage of the clay fraction. In this case the clay fraction probably consists of the same material as the sand and silt components, that is, comminuted primary rock fragments derived from gneisses and granites by glaciation.

A constant total loss of 4% was generally obtained for the samples from West and South Africa, but the soils from North Africa appeared to contain more hydrated minerals, giving total losses of 6 - 8%. It does not appear possible to relate these losses to the clay contents of the soils, however.

The kaolin clay from Hong Kong had a similar percentage loss, on the clay content basis, as the total loss figures for the British kaolin clays, suggesting that in this case kaolinite was only present in the clay fraction.

Further ignition tests were made on the clay fractions isolated from a number of cohesive soils. The clay was separated by sedimenting suspensions of the soils dispersed with sodium oxalate, and converted to hydrogen-clay by leaching first with dilute acid and then with water. The ignition tests were performed in duplicate on the clay, after drying at 105°C. and the results are shown in Table 4 below:

Table 4

Ignition losses on the clay fractions (<0.002μ) of some cohesive soils.

Soil	Source	Ignition loss %
Kaolin clay,	St. Austell, Cornwall	14
Montmorillonite clay,	Redhill, Surrey	9
Gault clay,	Culham, Oxfordshire	12
Oolitic clay,	Stewartby, Bedfordshire	15
Moraine clay,	Gothenburg, Sweden	4
----	Greyvillers, France	8
Lateritic clay,	Cape Province, South Africa	7

These results confirm the figure of 14% loss for kaolin clay, and the value of 4% for the moraine clays from Scandinavia. The montmorillonite clay had a very low loss (9%), which appears to correspond with that calculated for the alluvial clay from Denmark (Table 3), and possibly with the clay fraction of the soil from Greyvillers.

The ignition losses of the Oolitic and

TABLE 3

Ignition losses of some cohesive soils

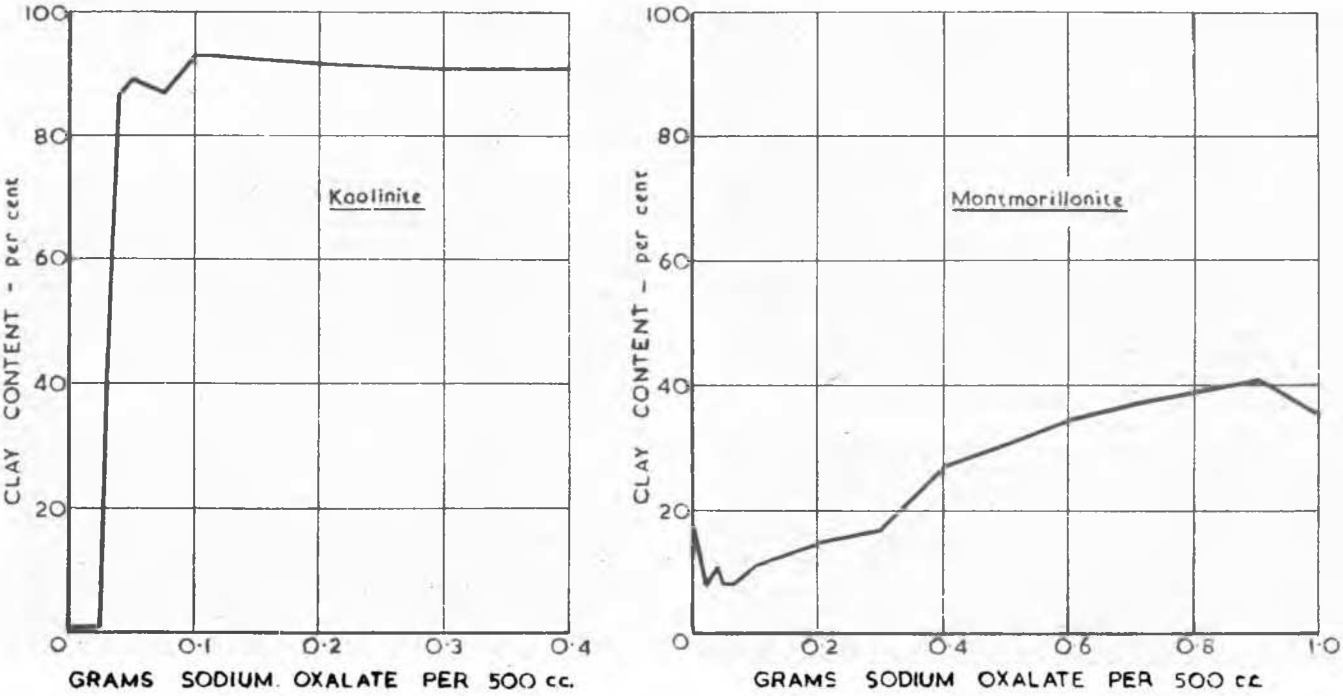
Soil	Source	Clay content (<0.002µ) %	Ignition loss %	Loss as a percentage of the clay content %
Great Britain				
Kaolin clay,	St. Austell, Cornwall	45	13	29
" "	"	72	13	18
" "	"	92	14	15
Montmorillonite clay,	Redhill, Surrey	11 x)	8	73
" "	"	35	11	31
x) Clay content not reliable				
Scandinavia				
Alluvial clay,	Røjle, Denmark	75	7	9
" sand,	- , Denmark	20	1	5
Moraine clay,	- , Denmark	14	3	21
" " ,	Kungsbacka, Sweden	45	3	7
" " ,	Gothenburg, Sweden	68	4	6
" " ,	Stockholm, Sweden	63	4	6
" " ,	Trondhjem, Norway	12	3	25
Western Europe				
--- ,	Cologne, Germany	12	3	25
--- ,	Greyvillers, France	8	2	25
Africa				
--- ,	Duzére, Tunisia	15	6	40
--- ,	Souk-el-Arba, Tunisia	35	8	23
--- ,	Oudemaine, Algeria	26	8	31
--- ,	Philippevile, Algeria	69	12	18
--- ,	--- , Gambia	14	9	64
--- ,	Brikama, Gambia	27	4	15
--- ,	Yundum, Gambia	26	4	15
--- ,	Tow's River, South Africa	8	4	50
Lateritic clay,	Cape Province, South Africa	34	4	12
Asia				
--- ,	---- , Hongkong	22	8	36
Kaolin clay,	---- , Hongkong	40	6	15
Decomposed granite,	Kiatak , Hongkong	21	7	33
" " ,	---- , Hongkong	10	5	50

Gault clay fractions were both somewhat lower than the values obtained by the ignition of the complete soils from these areas (Table 2), suggesting that some additional losses occurred in the silt fractions. This is also the case with the lateritic clay from South Africa.

3. PARTICLE SIZE ANALYSIS BY MICRO-SEDIMENTATION METHOD.

A more fundamental approach is to consider the size distribution and shape of the particles in the clay fraction. Some preliminary work on these lines has been carried out at the Road Research Laboratory, using a modification of the usual sedimentation technique for particle size analysis.

For this purpose, it was first necessary to obtain some idea of the correct amount of dispersing agent to employ in order to obtain maximum dispersion. A series of experiments was therefore made in which the particle size distributions of a kaolin clay soil and a montmorillonite clay soil were determined,



Effect of sodium oxalate concentration on apparent clay content in particle size analysis of kadlinite montmorillonite clays.

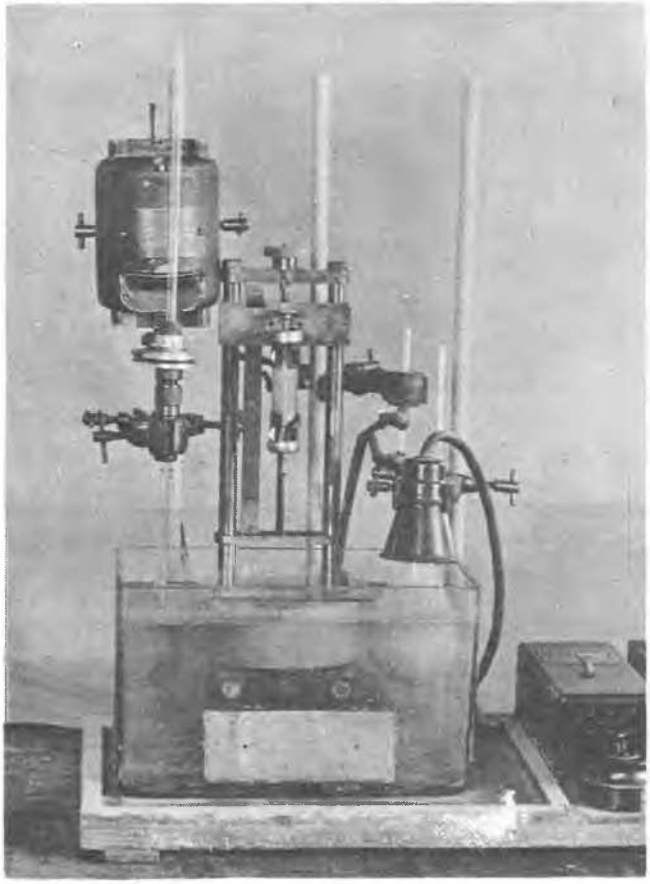
FIG.3

using varying quantities of sodium oxalate as the deflocculating agent. A series of experiments was also made with the kaolin clay using sodium hexametaphosphate for dispersion. The sedimentation analysis was done in the manner employed at the Road Research Laboratory for routine testing. In this, an Andreasen pipette is used for taking samples of a suspension containing 10 gm of soil in 500 cc.

The results of the experiments with sodium oxalate are shown in Fig. 3. The experiments with sodium hexametaphosphate are not shown, as the results obtained were almost the same as those obtained with the oxalate. It will be seen that a maximum dispersion of the kaolin clay occurred over a range of concentrations of from 0.1 to 0.4 gm of oxalate, for approximately 9 gm of clay particles. On the other hand, the dispersion of the montmorillonite clay increased slowly with the concentration of dispersing agent, until a maximum was reached corresponding to 0.9 gm of sodium oxalate for about 4 gm of clay. It appears, therefore, that unit weight of the montmorillonite clay requires about twenty times the quantity of dispersing agent needed by the kaolin to produce maximum deflocculation. It was also concluded that 0.1 gm of sodium oxalate could be used to deflocculate 10 gm of a kaolin clay of this type having a clay content in the range 22% - 90% under the experimental conditions employed. It was felt that such a generalization could not be applied to montmorillonite clays and that seprate experiments to determine the optimum dispersing agent concentration are required for each soil.

The apparatus constructed for extending the particle size analysis into the clay fraction is shown in Fig. 4. The technique employed is similar to that used by Puri and Puri 4) and E.W. Russell 5).

The sampling device consists of a 10 ml.



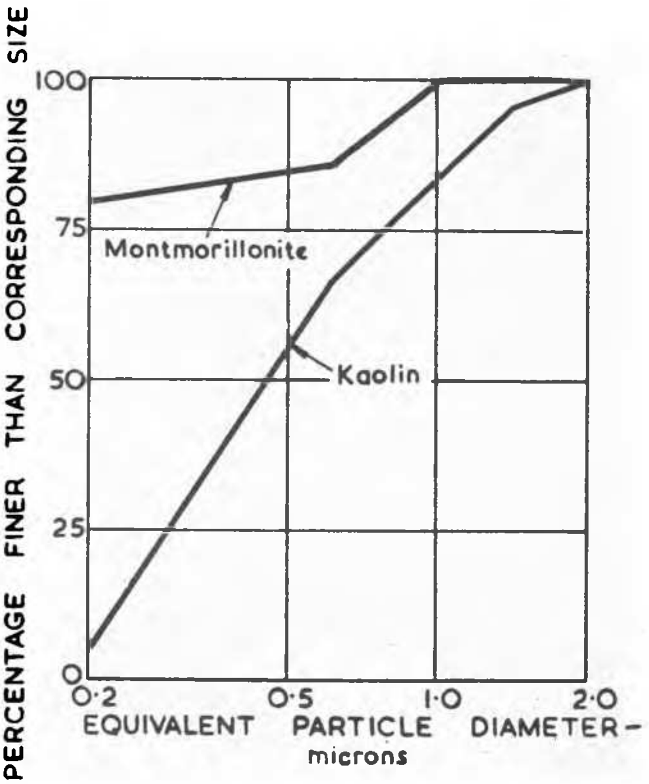
Micro-sedimentation apparatus for particle size analysis of clay soils using a hypodermic syringe.

FIG.4

hypodermic syringe, the tip of which can be set at various depths below the surface of the suspension with an accuracy of 0.01 cm. A sample of approximately 1 ml is taken from a depth of 1 cm after appropriate periods of sedimentation, and discharged into a weighed glass weighing bottle. The weight (and hence the volume) of the aqueous component of the sample is determined from the loss in weight after drying at 105°C. The weight of the solid residue is also determined, from which the volume of the solid component of the sample can be calculated, knowing the specific gravity of the particles and allowing for the presence of the dispersing agent. The concentration of the suspension in the sample is then calculated in the ordinary way, from the weight of the particles and the total volume of the sample.

This technique has been compared with the normal method for particles of 0.006 mm and 0.002 mm equivalent diameters, and the two procedures were found to give results that differed by not more than 1% of material in the case of two soils investigated. The accuracy of the syringe was found to be of this order even at sampling depths of 2 mm.

In a preliminary investigation the method was used to determine the size distribution in the coarser part of the clay fractions of the kaolin and montmorillonite clays previously referred to. The quantities of sodium oxalate employed for deflocculation were those giving maximum dispersion. The results (Fig. 5) show the size distribution in the range 2.0 - 0.2 microns equivalent particle diameter (1 micron = 0.001 mm). It will be seen that the particle diameter decreased very rapidly in the kaolin clay below 2.0 microns, but that about 80% of the montmorillonite particles were smaller than 0.2 microns equivalent diameter.



Size distribution in clay particles from kaolin and montmorillonite soils.

FIG. 5

4. ELECTRON MICROGRAPHS OF CLAY PARTICLES.

Attempts have been made to study the shape and size of particles of clay by means of the electron microscope, and for this purpose the Metallurgical Division of the National Physical Laboratory has taken 48 photographs of clays from eight British soils supplied by the Road Research Laboratory. Samples of the fraction having equivalent particle diameters smaller than 2 microns were prepared from the complete soils by sedimentation. For the examination, a small quantity of this material was shaken up in a N/100 sodium citrate solution, a drop of which was allowed to dry on the thin nitro-cellulose film that forms the object support in the microscope. The dispersing agent was then removed by washing the specimens in distilled water.

Figs. 6 and 7 show the photographs obtained with clay fractions from five different localities, the lines at the side of each photograph representing a length of 2 microns at the magnification given. Sharp outlines were in general only obtained with the larger particles (>1μ) but the thin plate-like nature of the particles is evident from the transparent images. However, in spite of the blurred nature of the outlines, two facts may be noted regarding the larger particles. One is the frequent occurrence of the 120° interfacial angle at the crystal edges, which may be found in all the photographs to some extent, but which is particularly visible in the samples from Cheddington (6c) and Brentwood (7d). The resulting similarity to micrographs of china clay and kaolin obtained both at the National Physical Laboratory and elsewhere, suggests that a proportion of kaolin-type minerals may be present in all the clays examined, and although the evidence is inconclusive it tends to support the evidence obtained from the loss on ignition determinations. More experimental work is required, however, before definite conclusions can be reached. The second point of interest is the occurrence of rod-shaped particles in the samples from Cheddington (6c) and Brentwood (7d), four such particles being distinctly visible in the latter. The large elongated particle in Fig. 6c which is 0.8μ long is very similar to the particles of halloysite shown by Shaw and Humbert in a recent paper to the American Society of Soil Science 6).

ACKNOWLEDGEMENT.

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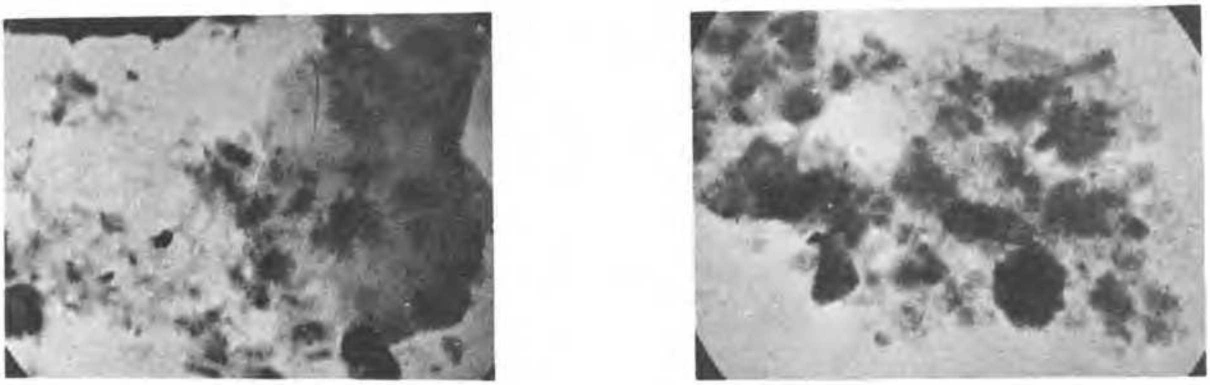
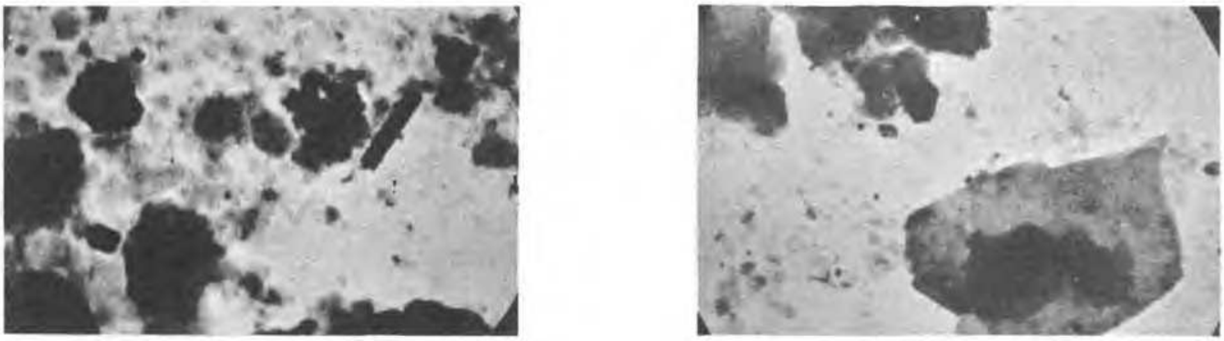
2) Standard method of test for Plastic Limit



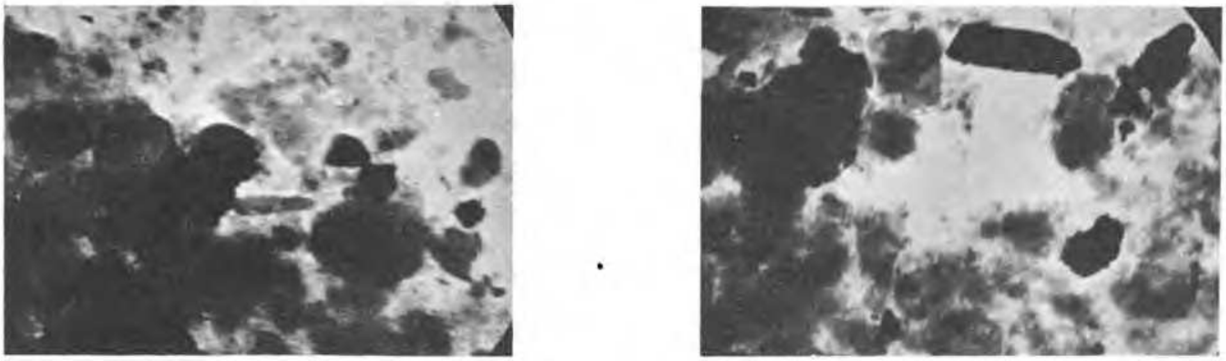
(a) Selby, Yorks x 13.000 (b) Selby, Yorks x 9.000



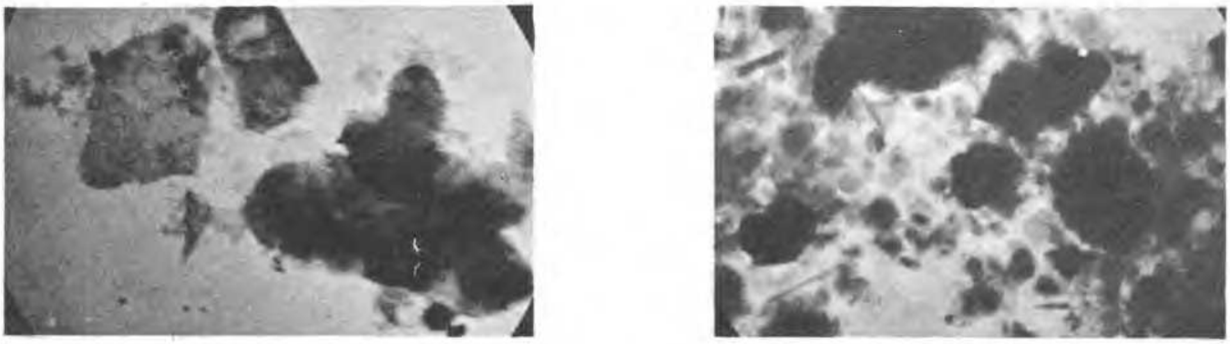
(c) Cheddington, Bucks x 15.000 (d) Cheddington, Bucks x 9.000

Electron micrographs of the 2 equivalent particle diameter fraction of some English clays.

FIG.6



(a) Maidstone, Kent x 13.000 (b) Maidstone, Kent x 9.000



(c) Laindon, Essex x 13.000 (d) Brentwood, Essex x 9.000

Electron micrographs of the 2 equivalent particle diameter fraction of some English clays.

FIG.7

And Plasticity Index of soils. A.S.T.M. designation: D.424-39. A.S.T.M. Standards. Part II. Non-metallic materials - Constructional. The American Society for Testing Materials Philadelphia, Pa., 1944 (The Society).

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SUB-SECTION II b

IDENTIFICATION TESTS

II b 1 AN EXPERIMENTAL STUDY OF THE MAXIMUM AND MINIMUM POROSITIES OF SANDS

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INTRODUCTION.

This paper presents the results of research to determine limiting porosities for any given sand.

These limiting porosities (maximum and minimum) if obtained by simple and reliable methods should provide convenient and useful values not only for the description of a sand but should serve as criteria for its expected behaviour, in other words should provide the same sort of comparable values as Atterberg's limits in case of clays.

It may, for example, be known that the porosity of sand in the field is n%, but by itself this value conveys little, and for its significance to become apparent it must be related to the maximum and minimum porosities at which the sand can exist in stable packing.

The main factors which have been considered in this study include the size of measuring vessel, the rate of pouring, the difference between pouring in air and water, the influence of tamping and vibration. Many tests were run to study these factors and the results were averaged so as to assure representative values. Every effort was made to keep all other minor variables constant (temperature, moisture content).

In all experiments special care was taken to repeat exactly the developed techniques.

A limited number of tests have been run to obtain supplementary information.

It must be clearly recognized that some of the results will require further investigation in order to complete the general picture of the research since this appears to be a first attempt to deal systematically with this problem.

THE SAND SAMPLES.

The sands which have been used are as follows:

1. Leighton Buzzard	18 - 25 B.S.S.
2. Stone Court	18 - 25 B.S.S.
3. Stone Court	52 - 100 B.S.S.
4. Stone Court	Medium-Uniform
5. Stone Court	Well-graded
6. Ham River	25 - 52 B.S.S.

Fig. 1 shows grain distribution curves for all of these sands. The roundness and sphericity of the grains were determined by inspection of the projected shapes, as outlined by KRUMBEIN 8) and 9).

SAND	Mean Roundness	Mean Sphericity
1. Leighton Buzzard 18 - 25	0'5	0'840
2. Stone Court 18 - 25	0'3	0'803
3. Stone Court 52 - 100	0'3	0'787
4. Stone Court Med.-Unif.	0'3	0'800
5. Stone Court Well-Graded	0'3	0'786
6. Ham - River 25 - 52	0'4	0'772

Specific gravities of the Sands are:

Leighton Buzzard	2'6
Stone Court	2'7
Ham River	2'7

Other Sands have been used for checking the results and techniques.

LOOSE PACKING.

Pouring in Air.

At an early stage of the research it was found that quick pouring of the same quantity (weight) of sand through air results in higher porosities than those obtained by slow pouring.

A series of tests thus were carried out and special techniques developed to investigate the rate of pouring through air.

The final technique was as follows:

1. Apparatus (see diagram No. 2)

The apparatus consisted of the following:

a) A series of paper funnels perforated to provide an uniform rain of sand partic-