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THE RELATION BETWEEN THE CLAY CONTENT AND CERTAIN PHYSICAL PROPERTIES OF A SOIL.

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(With Five Text-figures.)

Introduction.

It is well known that the behaviour of most soils is largely determined by the percentage of clay they contain. A considerable amount of work has been done from this point of view, some of which has been already discussed by one of us[1] and hence need not be repeated here.

In the present paper a simple method is described for measuring various fundamental properties of soil, such as pore space, apparent and real specific gravity, volume expansion and so on. The results for successive depths of one soil are given here for illustrative purposes. They have proved of sufficient promise to warrant the application of the method to a large variety of soils, and we have been fortunate in enlisting the aid of the Science Masters Association who have arranged for tests to be made at a number of schools.

Description of Soil used.

The soil was obtained from Mr Alfred Amos, of Spring Grove, Wye, Kent, from a deeply cultivated portion of a hop garden. It was taken some years ago, and was kept tightly corked in an air-dry condition until used. Six successive depths of the soil were separately stored as follows: 0–6″, 6–12″, 12–18″, 18–24″, 2–3′, 3–4′. The mechanical analysis of each depth is shown in Table I. For reasons which are mentioned below, each sample was passed through a sieve of 100 meshes to the linear inch before use and the figures refer to the soil passing the sieve.

[1] B. A. Keen, *J. Agric. Sci.* **10** (1920), 44.

Table I. *Mechanical analysis of successive depths of the same soil.*

Depth	0–6″	6–12″	12–18″	18–24″	2–3′	3–4′
Fraction:						
Fine sand ...	28·2	33·8	51·7	41·0	45·0	54·6
Silt	37·3	37·2	21·3	28·7	24·6	21·4
Fine silt, I ...	9·5	6·7	·75	4·7	5·2	1·7
Fine silt, II ...	2·8	1·8	·3	1·6	2·2	·8
Clay	10·2	10·1	16·7	17·1	15·3	14·1
Solution loss ...	3·95	3·9	2·95	2·6	2·2	2·9
Loss on ignition ...	7·5	6·7	6·0	4·55	3·8	4·0
Totals ...	99·45	100·2	99·70	100·25	98·3	99·5

Experimental Method.

A number of small brass boxes are used, made as follows: a piece of stout brass sheet 8″ × 1″ is bent into four sides of a box, 2″ square by 1″ deep, and the join carefully soldered. Another portion of the metal is made into a detachable bottom piece slightly larger than 2″ square and provided with a turned up edge about ½″ high which should fit closely round the first portion. The bottom is pierced with 11 rows of 11 holes each about ·75 mm. in diameter and ·5 cm. apart. A square of filter paper which is cut to the internal measurement of the box-bottom is placed therein, and held firmly by the lower edge of the sides of the box when this is placed in position. The box is weighed and is then filled with the sieved and air-dry soil in a systematic manner, so that the method of packing may be as uniform as possible. From 8–10 grms. are added at a time and the box tapped on the bench after each addition. When the box is nearly full, sufficient soil is added to allow the surface to be struck off flat with a spatula. The upper edges of the box are then in turn tapped smartly with the edge of the spatula, and more soil is added. This is struck off flat as before and the process repeated until very slight settling of the soil occurs, when the surface is finally struck off flat and the box and contents weighed. The box and contents are then placed in a flat bottomed dish containing about ¼″ depth of distilled water and left over night. When a number of boxes are placed in the same dish, additions of water must be made at intervals to keep the level constant. The behaviour of the soil while moistening is taking place is interesting. Considerable movement takes place[1], the top of the block of soil retreating from the sides of the box before it becomes moist, and at the same time rising in height. Eventually when the interstices are saturated the wet soil expands back to the sides of

[1] In some cases this initial movement is accompanied by a cracking of the surface soil. These cracks may persist when the soil is saturated. It is not yet certain whether they are solely due to slight variations in the method of packing; some soils show the effect more than others.

the box but the vertical expansion remains. The next morning the boxes are rapidly dried on the outside, weighed, and replaced in the water for a few minutes. The portion of the soil which has expanded above the top of the box is then removed as follows: an ordinary razor blade held at a slight angle with the horizontal is placed along one edge of the box and then drawn across the top. The removal of the soil is facilitated if, previous to the use of the razor, a flat-edged spatula is used to divide the expanded soil into three rectangular blocks, of approximately equal volume. Each block is then removed in turn with the razor. This surplus soil is transferred from the razor to a small glass or metal dish as cleanly as possible, and weighed. Any soil adhering to the under side of the razor should not be put into the dish but replaced on soil in the brass box, to which it belongs. The box and residual soil are weighed after the outside has been dried, and then placed, together with the dish containing the surplus soil, in a water oven for 24 hours[1]. At the end of this period they are cooled in a desiccator and weighed again.

In addition to these weighings it is necessary to measure carefully the internal volume of each brass box, which is done by taking a series of measurements of the height, breadth and length, and averaging; also to determine in the usual way the moisture present in the air-dry soil used in the experiments; to measure the amount of water taken up by the wet filter paper which is best done by taking six squares, saturating them with water, removing the surplus with a glass rod, and measuring the increase of weight due to the water remaining.

It will be found convenient to have a rectangular metal box and lid in which the brass box and soil—whether air-dry or saturated—are placed for weighing purposes.

The necessary weighings and measurements are therefore:

Weight of weighing box, brass box, and filter paper	a grms.
,, ,, ,, ,, air-dry soil ...	b ,,
,, ,, ,, wet ,, saturated soil ...	c ,,
,, ,, ,, ,, ,, {saturated residual} ,, ...	d ,,
,, ,, ,, dry ,, {oven-dry residual} ,, ...	e ,,
,, metal dish (or watch glass)	f ,,
,, ,, ,, ,, saturated surplus soil ...	g ,,
,, ,, ,, ,, oven-dry ,, ,, ...	h ,,
Percentage of moisture present in air-dry soil	x %
Internal volume of brass box	v c.c.

[1] In view of the large mass of soil to be dried, heating for 48 hours at 100° C. was also tried; 24 hours was found to be long enough.

From these weighings the following results are obtained:

(1) Weight of unit volume (100 c.c.) of air-dry soil (apparent specific gravity) $\frac{b-a}{v} \times 100$.

(2) Amount of water taken up by unit weight of soil $= \frac{(c-a)-(b-a)}{(b-a)}$.

Note. Correct $(b-a)$ for the x % of water contained in the air-dry condition, and $(c-a)$ for the water in the filter paper.

(3) Pore space $= \frac{\text{Volume of water in box}}{\text{Volume of box}} = \frac{(d-a)-(e-a)}{v}$.

Note. Correct $(d-a)$ for the water in the filter paper.

(4) Specific gravity of soil $= \frac{(e-a)}{v-(d-p)}$.

(5) Volume expansion of 100 c.c. of soil

$$= \frac{\text{Volume of water in saturated surplus soil} + \text{volume of surplus soil}}{\text{Volume of box}}$$

$$= \frac{(g-h) + \frac{h-f}{\text{sp. gravity}}}{v} \times 100.$$

As mentioned above, the soil on which these measurements are made is that passing the sieve having 100 meshes to the inch. A number of trials were made with the soil passing the 1 mm. sieve, but concordant results could not be obtained. This is due not so much to the larger soil particles but to the varying amounts of soil crumbs or compound particles passing the sieve. The presence of these particles undoubtedly affects the packing of the soil into the boxes, and consequently all the subsequent weighings. The results discussed below apply therefore to a soil whose mechanical analysis differs somewhat from that of the unsieved soil in having a greater percentage of the finer particles. For the majority of ordinary soils the difference is not serious, but it is appreciable on soils containing a larger percentage of fine sand. It is probable that in this case the better experimental procedure would be to sieve the soil through the 100 mesh sieve so as to break up any compound particles, and then to remix this portion with that which passed the 1 mm. sieve but was held by the 100 mesh. It is intended to experiment in this direction not only on sandy soils but on those containing more clay.

Discussion of Results.

The experimental figures of duplicate determinations for the successive depths of soil are given in Table II. Columns (5) and (6) have been corrected for the water taken up by the filter paper. A measure of the experimental error in slicing off the surplus soil with the razor, is given by comparing the values in column (5) with the sum of the corresponding figures in columns (6) and (7). There should be no difference; actually there is a small loss in each case varying from ·01 grm. to ·63 grm. The average loss is under ·25 grm. and well within experimental error from other sources. After a little practice, the maximum loss can be kept well below ·25 grm. From the values in Table II the various constants

Table II.

(1) Depth of soil	(2) Vol. of brass box in cu.cms. (v)	(3) Wt. of air-dry soil in grms. (b − a)	(4) % moisture in air-dry soil x	(5) Wt. of satd. soil in grms. (c − a)	(6) Wt. of satd. soil less surplus in grms. (d − a)	(7) Wt. of satd. surplus soil in grms. (g − f)	(8) Wt. of oven-dry soil less surplus in grms. (e − a)	(9) Wt. of oven-dry surplus in grms. (h − f)
0–6″	68·7 66·7	79·93 79·16	3·2	116·55 114·86	111·60 109·50	4·82 5·24	75·09 74·13	2·99 3·23
6–12″	67·9 68·2	79·26 79·39	2·2	115·44 115·49	111·46 111·91	3·88 3·57	75·14 75·49	2·41 2·20
12–18″	67·1 67·9	78·86 79·34	3·2	120·96 121·38	105·89 105·38	14·44 15·62	68·01 67·69	8·97 9·70
18–24″	68·4 67·4	79·39 76·62	3·15	121·75 118·63	106·80 104·69	14·72 13·55	68·05 66·15	9·08 8·24
2–3′	67·8 68·3	80·16 81·98	2·85	120·60 122·75	107·66 109·94	12·65 12·57	70·21 72·14	7·99 7·90
3–4′	68·1 68·1	85·21 87·82	3·3	124·67 127·12	112·06 113·77	12·37 13·13	75·66 77·47	8·04 8·58

Table III.

Constants		Depths: 0–6″	6–12″	12–18″	18–24″	2–3′	3–4′
I. Wt. of unit vol. (100 c.c.) of air-dry soil. (Apparent specific gravity)	Duplicates	116·3 118·7	116·7 116·4	117·5 116·8	116·0 113·7	118·2 120·0	125·0 129·0
	Average...	117·5	116·5	117·1	114·8	119·1	127·0
II. Amount of water taken up by unit weight of soil	Duplicates	·50 ·50	·49 ·49	·58 ·58	·58 ·60	·55 ·54	·51 ·49
	Average...	·50	·49	·58	·59	·545	·50
III. Pore space	Duplicates	53·1 53·0	53·5 53·4	56·4 55·5	56·7 57·2	55·3 55·3	53·5 53·5
	Average...	53·05	53·45	55·95	56·95	55·3	53·5
IV. Specific gravity	Duplicates	2·33 2·36	2·38 2·38	2·33 2·24	2·29 2·29	2·31 2·36	2·39 2·44
	Average...	2·345	2·38	2·285	2·29	2·335	2·415
V. Volume expansion of unit volume of soil	Duplicates	4·53 5·07	3·65 3·36	13·9 15·1	14·0 13·2	11·95 11·75	11·3 11·85
	Average...	4·80	3·50	14·5	13·6	11·85	11·57

indicated above are easily determined. They are given in Table III and are plotted against the corresponding percentage of clay in Figs. 1–5. In each of these figures the actual duplicates are shown as crosses and

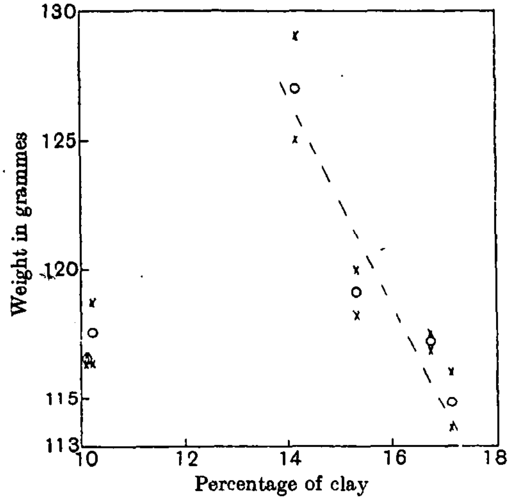

Fig. 1. Relation between clay content and weight of unit volume of air-dry soil.

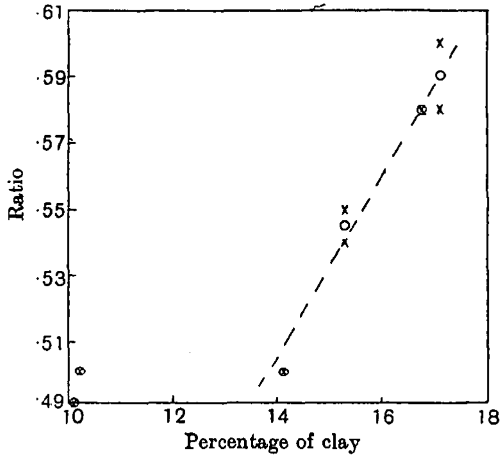

Fig. 2. Relation between clay content and ratio: $\frac{\text{weight of water taken up}}{\text{weight of soil}}$.

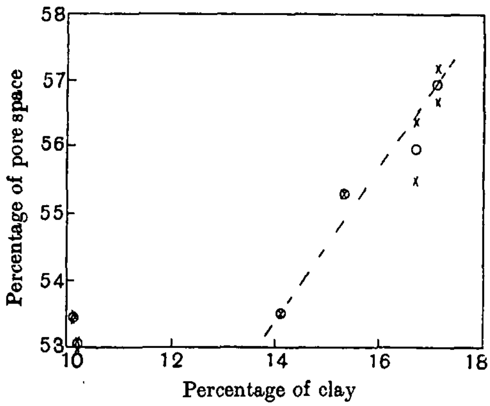

Fig. 3. Relation between clay content and pore space.

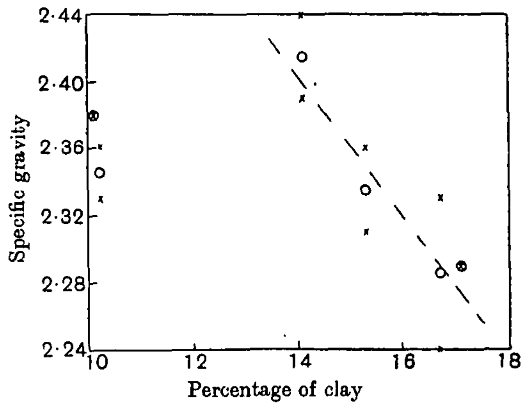

Fig. 4. Relation between clay content and specific gravity of soil.

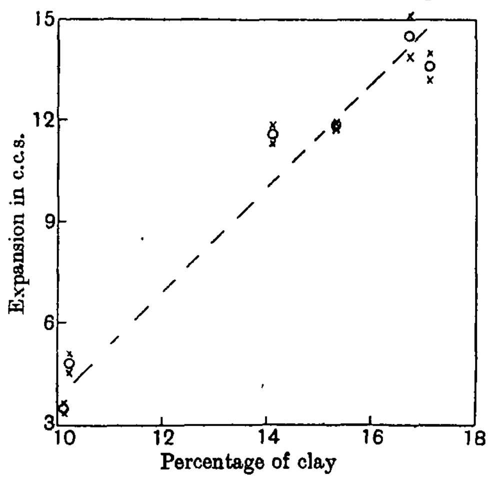

Fig. 5. Relation between clay content and volume expansion of soil.

mean of each pair as a circle. In interpreting the relations of the experimental results to the percentage of clay it must be remembered that the soil contains considerably more organic matter in the top 12″ than in the lower depths; hence the top layer will in some respects behave as if its clay content were in excess of the value given in Table I. Ignoring for the moment the values for the 0–6″ and 0–12″ layers and paying attention to the remaining four depths, it will be seen that in each of the Figs. 1–5 there exists a general relationship between the amount of clay and the variations in the given constant. The straight line in each figure is, of course, only an indication of the general trend of the values. The apparent and real specific gravities (Figs. 1 and 4 respectively) show an inverse relationship with the percentage of clay, while the amount of water taken up by the soil (Fig. 2), the pore space (Fig. 3), and, to a lesser extent, the volume expansion (Fig. 5) are directly related to the clay percentage. The effect of the organic matter is shown in Figs. 1–5 by the soils corresponding to the 0–6″ and 6–12″ layers, which contain just over 10 % of clay. These two layers give values for the various constants very similar to those of the layers containing more clay except in the case of the volume expansion (Fig. 5). Elsewhere it will be shown that, if the bottom layer of this soil be assumed devoid of organic matter, the approximate percentages in the top two layers are 3·7 and 3·95 respectively. Inspection of Figs. 1–5 in detail shows that the apparent and real specific gravities (Figs. 1 and 4) of the top two layers are equivalent to the values given by the layer with 15 % of clay, while the pore space (Fig. 3) and amount of water taken up by the unit weight of soil (Fig. 2) correspond to 14 % of clay. The volume expansion (Fig. 5) is apparently not affected by the organic matter. The organic matter therefore is, weight for weight, equivalent to clay except in the volume expansion measurements, where its possible effect is within the experimental error.

The fraction fine silt II (upper limit of diameter ·005 mm.) possesses similar properties to the clay, and if included with it, does not appreciably affect the order of the above results. In most soils this fraction is not present in considerable quantity.

There are a number of other points brought out by the further inspection of the tables and diagrams.

In the calculation for the ratio: weight of water taken up by a given weight of soil, the weight of the whole of the soil in the box was used. It is possible to obtain similar ratios for both the surplus soil (that which was removed by the razor) and the residual soil (that remaining in the box). These ratios are obtained from Table II in the forms

$$\frac{\text{column 7} - \text{column 9}}{\text{column 9}} \text{ and } \frac{\text{column 6} - \text{column 8}}{\text{column 8}},$$

respectively.

It will be found that the values for the residual soil are slightly below those for the total soil given in Table III, while those for the surplus soil are considerably in excess. There are a number of possible causes which may account for this. In addition to the water taken up by the surplus soil there is an obvious film of water on the surface of the soil which will increase the above ratio for the surplus soil; the lower layers of soil, being confined by the rigid brass box, can only swell vertically against the resistance of the superincumbent layers so that the ratio for the residual soil will be diminished; there is probably some air trapped in the interstices of the soil as the water ascends. It is not likely that the presence of air is the sole cause of difference, because the amount of air so trapped would be very variable from box to box, whereas the experimental results show very little erratic variation. It is possible by suitably manipulating the figures to obtain an idea of the amount of trapped air, as follows:

The calculation of the absolute specific gravity of the soil was obtained from the expression:

$$\frac{\text{wt. of residual soil}}{\text{vol. of box} - \text{vol. of water}}.$$

The low values of the specific gravity (Table III) can be explained by the presence of air, which reduces the volume of water. Taking the true value of the specific gravity to be 2·70, it is easy to calculate for any given soil what should be the volume of water completely filling the pore space. The difference between this volume and the experimental figure may be regarded as the volume occupied by the trapped air. Taking for illustration the first duplicate of the 0–6″ depth (*i.e.* the top row of figures in Table II) we obtain

$$2{\cdot}70 = \frac{75{\cdot}09}{68{\cdot}7 - x},$$

i.e. $x = 40{\cdot}9$ c.c. of water.

The experimental figure is $111{\cdot}60 - 75{\cdot}09 = 36{\cdot}51$ c.c.; *i.e.* 4·4 c.c. are occupied by air, which is equivalent to 6·4 % on the total volume of the brass box. Turning now to the already mentioned variation in the ratio of weight of water taken up to weight of soil we find from

Table II that in the surplus soil it is $\frac{1\cdot83}{2\cdot99} = \cdot61$ and in the residual soil $\frac{36\cdot51}{75\cdot09} = \cdot49$.

Assuming that the value for the residual soil has been reduced solely owing to the air entrapped, and that the true value is ·61, 75·09 grms. of soil should take up 45·8 grms. of water, instead of 36·51, the experimental value. Using this value of 45·8 grms. of water for x in the calculation of the specific gravity immediately above, we obtain the figure 3·28. This is obviously incorrect. Hence the diminished value in the residual soil of the ratio of weight of water taken up to weight of soil, cannot be wholly due to the entrapping of air within the box. The other possible causes have been already mentioned above.

Summary.

A simple experimental method has been described for measuring certain physical constants of soil, using small brass boxes into which soil passing a sieve of 100 meshes to the inch has been packed by hand. The quantities determined are:

(1) The weight of unit volume (100 c.c.s.) of air-dry soil, or the apparent specific gravity.
(2) Amount of water taken up by unit weight of soil.
(3) Pore space.
(4) Specific gravity of the soil.
(5) The volume expansion of unit volume (100 c.c.) of soil when saturated.

The results for one soil only are given, and discussed, to illustrate the method. With the co-operation of the Science Masters Association it is being applied to a number of soils by various schools.

The particular soil used was obtained in six depths as follows: 0–6″, 6–12″, 12–18″, 18–24″, 2–3′, 3–4′, and the above constants were determined on each depth. It was shown that (1) and (4) varied inversely with the percentage of clay in the soil, while (2), (3), and (5) varied directly with the clay percentage. The effect on the constants of the larger quantities of organic matter present in the top two layers of soil was, weight for weight, approximately equal to that of the clay, except in the volume expansion results where the effect if any was within experimental error.

It is possible that the fraction fine silt II, whose upper limit of diameter is ·005 mm., has similar effects to the clay fraction.

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