ROTHAMSTED RESEARCH

Report for 1934

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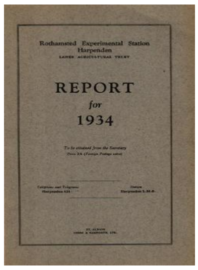

The Contribution of Rothamsted to Soil Physics

The Contribution of Rothamsted to Soil Physics (1935) Report For 1934, pp 35 - 48 **- DOI: https://doi.org/10.23637/ERADOC-1-66**

In addition a considerable amount of assistance is given to agricultural experimenters from overseas. Some send or bring their proposals for field experiments so as to ensure good design, others bring their accumulated data for help in extracting all the valid information they can be made to yield. There is a growing demand for this kind of help and it is hoped that permanent provision may be made for it.

As special pieces of work during the year Mr. Yates has studied the applicability of the χ^2 test to contingency tables, especially 2 x 2 tables, involving small numbers, while he and Mr. Cochran both devoted considerable time to the study of the Woburn data. This Report is now complete and is being prepared for the press.

THE CONTRIBUTION OF ROTHAMSTED TO SOIL PHYSICS

B. A. Keen

Until 1913 no systematic work on the physical properties of soil had been done at Rothamsted or indeed in Great Britain. The investigations were suspended during the War and resumed in 1919. Most of the publications of the Physical Department fall conveniently into a few groups, and these have been utilised, rather than a chronological order of papers, in the short account that follows. A full discussion will be found in the Rothamsted Monograph entitled " The Physical Properties of the Soil."

Mechanical Analysis

The methods of mechanical analysis have been developed in two main directions : existing methods based on the separation into a few groups or fractions have been improved both in simplicity and accuracy ; and much attention has been paid to the elegant procedure, first evolved by Odén in Sweden, by which a particle size distribution curve is obtained.

In Great Britain a co-operative investigation was organised from Rothamsted to test the suitability of two important improvements devised by Robinson of Bangor, Wales : pre-treatment of the sample with hydrogen peroxide to remove organic matter, and the substitution of pipette sampling for separation by sedimentation. Two reports(1) were issued, recommending for official adoption in Great Britain the use of hydrogen peroxide in the pre-treatment of the sample, and the employment of the pipette for determining the percentage of the silt and clay fractions. The new method was subsequently adopted, with a minor modification, as the Official Method A, of the International Society of Soil Science. Thus, the International and British methods of mechanical analysis are identical, except for one minor difference. In changing their method, British workers were faced with many difficulties in preserving continuity with the extensive results accumulated by the older methods ; but the international character of soil science, and the ultimate advantages of a generally accepted universal method, were

(1) A Sub-Committee of the Agricultural Education Association—" The Mechanical Analysis of Soils : a Report on the Present Position, and Recommendations for a New Official Method." J. Agric. Sci., 1926, Vol. XVI, pp. 123-144 ; " The Revised Official British Method for Mechanical Analysis." J. Agric. Sci., 1928, Vol. XVIII, pp. 734-739. See also " The Official Method for the Mechanical Analysis of Soils Adopted by the Agricultural Education Association in 1925." Agric. Progress, 1926, Vol. III, pp. 106-110 ; and " Revised Official Method for the Mechanical Analysis of Soils Adopted by the Agricultural Education Association in 1927." Agric. Progress, 1928, Vol. V. pp. 137-144.

considered to have over-riding importance. An appeal ([2]) was made to all soil workers to take similar action, with little or no effect.

In the International and British methods, as in many others, a fine mesh wire gauze sieve is used to separate the coarse sand. The gauze stretches gradually with use, and the originally plane surface becomes bowl-shaped ; in addition the warp and weft wires undergo relative movements which produce mesh apertures both larger and smaller than the original ones. A mathematical and experimental examination of these two factors showed that no serious error was probable until the sieve had become badly worn.

Odén's method is based on the measurement of the progressively changing density or hydrostatic pressure during the sedimentation of a suspension. The particles settle on a pan immersed in the suspension, and the increase in weight is recorded at intervals. Evidently it is desirable that these intervals should be as short as possible : in other words, the balance should be automatic and continuous recording. A balance fulfilling these requirements was developed ([3]) by the Physical Department at Odén's suggestion. An apparatus which gives a continuous record of weight changes has, of course, uses beyond mechanical analysis ; this was demonstrated in an interesting way during the final trials of the apparatus, when a discontinuity in the dehydration of certain salt hydrates was discovered.([4]) Further work with the apparatus in an attempt to eliminate a discrepancy between the calculated and actual final weight caught by the pan, led to the disconcerting discovery of an inherent defect in the Odén procedure ([5]) and, indeed, in every other method of obtaining size distribution curves. The error arises because any attempt to measure changes of density or hydrostatic pressure in a sedimenting suspension is bound to disturb in a complex fashion the very factor it is desired to measure. Thus, in Odén's method, the pan shields the liquid below it from the descent of particles, while the liquid in the annular space around the pan is not so shielded, and a density difference is set up between them. Interchange of suspension between these two regions inevitably occurs, which interferes with the free vertical fall of the particles and destroys the fundamental assumption on which the mathematical analysis is based. Many experiments were made in the hope of removing the trouble, or at least of reducing it to a systematic error, without success. Although this seriously limits the use of these methods for purposes of research, they are useful for specifying rapidly the approximate mechanical analysis of a soil. An exceedingly convenient and quick method has been devised ([6]) which gives, in effect, the time-rate of change of the excess density of the suspension at a given fixed point. The readings of the manometer

(2) B. A. Keen—" Mechanical Analysis : National and International." Soil Research, 1928 Vol. I, pp. 43-49.

(3) J. R. H. Coutts, E. M. Crowther, B. A. Keen, and S. Odén—" An Automatic and Continuous Recording Balance. (The Odén-Keen Balance.) " Proc. Roy. Soc., A, 1924, Vol. CVI, pp. 33-51.

(4) E. M. Crowther and J. R. H. Coutts—" A Discontinuity in the Dehydration of Certain Salt Hydrates." Proc. Roy. Soc., A, 1924, Vol. CVI, pp. 215-222.

(5) J. R. H. Coutts and E. M. Crowther—" A Source of Error in the Mechanical Analysis of Sediments by Continuous Weighing." Trans. Faraday Soc., 1925, Vol. XXI, pp. 374-380.

(6) E. M. Crowther—" The Direct Determination of Distribution Curves of Particle Size in Suspensions." J. Soc. Chem. Ind., 1927, Vol. XLVI, pp. 105T-107T. E. M. Crowther—" A Manometric Apparatus for the Direct Determination of Summation Percentage Curves in Mechanical Analysis." Proc. First Internat. Cong. Soil Sci., 1927, Vol. I, pp. 394-398.

are then directly proportional to the summation curve, and only one differentiation is needed to obtain the distribution curve instead of two, as in Odén's method. The apparatus is particularly suitable for giving summation curves for the coarser fractions of soils, and for sandy soils, and is apparently accurate to within 2-3 per cent.

Soil Reaction

There is no sharp boundary between physico-chemical and physical properties of soils, and the Department has therefore examined certain physico-chemical aspects of the subject. After a preliminary investigation of colorimetric methods (7), the electrometric method was taken in hand ; the important technical problem of designing a satisfactory hydrogen electrode vessel for pH measurements of soil suspensions was solved(8), and the apparatus was used in a series of investigations. The relations between pH, buffer action, the effects of electrolytes and lime requirements were clarified. The unique series of classical experimental plots at Rothamsted and Woburn was examined and the changes in pH produced by the long continued applications of various manures was determined ; one conclusion of practical importance was that the changes in pH value as a result of applying lime to the soil is less than that shown in the laboratory owing in part to the subsoil acidity.(9) A detailed study of the depth distribution of reaction(10) on the classical plots showed that changes of reaction in the surface layer affected the lower depths to at least 36 inches. These depth changes in pH were also associated with marked differences in soil texture, which are not, however, a simple function of the pH. The top soil, although the most acid, showed no flocculation, probably owing to the protective action of the humus colloids ; the 4½-9 inch depths showed distinct flocculation but the suspension remained turbid ; the lower depths flocculated completely and immediately, possibly owing to the accumulation of calcium and aluminium ions leached down from the very acid surface layer. These textural differences will affect air and water movement within the soil ; they are important indirect factors in the relationship between soil reaction and crop growth.

In practice, the amount of lime needed to correct soil acidity is usually determined by one or other of numerous "lime-requirement" methods which, on different soils and in the hands of different workers may give widely varying results. The well-known Hutchinson-MacLennan method, which measures the interaction of soil with a calcium bicarbonate solution saturated with carbon-dioxide, was shown (11) to underestimate the amount of lime needed to produce a neutral soil, and the value obtained depended on the amounts of soil

(7) E. A. Fisher—" Studies on Soil Reaction. I. A Résumé. II. The Colorimetric Determination of the Hydrogen Ion Concentration in Soils and Aqueous Soil Extracts. (Preliminary Communication.) " J. Agric. Sci., 1921, Vol. XI, pp. 19-65.

(8) E. M. Crowther—" Studies on Soil Reaction. III. The Determination of the Hydrogen Ion Concentration of Soil Suspensions by Means of the Hydrogen Electrode." J. Agric. Sci., 1925, Vol. XV, pp. 201-221.

(9) E. M. Crowther—" Studies on Soil Reaction. IV. The Soil Reaction of Continuously Manured Plots at Rothamsted and Woburn." J. Agric. Sci., 1925, Vol. XV, pp. 222-231.

(10) E. M. Crowther—" Studies on Soil Reaction. V. The Depth-Distribution of Reaction and Flocculation in Cont nuously Manured Soils." J. Agric. Sc., 1925, Vol. XV, pp. 232-236.

(11) E. M. Crowther and W. S. Martin—" Studies on Soil Reaction. VI. The Interaction of Acid Soils, Calcium Carbonate and Water, in Relation to the Determination of 'Lime Requirements.' " J. Agric. Sci., 1925, Vol. XV, pp. 237-255.

and of calcium bicarbonate solution used, owing to the buffer action of the soil. Indirect titration curves derived from these results diverged systematically from direct electrometric titration curves because of the variable calcium concentration of the final bicarbonate solutions. The " lime-requirement," therefore, should be obtained by interpolation to some agreed arbitrary concentration. The inconvenience of making several separate measurements to obtain the curve was avoided by the discovery of an empirical relationship which enables the interpolation to be made from a simple determination. Recently, a new method has been devised ([12]) for assessing the lime-status of a soil, which should prove very useful owing to its rapidity and simplicity. The organic acid, *p*-nitrophenol, is half neutralised by lime water ; the *p*H is then close to 7. When soil is added lime will be abstracted from or supplied to the solution, depending on whether the soil was originally more acid or more alkaline than the solution. If this quantity of lime is not large compared with the total lime in the solution, the *p*H of the solution remains close to 7. Simple titrations of the filtered and original solutions are made, from which is calculated the quantity of lime that must be given to or taken from the soil to bring it to neutrality. Other *p*H values can be used by employing different acids which, like *p*-nitrophenol, have soluble calcium salts, and the range can be further widened by increasing their concentration. A buffer-curve for a soil can therefore be traced in detail, since lime is the principal exchangeable base in normal soils.([13]) The individual points on the curve can be determined by an electrical conductivity or, if the widest range of *p*H is needed, by titration. Both methods are rapid and simple, the former being especially so. Examination by these means of soils of different types, and of plots that have received markedly different manuring, shows that the form of the curves will throw much light on soil differences and soil genesis, as the curves for different soil samples show both marked similarities and differences. For example, the partial buffer capacity at *p*H 7—which can rapidly be measured by the change in electrical conductivity produced when soils are put into a mixture of 0.1 molar K_2HPO_4 and 0.05 molar KH_2PO_4([14])—is closely correlated with other physical characteristics of the soils, such as the heat of wetting, and the moisture content at 50 per cent. relative humidity (See p. 43).

Plastic Behaviour of Soil and Clay

The Department has given much attention to this subject. A wide range of moisture content has been used, giving all stages of consistency of the soil, or clay, between plastic behaviour (c.f., modelling clay) and quite thin pastes. Special interest attaches to the latter as, in addition to its intrinsic importance as a problem in a neglected field of pure physics, it offers a means of studying the colloidal properties of clay particles over a range of moisture content in which

(12) R. K. Schofield—" Rapid Methods of Examining Soils. II. The Use of *p*-Nitrophenol for Assessing Lime Status." J. Agric. Sci., 1933, Vol. XXIII, pp. 252-254.

(13) R. K. Schofield—" Note on the Usefulness of Buffer Capacity in Soil Examination." Trans. Sixth Comm. Internat. Soc. Soil Sci., 1933, Vol. B, pp. 80-84.

(14) R. K. Schofield—" Rapid Methods of Examining Soils. III. The Use of Dihydrogen Potassium Phosphate in Studying Base Exchange Capacity." J. Agric. Sci., 1933, Vol. XXIII, pp. 255-260.

both solid and fluid (or viscous) properties are displayed; in field conditions, of course, the former only is predominant.

In the ceramic and allied industries, a number of measurements, more or less empirical, have long been used to specify the clays at different stages of their preparation. Preliminary examination of the behaviour of clay and soil pastes showed that improvement, both in the theory, and in the design of suitable apparatus, was badly needed before progress could be made. A series of papers ([15]) describes the development of the theory and the experimental results obtained with a specially devised plastometer and flowmeter.

Examination of the flow curve when the stress is progressively increased from zero to a value which is still below that producing turbulent flow, shows that four stages can be recognised. Stage I, no flow until a critical shearing stress is reached—the paste remains immovable. Stage II, plug flow—the paste moves like a solid rod in the capillary tube. This agrees mathematically with the hypothesis that the plug is sliding through a very thin layer of "liquid" of constant thickness, probably hydration envelopes of the outermost particles modified by the proximity of the capillary wall. Stage III, mixed flow—a complex range which can be qualitatively described as a central plug moving through a sheath of paste that approximates to streamline flow. As the stress is increased, the diameter of the central plug progressively diminishes. Stage IV, pseudo-streamline flow, as for a truly viscous fluid, with the restriction that the properties of the clay paste are modified in the annular region near the wall of the capillary tube. In effect, the consistency of the paste in this region is lowered; the cause is not yet understood, but experiment shows it is not due to orientation of laminar particles in the direction of flow, nor to a decrease of concentration as compared with the paste in the centre portion of the capillary. This modification must not be confused with the layer of hydration envelopes described in stage II. This stage is inhibited if the inside of the tube is previously lightly etched, whereas stage IV is unaffected.

This work has a most important bearing on the extensive studies of other workers on "structure viscosity" and "structure turbulence." There is some obscurity of meaning in these terms, and no simple relationship has yet been demonstrated between the properties they are supposed to describe. Nevertheless, if they exist, our work shows that their effects must cancel each other exactly in all the hundreds of soil and clay pastes we have investigated over a wide range of stress. ([16]) This is so improbable, that it raises grave doubts as to the reality of "structure turbulence" and "structure viscosity" in soil and clay pastes, and indeed, in other systems.

The value of the above work on soil pastes is to provide a link

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(15) G. W. Scott Blair and E. M. Crowther—"The Flow of Clay Pastes through Narrow Tubes." J. Phys. Chem., 1929, Vol. XXXIII, pp. 321-330; R. K. Schofield and G. W. Scott Blair—"The Influence of the Proximity of a Solid Wall on the Consistency of Viscous and Plastic Materials." J. Phys. Chem., 1930, Vol. XXXIV, pp. 248-262; G W. Scott Blair—"A Further Study of the Influence of the Proximity of a Solid Wall on the Consistency of Viscous and Plastic Materials." J. Phys. Chem., 1930, Vol. XXXIV, pp. 1505-1508; R. K. Schofield and G. W. Scott Blair—"The Influence of the Proximity of a Solid Wall on the Consistency of Viscous and Plastic Materials. III." See also G. W. Scott Blair—"The Rheology of Soil Pastes." J. Rheology, 1930, Vol. I, pp. 127-138; and R. K. Schofield—"Simple Derivations of Some Important Relationships in Capillary Flow." Physics, 1933, Vol. IV, pp. 122-128.

(16) G. W. Scott Blair—"Ueber die Geschwindigkeitsfunktion der Viskosität disperser Systeme." Koll. Zeits., 1929, Vol. XLVII pp. 76-81; Vol. XLVIII, p. 283.

between the extreme condition represented by soil in the field and the weak suspensions used for flocculation and sedimentation studies and in mechanical analysis, and to show, in a fresh aspect, certain familiar properties of soil.[17] A number of examples follow. The behaviour of soil and clay pastes depends on their previous history: a paste made from soil that has been dried does not show the plug-flow of stage II. The variations in the resistance to the plough over a field are closely correlated with the shearing strengths of pastes made from soil samples taken from that field. Since shearing strength is independent of rate of shear it follows that ploughing speed should not appreciably affect the resistance to ploughing—a fact that was observed in the dynamometer measurements. (See the section on Soil Cultivation.) Farmyard manure, and large dressings of chalk reduce the plough draft and also the shearing strength of the soil pastes. Changes in the elusive but fundamental soil property known as " tilth " can be studied by plastometric measurements on pastes made from samples taken at suitable times during the year.

Finally, at the request of the International Society of Soil Science a report has been drawn up containing recommendations for standardising the use and meaning of the numerous terms employed in this subject in the English, French, German and Russian languages.[18]

Behaviour of other soft materials.—The work on clay which behaves predominantly as a plastic material, was extended to another substance which shows both plastic and elastic properties. Flour dough was selected for study, as this material has considerable elasticity and a high degree of plasticity, and it was anticipated that the result would be of interest to the milling and baking industries. For this reason the technological aspects were investigated jointly with the Research Association of British Flour Millers. Theoretical and laboratory studies of dough have been made[19], in addition to an extensive study of the baking qualities of flours in relation to their behaviour in the laboratory tests. An important feature of the work is that dough shows a phenomenon similar to the work-hardening of metals, since the time of relaxation and the viscosity for a given stress depend on the total deformation; two further properties, well known in the study of metals, are also present: elastic after-effect and elastic hysteresis.

RELATIONS BETWEEN SOIL AND ITS WATER CONTENT

The classification of soil moisture first adopted by earlier workers on soil physics recognised three main divisions: hygroscopic water, held so tightly to the soil particles as to be unavailable for plants; capillary water, free to move under surface tension forces; and gravitational water, which drained away because it was in excess of what the soil could hold. Although these terms were introduced

(17) B. A. Keen and G. W. Scott Blair—" Plastometric Studies of Soil and Clay Pastes." J. Agric. Sci., 1929, Vol. XIX, pp. 684-700; G. W. Scott Blair and F. Yates—" The Effect of Climatic Variations on the Plasticity of Soil." J. Agric. Sci., 1932, Vol. XXII, pp. 639-646; G. W. Scott Blair—" Consistency Constants of the Soil with Special Reference to Field Operations." Trans. Sixth Comm. Internat. Soc. Soil Sci., A, 1932, pp. 246-252.

(18) G. W. Scott Blair—" Definition and Translation of Rheological Terms used in Soil Physics." Trans. First Comm. Internat. Soc. Soil Sci., 1934, pp. 159-167.

(19) R. K. Schofield and G. W. Scott Blair.—" The Relationship between Viscosity, Elasticity and Plastic Strength of Soft Materials as Illustrated by some Mechnaical Properties of Flour Doughs." Proc. Roy. Soc., A, 1932, Vol. CXXXVIII, pp. 707-718; 1933, Vol. CXXXIX, pp. 557-566; 1934, Vol. CXLI, pp. 72-85.

purely as a convenient qualitative description, they acquired an air of reality, partly, no doubt, owing to the lack of adequate physical investigations on soil moisture relationships. The increasing attention paid in pure science to colloidal phenomena led to the recognition of colloidal properties in soil. The colloidal material has its origin in the clay and organic matter and, although little direct evidence was produced, it was considered to be distributed in a thin layer over the larger mineral particles as a kind of gel or emulsion coating. Many of the earlier experiments of the Department dealt with the possible effect of such a coating on the soil moisture relationships. [20] It was shown that the vapour pressure of moist soil was very close to that of free water until the soil moisture content had reached quite a low value. (See the remark on "hygroscopic coefficient," p.44.) It was concluded that over this range—which is at least equal to, and probably greater than, that on which plant roots can draw—the physical properties of the soil moisture were not appreciably different from that of free water; although later work [21] suggests that an appreciable proportion of soil-water is held or imbibed by soil colloids, it is improbable that the association is the intimate one visualised by other workers who use the term ' bound-water,' which implies a profound change in its physical properties.

Attention was therefore turned to the moisture ranges defined as "capillary water" and "gravitational water" in the old classification, to see how far its behaviour could be interpreted by the simple laws of surface-tension over curved surfaces. [22] The ideal soil of equal sized spheres, arranged in regular packing, and free from colloidal material was employed in both the theoretical and practical studies. The important feature of these investigations was that attention was focussed on the geometry of the pore spaces in the ideal soil. The pore space is essentially cellular, and the cells communicate with one another through narrow necks. This structure imposes a quantum character on the moisture changes over a great part of the higher moisture range. The individual cell does not fill or empty by smooth reversible changes, but shows two unstable stages at which filling or emptying is completed at a bound. The movement into or out of the cell is controlled by the pressure-deficiency under the curved water meniscus and, owing to the geometry of the cells and their communicating necks, the pressure deficiency for a cell to empty (decreasing moisture content) has a higher value than that at which

(20) B. A. Keen—" The Relations Existing Between the Soil and its Water Content." J. Agric. Sci., 1920, Vol. X, pp. 44-71 ; " A Quantitative Relation Between Soil and the Soil Solution Brought out by Freezing-Point Determinations." J. Agric. Sci., 1919, Vol. IX, pp. 400-415 ; " The Evaporation of Water from Soil," J. Agric. Sci., 1914, Vol. VI, pp. 456-475 ; " The Evaporation of Water from Soil. II. Influence of Soil type and Manurial Treatment." J. Agric. Sci., 1921, Vol. XI, pp. 432-440 ; B. A. Keen, E. M. Crowther, and J. R. H. Coutts—" The Evaporation of Water from Soil. III. A Critical Study of the Technique." J. Agric. Sci., 1926, Vol. XVI, pp. 105-122 ; A. N. Puri, E. M. Crowther, and B. A. Keen—" The Relation between the Vapour Pressure and Water Content of Soils." J. Agric. Sci., 1925, Vol. XV, pp. 68-88 ; E. M. Crowther and A. N. Puri—" The Indirect Measurement of the Aqueous Vapour-Pressure of Capillary Systems by the Freezing-Point Depression of Benzene." Proc. Roy. Soc. A, 1924, Vol. CVI, pp. 232-242.

(21) E. W. Russell and R. S. Gupta—" On the Measurement of Imbibitional Water." J. Agric. Sci., 1934, Vol. XXIV, pp. 315-325.

(22) B. A. Keen—" On the Moisture Relationships in an Ideal Soil." J. Agric. Sci., 1924, Vol. XIV, pp. 170-177 ; W. B. Haines—" Studies in the Physical Properties of Soils. IV. A Further Contribution to the Theory of Capillary Phenomena in Soil." J. Agric. Sci., 1927, Vol. XVII, pp. 264-290 ; " Studies in the Physical Properties of Soil. V. The Hysteresis Effect in Capillary Properties and the Modes of Moisture Distribution Associated Therewith." J. Agric. Sci., 1930, Vol. XX, pp. 97-116 ; B. A. Keen—" A Note on the Capillary Rise of Water in Soils." J. Agric. Sci., 1919, Vol. IX, pp. 396-399 ; " The Limited Role of Capillarity in Supplying Water to Plant Roots." Proc. First Internat. Cong. Soil Sci., 1927, Vol. I, pp. 504-511.

it fills (increasing moisture content). Hence the graph connecting moisture content of the ideal soil with pressure deficiency shows a well marked hysteresis loop, one side of which corresponds to increasing moisture content, and the other to decreasing moisture content.

In natural soil the pore spaces are much more irregular, but the same considerations apply. The practical effect is that there is no unique value of moisture content associated with a given pressure deficiency : it will be one value if the soil moisture is decreasing, another if it is increasing. Hence the numerous attempts to measure soil moisture content *in situ*, by placing a porous pot in contact with the soil and observing the reading of an attached manometer have given conflicting results.

A further conclusion is that water can rise by capillary action in the soil only to a limited distance : in a heavy loam soil it will not exceed 3-4 feet and the rate of movement is exceedingly slow.

SOIL PROPERTIES CONCERNED IN CULTIVATION

The mechanical properties of soil likely to be of importance in cultivation have been discussed by numerous workers, and especially by Atterberg. Certain of his methods were re-examined in the Physical Department, in particular his cohesion test. Atterberg found abrupt changes in direction of the curves connecting cohesion and moisture content and used the position of these breaks for classifying the field behaviour of different soils. However, our experimental irregularities were too great to confirm the existence of the breaks, although soils of widely differing properties were employed.(23) The cohesion forces were ascribed in the main to the surface tension of the contained water in the minute interstices and points of contact of the soil grains,(24) and it appeared that the electrical resistance of soil blocks might throw light on the water distribution. Some preliminary measurements gave wide differences between different soils(25); later, a more elaborate investigation (26) showed that the nature of the electrode and the rate the blocks dried had considerable effect, but four characteristic breaks in the curve were found, two of which were readily identified, by separate experiments, with Atterberg's "Ausrollgrenze " (the lower plastic limit) and the " Schwindungsgrenze " (moisture content at which air enters the pores) while the two lower ones were hitherto unrecorded.

In work of this kind much confusion will arise unless the full difference between natural soil and the simplified " ideal " soil, consisting of equal sized spheres, uniformly packed and free from colloidal material is very clearly kept in mind. The volume shrinkage of moist soil blocks as drying proceeds takes place in two stages. At first the volume shrinkage is exactly equal to the volume of water evaporated, but later, as the grains come closer

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(23) W. B. Haines—" Studies in the Physical Properties of Soils. I. Mechanical Properties Concerned in Cultivation." J. Agric, Sci. ,1925, Vol. XV, pp. 178-200.
(24) W. B. Haines—" Studies in the Physical Properties of Soils. II. A Note on the Cohesion Developed by Capillary Forces in an Ideal Soil." J. Agric. Sci., 1925, Vol. XV, pp. 529-535.
(25) W. B. Haines—" Studies in the Physical Properties of Soils. III. Observations on the Electrical Conductivity of Soils." J. Agric. Sci., 1925, Vol. XV, pp. 536-543.
(26) G. H. Cashen—" Measurements of the Electrical Capacity and Conductivity of Soil Blocks' J. Agric. Sci., 1932, Vol. XXII, pp. 145-164.

together, the shrinkage is smaller, although still linear. In the case of materials that are free from a colloidal or gel-like coating(27) this second stage is absent, and no warping occurs in the later stages fo drying, and differential stresses which lead to rupture of the blocks on remoistening are absent. In the case of natural soils, however, such stresses are instrumental in the disintegration by weather of the large lumps of soil left by autumn ploughing.

" *Single value* " *measurements*.—Attempts by many workers have been made to assess the general character of a soil by measuring one property, or group of properties, thus specifying the soil by a single number (or " single value ") in place of the group of figures given by a mechanical analysis. The underlying idea is that such a " single value " would place the soils in an order that closely reflects their field behaviour. The Physical Department has given much attention to this problem(28) and has tested many of the suggested methods on a wide range of soils. The methods were chosen as far as possible from those requiring only simple apparatus. The measurements were repeated after the soils had been treated with hydrogen peroxide, to obtain some idea of the contribution of organic matter to the result. A preliminary examination showed that certain methods gave highly correlated results, presumably because they were measuring the same, or closely related physical properties. At a later stage, a full statistical examination was carried out on extensive data for Natal soils, obtained in Mr. J. R. H. Coutts' experiments. It was shown that from a knowledge of the base exchange capacity of the soil, a good prediction could be made of the sticky point, the moisture content at 50 per cent. relative humidity, and the weight of water held by the saturated soil; the clay content, on the other hand, was of minor importance in predicting these properties but, in conjunction with the silt content, it was closely related to the xylene equivalent. The xylene equivalent—which is obtained by using xylene in the moisture equivalent apparatus instead of water—is of interest: it measures a soil property that is independent of the organic matter present, for it can be almost completely predicted from other measurements made on the soil after treatment with hydrogen peroxide. The net result of the statistical examination of this series of Natal soils was to show that certain single-value measurements were controlled by the base exchange capacity, while others depended more on the content of clay and silt. How far this

(27) W. B. Haines—" The Volume-Changes Associated with Variations of Water Content in Soil." J. Agric. Sci., 1923, Vol. XIII, pp. 296-310.

(28) B. A. Keen and H. Raczkowski—" The Relation between the Clay Content and Certain Physical Properties of a Soil." J. Agric. Sci., 1921, Vol. XI, pp. 441-449; B. A. Keen and J. R. H. Coutts—" ' Single Value ' Soil Properties: A Study of the Significance of Certain Soil Constants." J. Agric. Sci., 1928, Vol. XVIII, pp. 740-765; B. A. Keen—" ' Single Value ' Soil Properties: a Study of the Significance of Certain Soil Constants. IV. A Further Note on the Technique of the ' Box ' Experiment." J. Agric. Sci., 1930, Vol. XX, pp. 414-416; J. R. H. Coutts—" ' Single Value ' Soil Properties: a Study of the Significance of Certain Soil Constants. VII. The Moisture Equivalent and Some Related Quantities." J. Agric. Sci., 1932, Vol. XXII, pp. 203-211; E. W. Russell—" The Significance of Certain ' Single Value ' Soil Constants." J. Agric. Sci., 1933, Vol. XXIII, pp. 261-310; H. Janert—" The Application of Heat of Wetting Measurements to Soil Research Problems." J. Agric. Sci., 1934, Vol. XXIV, pp. 136-150; A. N. Puri—"A Critical Study of the Hygroscopic Coefficient of Soil." J. Agric, Sci., 1925, Vol. XXV, pp. 272-283; A. Sen and C. H. Wright—" The Electrical Conductivity of Aqueous Soil Suspensions as a Measure of Soil Fertility." J. Agric. Sci., 1931, Vol. XXI, pp. 1-13; A. Sen—" The Measurement of Electrica Conductivity of Aqueous Soil Suspension and its Use in Soil Fertility Studies." J. Agric. Sci., 1932, Vol. XXII, pp. 212-234; B. A. Keen—" Physical Measurements of Soil in Relation to Soil Type and Fertility." Emp. Cotton Growing Corporation Conference, July, 1934; J. M. Albareda—" Caracterización de Suelos Tropicales y Sub-Tropicales Mediante Determinaciones Físicas y Físicoquimicas." " Sobre la Fertilidad de Algunos Suelos Tropicales." Publicado en la Revista de la Acad. de Ciencias, de Madrid, 1934, Vol. XXXI, pp. 320-350, 457-514, and 515-519.

generalisation may apply to a wider range of soil types is uncertain. Some departure is to be expected ; for example, the loss on ignition of the natural and peroxide treated soils of the Natal series gave results of no great importance, whereas the inherent fertility of a series of Malayan rubber soils was reasonably well predicted by the ignition loss of the soils and of the clay fractions.

The relationships become more diffuse when single-value measurements are considered as an aid in distinguishing one soil type from another. Ideally, one would desire to obtain very good correlation between two different measurements when done on soils from the same type and to find that the regression constants of the curve connecting these two measurements varied with the soil type. Up to the present it appears that within a broad soil-type the sub-types are sufficiently variable to affect the correlation between the measurements ; it may, therefore, be that a soil type will not be characterised by regression constants of a curve connecting two measurements, but by an area on the diagram.

Four other single-value measurements that fall somewhat apart from the main line of argument developed above may be briefly mentioned.

An interesting method of measuring soil fertility developed by Atkins has been studied. The electrical conductivity of a soil suspension is measured and the increase in conductivity after a fixed period (seven days) is taken as an index of the biological activity in the soil, and therefore of its inherent fertility. The method was applied to soil samples taken in the past from the classical plots and stored in the air-dry condition ; the increase in conductivity of the suspensions made from these samples fall in the same order as the corresponding crop-yields in the year of sampling. The method might repay an extended trial as a simple qualitative measurement of soil fertility.

The so-called hygroscopic coefficient, which has been much used in America as a single-value measurement for soils, was subjected to critical examination and found to be unamenable to accurate measurement. The conception of a hygroscopic coefficient is, in fact, fundamentally unsound ; the moisture content at 50 per cent. relative humidity is much to be preferred.

The heat-of-wetting measurement was introduced by Mitscherlich as an index of soil heaviness, but subsequently abandoned in favour of a hygroscopicity determination. Recently, refinements have been introduced in the method, and the results seem, in certain circumstances, to be related to the physical condition of the soil, and to be correlated with other soil properties determined in the field or by laboratory methods. Experiments on pure single-base clays gave the interesting result that the heat-of-wetting represents a specific proportion of the heat-of-hydration of the adsorbed cations in their free state.

Returning to the question of soil heaviness, a new method has been developed([29]) which gives a satisfactory and rapid laboratory

(29) R. K. Schofield and G. W. Scott Blair—" Rapid Methods of Examining Soils. I. Measurements of Rolling Weights." J. Agric. Sci., 1932, Vol. XXII, pp.135-144 ; R. K. Schofield and G. W. Scott Blair—" The Pachimeter, a Machine for Measuring the Shearing Strength of Plastic Bodies." Trans. Ceramic Soc., 1932, Vol. XXXI, pp. 79-82 ; G. W. Scott Blair and R. K. Schofield—" The Pachimeter as an Instrument for Testing Materials, with Special Reference to Clays, Soils, and Flours." J. Rheology, 1932 , Vol. III, pp. 318-325.

measure of this factor. A plastic cylinder of the soil is rolled backwards and forwards between two plates and the weight on the upper plate is slowly increased until it exerts a certain critical stress which causes the cylinder to lengthen.

Clay aggregates and tilth.—The phenomenon of crumb, or compound particle, formation in soils is well known to all practical men; their cultivation methods are designed to produce this aggregation, to which the term "good tilth" is generally applied. Although good tilth is at once apparent to visual inspection, explanations in scientific erms are almost completely non-existent, and most text-books give only the attractive but strained analogy with the flocculation and deflocculation of weak clay suspensions. The subject has recently been taken up in the Physical Department and, for the first time, a satisfactory explanation of the main factors concerned in the process of tilth formation has been given.(30)

It has been shown that clay particles can form strong aggregates, or crumbs, when dry, only if the clay particles are sufficiently small, if there are a sufficient number of small exchangeable ions on the clay, and if the clay has been dried from a dispersion medium whose molecules are polar and sufficiently small.

An hypothesis in accordance with the experimental results is that cations can orientate polar molecules of the dispersion liquid around them with a power proportional to their surface density of charge; this power is also possessed by the free negative charges on the clay particle, so that when the dispersion liquid has nearly all been removed (i.e. when the soil or clay has dried appreciably) the cations bind the negative charges on two clay particles together by means of bridges of strongly orientated molecules of the polar dispersion liquid.

Soil Cultivation

When an implement is drawn through the soil its resistance is determined by two groups of factors relating to the design and construction of the implement itself and the physical properties of the soil. The group belonging to the implement lie within the province of agricultural engineering and form the subject of study at another Institution; only incidental references will be made to them here. The second group—the soil factors—exert their influence through such properties as soil cohesion, plasticity and friction. They are susceptible to laboratory examination, and instances of their relation to the behaviour of soil during cultivation have been given in the preceding sections. The soil resistance to cultivation is a kind of integrated effect of numerous physical properties; hence, the study of soil resistance has considerable scientific as well as practical interest. The field experiments have taken both these aspects into account: the growth and response of farm crops to different systems of cultivation has been investigated as well as the relations between the cultivation systems and the soil properties.

It was necessary to evolve a dynamometer that would give a continuous trace of soil resistance, together with accessory measurements such as speed and depth of cultivation. For some time, a

(30) E. W. Russell.—"The Interaction of Clay with Water and Organic Liquids as Measured by Specific Volume Changes and its Relation to the Phenomena of Crumb Formation in Soils." Phil. Trans. Roy. Soc. London, A, 1934, Vol. CCXXXIII, pp. 361-389.

modified form of a dynamometer designed for road-traction measurements was used [31]. The instrument gave quite satisfactory service, but the recording system needed skilled attention, and, owing to its weight, the dynamometer was not suitable for tests with the lighter forms of cultivation. A new type was therefore constructed [32], based on the " Stress Recorder " made by the Cambridge Scientific Instrument Company. The new instrument is much lighter than the old one, and the records are impressed in the form of a groove on a narrow ribbon of celluloid by styluses with hard points. The celluloid is not scratched but flows under the pressure of the point ; the groove has excellent optical properties so that a greatly magnified copy can be obtained in the ordinary way. In addition to the trace of soil resistance, a time scale is impressed automatically on the ribbon, and the operator carries a tapping key connected to an electro-magnetic stylus, so that notes in the Morse code can be also impressed on the ribbon. This last feature is of great use, since it obviates the risk of confusion in examining the records of cultivation when a complicated set of plots is being cultivated.

The dynamometer was used in a series of investigations [33], and the main conclusions are summarised below. One very interesting and unexpected result was to demonstrate the heterogeneity of soil. A field that was judged by practical farmers to be quite uniform in its soil properties showed the most surprising changes in soil resistance from point to point. These variations—which are reflections of corresponding variations in the inherent soil properties—are substantially permanent : the magnitude of the soil resistance depends, of course, on the season of cultivation, the kind of implement, its depth of work, etc., but the relative fluctuations of soil resistance from point to point are not affected. Heavy applications of artificial manures, and the long continued differences in crop yields of the classical Rothamsted plots have not produced any appreciable modification of the original and inherent heterogeneity of the soil, with the exception of plots receiving a heavy dressing of dung or of chalk, where, as would be expected, there is a definite lowering of the soil resistance. The inherent variations in soil resistance, disclosed by the dynamometer during soil cultivation with implements, change slowly from point to point. The question whether these changes were themselves average values of larger and more rapid fluctuations within distances of a few inches was examined with another instrument which measures the force needed to drive a vertical rod into the soil : the instrument is, in principle, a miniature pile-driver. Wide variations of resistance

(31) B. A. Keen and W. B. Haines—" Studies in Soil Cultivation. I. The Evolution of a Reliable Dynamometer Technique for Use in Soil Cultivation Experiments." J. Agric. Sci., 1925, Vol. XV, pp. 375-386.

(32) W. B. Haines and B. A. Keen—" Studies in Soil Cultivation. IV. A New Form of Traction Dynamometer." J. Agric. Sci., 1928, Vol. XVIII, pp. 724-733 ; " A New Dynamometer, Suitable for all Types of Horse and Power Drawn Implements." Proc. First Internat. Cong. Soil Sci., 1927, Vol. I, pp. 405-411.

(33) B. A. Keen and W. B. Haines—" Studies in Soil Cultivation. II. A Test of Soil Uniformity by Means of Dynamometer and Plough " ; " Studies in Soil Cultivation. III. Measurements on the Rothamsted Classical Plots by Means of Dynamometer and Plough." J. Agric. Sci., 1925, Vol. XV., pp. 375-406 ; B. A. Keen and G. H. Cashen—" Studies in Soil Cultivation. VI. The Physical Effect of Sheep Folding on the Soil." J. Agric. Sci., 1932, Vol. XXII, pp. 126-134 ; B. A. Keen—" The Use of the Dynamometer in Soil Cultivation Studies and Implement Trials." J. Roy. Agric. Soc. England, 1925, Vol. LXXXVI, pp. 30-43 ; " The Value of the Dynamometer in Cultivation Experments and in Soil Physics Research." Proc. First Internat. Cong. Soil Sci., 1927, Vol. I, pp. 412-428 ; B. A. Keen and E. J. Russell—" The Effect of Chalk on the Cultivation of Heavy Land." J. Min. Agric., 1921, Vol. XXVIII, pp. 419-422.

were found between points whose horizontal distanced apart was only 6 ins. The large and small scale heterogeneity thus demonstrated is one of the reasons for the modern statistical arrangement of field plots which was described at length in last year's Report.

A result of considerable practical importance is that soil resistance increases only slowly with speed of cultivation. The design of cultivation implements is of necessity a compromise between numerous conflicting requirements, but the farmer requires the maximum speed of travel, and it is important to note that the possibility of increased soil resistance at higher speeds can be ignored.

One means of reducing the soil resistance at any given speed has been demonstrated both in the laboratory and in full-scale practical trials.(34) The soil colloids carry a negative charge, hence under the action of an electric current water will move through the soil and be deposited on the negative electrode. If the mouldboard of a plough is insulated from the frame, and made the negative electrode, a film of water will be deposited on it, and the frictional resistance of the furrow slice passing over the mouldboard will be reduced. Measurable reductions of draft were obtained in field trials with an improvised and inefficient arrangement, and the method deserves commercial attention. It is likely to be of considerable use on soils that do not scour easily. The " gumbo " soils of Mexico are a well-known example and instances of English soils in Northamptonshire and Lincolnshire have also been observed. In the latter cases the probable cause is a high percentage of silt in the soil.

The effect of different methods of cultivation has also been studied at Rothamsted.(35) The immediate disintegration of soil by implements has been investigated by passing blocks of soil before and after cultivation through a series of sieves with mesh sizes varying from $1\frac{1}{2}$ ins. square to $\frac{1}{10}$ in., and comparing the percentages of the original sample left on the sieves. The kind of tilth produced by spring ploughing or cultivations is much more controlled by the weather of the previous winter than by the intensity of the spring treatment. In the case of summer cultivations, e.g., hoeing between root crops, there is a strong suggestion that extra cultivations above those necessary to kill weeds, are without benefit to the final yield and may even lead to appreciable reduction, but further experiments in a variety of seasons will be made before a final conclusion is given. Much attention has been given to rotary cultivation. In this method the soil is acted upon by rotating tines and it is claimed that a seed-bed can be produced in one operation, in place of the series that is needed with the traditional range of implements. The main purpose of these experiments is to ascertain if the method is suitable for arable agriculture on medium and heavy soils, which are commonly stated by practical men to require careful and skilled cultivations if a good tilth is to be secured. One of their objections to rotary cultivation is that it gives too fine a tilth. The sieving method described above shows this is not the case ; the tilth is no finer than that

(34) E. M. Crowther and W. B. Haines—" An Electrical Method for the Reduction of Draught in Ploughing." J. Agric. Sci., 1924, Vol. XIV, pp. 221-231 ; " An Electrical Method for the Reduction of Draught in Ploughing." Imp. and Mach. Rev., 1924, Vol. L, pp. 1003-1005.

(35) B. A. Keen and the Staff of the Soil Physics Department—" Studies in Soil Cultivation. V. Rotary Cultivation." J. Agric. Sci., 1930, Vol. XX, pp. 364-389 ; B. A. Keen—"Experimental Methods for the Study of Soil Cultivation." Emp. J. Exper. Agric., 1933, Vol. I, pp. 97-102.

obtained with the ordinary implements. It is, however, much looser, and the methods for dealing with this new condition and turning it to advantage are still being worked out. In the early stages of growth a rotary cultivation tilth is superior to the normal type : germination and early growth are both better, and although the advantage is usually lost by harvest time, the final yields are usually as good as those given by normal cultivations. This result is obtained in spite of the extra weediness of rotary cultivated plots, which is probably a consequence of the action of the rotating tines. The weed seeds are distributed throughout the depth of cultivation whereas the normal methods encourage germination only in the thin surface layer, where hoeing can easily deal with them.

If these technical difficulties of rotary cultivation can be overcome, the way is clear for an appreciable reduction in the heavy costs of cultivations that the arable farmer must face. The field experiments are therefore being actively continued.

THE CHEMISTRY OF SOILS AND FERTILISERS

E. M. Crowther

The general object of the work of the Chemistry Department under Mr. H. J. Page, from 1920 to 1927, and since then under the writer, has been the study of the chemical aspects of soil fertility and soil formation. In recent years most of the investigations have dealt with material provided by field experiments at Rothamsted, Woburn and commercial farms on which field experiments are conducted by the Rothamsted staff or local agricultural officers. Several soil investigations have also been carried out on overseas soils, especially from the tropics.

One of the most urgent problems is to devise better methods of obtaining precise agricultural information on soil fertility and crop nutrition. Much of the work of the Department is, therefore, devoted to improving the methods of field experimentation, especially on fertilisers, and to supplementing the crude yields by analyses of the crops. Soils from the experimental centres are analysed by a variety of chemical methods to ascertain how far the results of chemical analyses agree with the agricultural experience expressed in the results of the field trials. The soils of the long-continued experiments at Rothamsted and Woburn are studied to measure the cumulative secondary effects of fertilisers. Systematic samplings and analyses on these classical plots and on those of some of the complex replicated experiments are made for periods of a few years to follow the seasonal cycles in some of the main factors in soil fertility. Much of the laboratory work involves parallel investigations in the pot culture house.

Soil Colloids and Ionic Exchange

It is now generally recognised that the amounts and composition of the soil colloids and the exchangeable ions associated with them are vital factors in determining the physical and chemical properties of soils and the availability of plant nutrients.(1) The first investigations on exchangeable bases were made on the soils of the Broadbalk

(1) H. J. Page—"The Nature of Soil Acidity." Trans. II Comm. Int. Soc. Soil Sci., Vol. A., Gron., 1926, pp. 232-244 ; C. E. Marshall—"Some Recent Researches on Soil Colloids. A Review." Journ. Agri. Sci., 1927, Vol. XVII, pp. 315-332.