A STUDY
ON SOIL STRUCTURE

J. VAN SCHUYLENBORGH

Dit proefschrift met stellingen van JOHANNES VAN SCHUYLENBORGH landbouwkundig ingenieur, geboren te Balik Papan (Borneo) de 17de December 1916, is goedgekeurd door den promotor: Ir J. Hudig, hoogleraar in de Scheikunde en de Bemestingsleer.

De Rector-Magnificus der Landbouwhogeschool,
Dr J. SMIT.

Wageningen, 5 November 1947.

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ON SOIL STRUCTURE

PROEFSCHRIFT
TER VERKRIJGING VAN DE GRAAD VAN
DOCTOR IN DE LANDBOUWKUNDE
OP GEZAG VAN DEN RECTOR-MAGNIFICUS
Dr J. SMIT, HOOGLERAAR IN DE MICROBIOLOGIE, TE VERDEDIGEN VOOR EEN
DAARTOE BENOEMDE COMMISSIE UIT DE
SENAAT VAN DE LANDBOUWHOGESCHOOL
OP VRIJDAG 28 NOVEMBER 1947 TE 3 UUR

DOOR

J. VAN SCHUYLENBORGH

DRUKKERIJ EN UITGEVERSBEDRIJF
FIRMA PONSEN & LOOIJEN - WAGENINGEN - TELEFOON 2128

STELLINGEN.

I

De kruimelstructuur is een mechanisch instabiel bouwsel en bevindt zich in een labiel evenwicht.

II

Het is volstrekt ongeoorloofd om de structuur van de bodem aan de hand van slechts één gegeven te karakteriseren.

III

De theorie van E. W. Russell over de kruimelvorming in de bodem is onjuist.

Phil. Trans. Roy. Soc., A 233, 1934, p. 361.
Trans. third Int. Congr. Soil Sci., 1, 1935, p. 26.
Imp. Bur. Soil Sci., Techn. Comm. No. 37, 1938.

IV

Het is onjuist om de op de akker achtergebleven stoppel voldoende te achten voor de instandhouding van de biologische buffer. Het is daarom noodzakelijk de organische bemesting van de bodem op te voeren.

V

De verhouding van de ionen-activiteiten in de bodem is een beter gegeven voor de interpretatie van verschillende verschijnselen dan de verhouding van ionen-concentraties.

A. C. Schuffelen: Landb. Tijdschr., 58, 1946, p. 367.

VI

De ionen-wisseling aan bodemkolloiden kan worden beschreven door deze voor te stellen als de instelling van een Donnan-evenwicht.

S. Mattson, Soil Sci., 28, 1929, p. 179, 373.
H. J. C. Tendeloo, G. J. Vervelde en A. J. Zwart Voorspuy, Rec. Trav. Chim., 63, 1944, p. 97.
G. J. Vervelde, Voordr. Bodemk. Vereniging, 1946.
Deze dissertatie, p. 105.

VII

Het uitéénwijken van de chromosomen na de metaphase is een gevolg van het krimpen van de spoeldraden.

G. Östergren, Hereditas, 31, 1945, p. 498.
G. Östergren, Botaniska Notiser, 1945, p. 467.
G. Östergren en R. Prakken, Hereditas, 32, 1946, p. 473.

VIII

De plantenwortel neemt aan de ionen-opname passief en niet actief deel.

L. K. Wiersum: Transfer of solutes across the young root. Diss. Groningen, 1947.
A. C. Schuffelen: Over het selecterend vermogen van de plant voor ionen. Versl. Nederl. Acad. Wetensch., Amsterdam (ingezonden).

IX

De bij de bodemkartering als maatstaf genomen opbouw van het profiel zal soms kunnen leiden tot een onjuist inzicht van het productievermogen van de bodem.

X

Een leerplan van de Landbouwhogeschool moet meer mogelijkheid bieden voor de beoefening van de natuurkunde, wiskunde en plantkunde.

Aan de nagedachtenis
van mijn Vader en Moeder
Aan mijn Vrouw

Bij het voltooien van dit proefschrift is het mij een behoefte allen, die aan mijn wetenschappelijke vorming hebben bijgedragen en mij hebben bijgestaan bij de uitvoering van de experimenten of anderszins, dank te zeggen.

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Zeergeleerde Schuffelen, Uw voortdurende belangstelling in de resultaten van mijn experimenten en Uw vaak genadeloze, doch steeds opbouwende kritiek worden door mij op hoge prijs gesteld.

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CHARTER I.

DESCRIPTION OF THE PROBLEM OF SOIL STRUCTURE.

§ 1. *Introduction.*

The constituent particles of many soils are held together and form aggregates, which differ in size, shape, firmness and colour. They may be arranged in different ways with respect to one another and leave pores between them. These pores (macro-pores) may be filled with water or with water and air, this depending on shape and size of the aggregates. The micro-pores, occurring in the aggregates and invisible to the naked eye, are often filled with water alone, but sometimes also with air alone.

Consequently, the soil is a three phase system, with the soil particles as the solid, the soil solution as the liquid and soil air as the gas phase, and the detailed distribution of these three phases throughout the soil mass can be referred to as the soil structure, a definition which will be precised later on.

Soils do not possess a unique structure. The ideal structure for the normal functioning of the root is one, in which the three phases are as uniformly distributed as possible, leaving the air spaces in connection with each other and with the atmosphere. But this distribution of pores and soil particles can never be a homogenous one; larger and smaller spaces are needed, because the micro- and macroflora and fauna make different demands on the circumstances of life, as has been pointed out by Stoeckli (1946). But a definite regularity must be present in the arrangement of the irregularites.

The shape of the pores depends on the arrangement of the solid particles. As an illustration of this, consider the picture which can be found in most handbooks, of a theoretical soil aggregate consisting of spheres of an uniform size. Fig. 1 shows spheres of the same

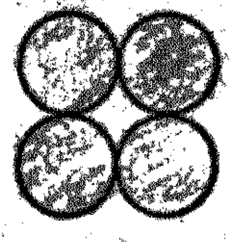

Fig. 1. Cubical type of open packing.

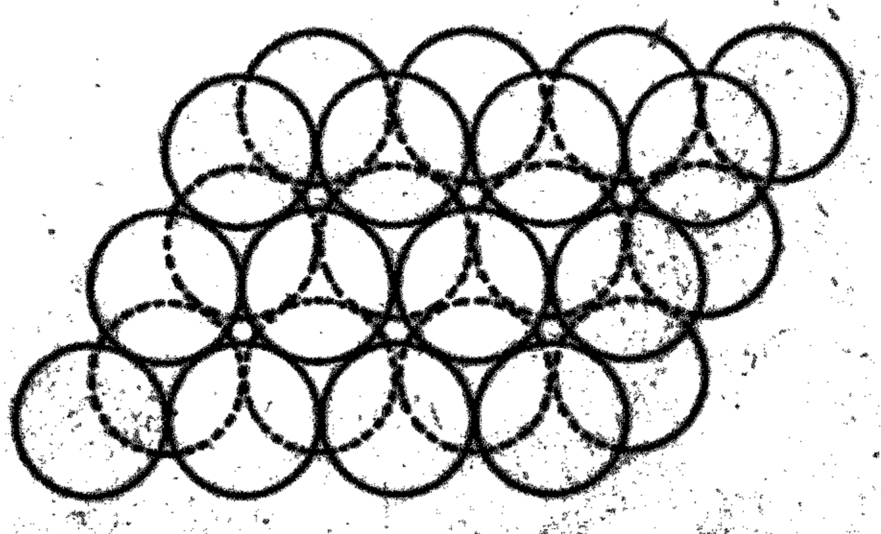

Fig. 2. Rhomboidal type of close packing.

radius on top of each other and fig. 2 fitted together. The arrangement in fig. 1, the most open system of packing, is cubical, that of fig. 2 rhombohedal. In the first case the pore space is the difference between the volume of a cube and that of the spheres, second between the volume of the rhombohedron and the spheres. Thus, in the first case, the pore space as a percent of the total volume is given by:

$$\frac{(8-\frac{4}{3}\pi)r^3}{8\,r^3} \times 100 = 47.64\ \%$$

and, in the second case, by:

$$\frac{\left(\frac{20\,r}{\sqrt{250+116\sqrt{5}}}\right)^3 \cdot \frac{15+7\sqrt{5}}{4} - \frac{4}{3}\pi r^3}{\left(\frac{20\,r}{\sqrt{250+116\sqrt{5}}}\right)^3 \cdot \frac{15+7\sqrt{5}}{4}} \times 100 = 24.51\ \%$$

Thus, in this theoretical case, it appears, that the pore space is independent of the sphere-radius and secondly that the pore space is 46.74 % in the case of the open packing and 24.51 % in the close packing. The pore space representing the total content of water and air, the difference between the two ways of packing from the point of view of life in soil is obvious.

These pore volumes can still be much reduced if there are also spherical particles, that would just fit into the spaces between the set of larger spheres, as is shown in fig. 3. When the remaining pores are supposed to be filled up with just fitting particles, a very compact system results, in which is no place either for air nor for water. It is evident that, clay particles being present, the amount of

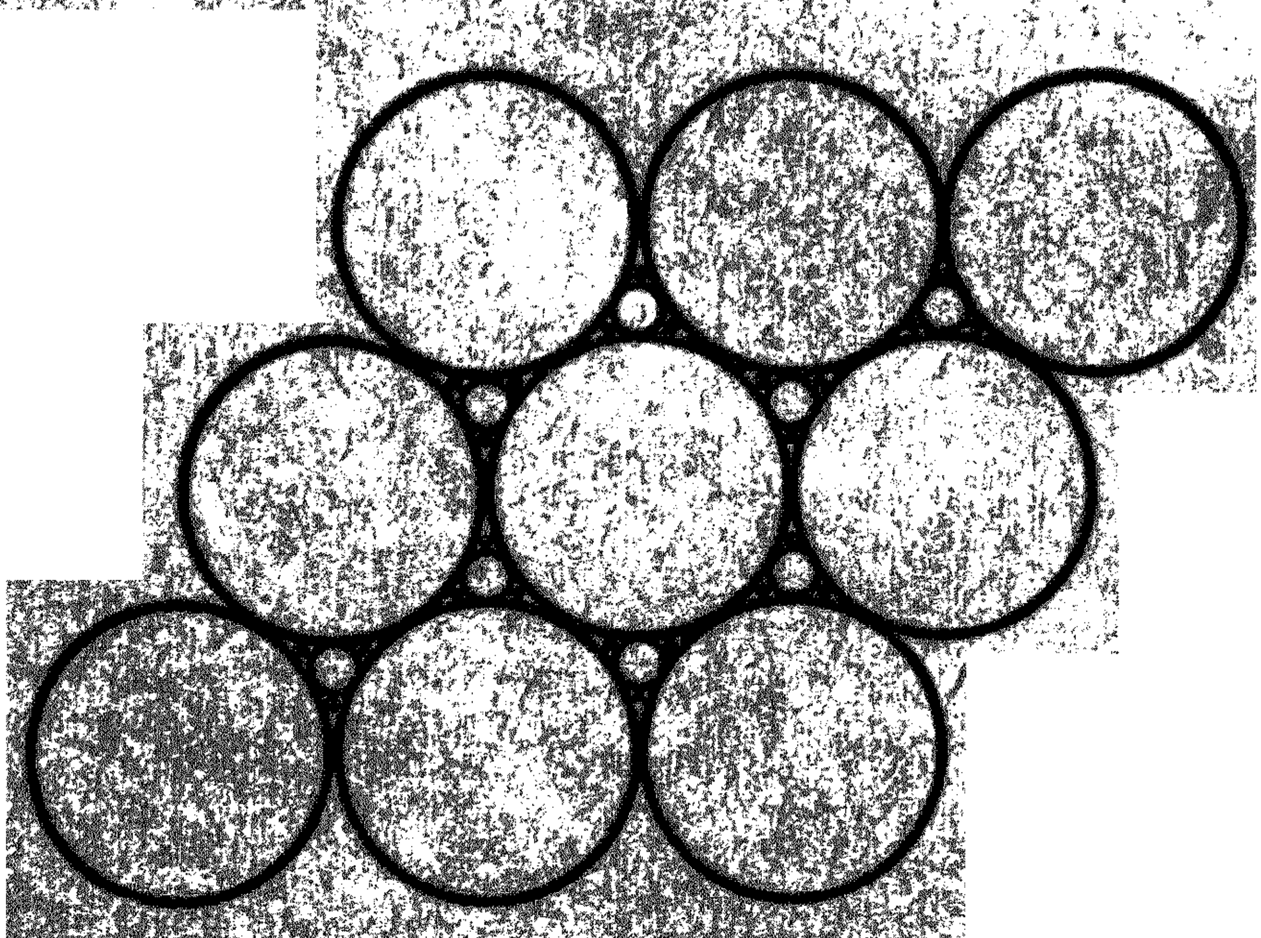

Fig. 3. Rhomboidal type of packing, the interspaces between the large spheres are filled up with particles of smaller radius.

clay will be very small to fill up the interspaces between the spheres. Therefore this system cannot swell or shrink appreciably. This may be found in a very peculiar type of soil, in the Netherlands, called „leem", which is preferably used for the construction of dams, because of its absolute impermeability.

Returning to the system consisting of uniform spheres, and taking the case that some spheres of the same radius are held together to form aggregates the latter may be arranged in several ways. The structural units may be packed closely and the spheres in these units closely (1) and open (2) and the structural units may be packed open, the spheres in them closely (3) and open (4). The pore spaces in these cases are:

$$1.\quad \frac{24.51\,(100-24.51)}{100} + 24.51 = 43.01\ \%;$$

$$2.\quad \frac{47.64\,(100-24.51)}{100} + 24.51 = 60.47\ \%;$$

$$3.\quad \frac{24.51\,(100-47.64)}{100} + 47.64 = 60.47\ \%;$$

$$4.\quad \frac{47.64\,(100-47.64)}{100} + 47.64 = 72.58\ \%.$$

The question now arises, if any practical use can be made of a theoretical picture, that contains assumptions which are certainly not true in practice. The soil particles are neither spherical nor of the same size. Yet it clearly shows, that the pores (of sandy and aggregated clay soils) form a system of cells connected by narrow necks and it elucidates the considerations concerning capillary attraction of water and soil particles (Rothamsted-school). Secondly it is remarkable, that the range of the theoretically computed percentages of pore space is actually found in nature. There are densely packed sands with a pore space of 20—30 %. On the other hand aggregated soils in a crumb structure are found with a pore space up to 70 %. Fig. 3 shows that pore spaces smaller than 24 % are possible. Such cases are actually found in nature.

§ 2. *Factors determining structure.*

It is clear, that forces are needed to hold the particles in open packing. These forces are determined by the special properties of the soil material. The soil constituents are heterogenous, in shape and properties, and consist of:

a. quartz and fragments of primary minerals from the parent rocks;
b. precipitates of silicic acids and Al- and Fe-hydroxides;
c. secondary formed clay minerals, e.g. montmorillonite, muscovite, kaolinite and furthermore the secondary formed carbonates, phosphates, etc.;
d. organic materials, easily decomposible by microorganisms;
e. organic materials of humus-like nature, that have taken up

combinations of Al, Fe and Si and have a more or less stable character (more or less decomposible by microorganisms). (Hudig and Siewertsz van Reesema, 1940.)

Beside the solid phase, the liquid phase, in which ions and molecules are dissolved, and the gas phase exist. It may be asked if it is possible to build up a system with this heterogenous material, in which the phases are arranged in a definite order . This is indeed possible, as nature shows that it does make such a system in some cases and solves the problem by forming a microstructure of fine and coarse material, which is held together in greater aggregates due to distinct forces. In this way the primary soil particles are aggregated to new and greater, much less differentiated, units, by which means a pore space distribution results in the aggregates and between the aggregates. Such a system has many advantages : It is buffering in several ways. The pores in the interior of the aggregates are different from those between the aggregates ; the former are narrower than the latter. This means that, during rains, the wider channels between the aggregates are the transport tracks of the percolating water, from which the aggregates absorb water and increase their moisture content. In this way the contact between soil and water is greatly limited and water retained in the aggregates is protected during a long time from moving away (see also : Bayer, Woodruff and Lutz, 1934). In the narrow capillary spaces, the circulation of air is less intensive than in the wider pores and tubes between the aggregates. It all depends on the size of the aggregates and on the kind of aggregation to what extent a given „structure" provides suitable conditions for an ideal root function and the easy supply of plant foods.

Referring to the calculations on page 2 and 3 it will be clear that a suitable pore space requires a condition, that approaches the open packing of the structural units and the open packing of the particles in these units. This may be obtained by

1. flocculating the soil colloids by adding electrolytes ;
2. mixing the soil with sticky materials, e.g. the mucus of bacteria and the humus substances, that have a more or less stable character (Kamerling, 1902, 1916) ;
3. cultivating the soil at the right moment. The factor, that determines this moment of cultivation is the water-content. It possesses the capacity to hold the solid particles by forces due to capillarity.
4. § 1 shows that the mechanical composition of the soil has a significant influence on soil structure. This factor relates to the stability of a definite structure.
5. In addition to these factors there is a fifth, that is necessary to give the stability to a definite structure. This factor may be represented as follows : There is an unstable equilibrium between the structure forming (see 1, 2, 3, 4) and the desintegrating forces (rains, pressure, sunshine, etc.). In the ideal case this labile equilibrium is maintained. This only is possible by supply

of energy. This energy is supplied by the oxidation of organic material by microorganisms. During the oxidation, organic material, such as bacterial mucus, is formed, that, in its turn, may be oxidized by other organisms (see: Sekara, 1941). Moreover the chemical energy in these organic substances is transformed in mechanical energy, by earth-worms, insects, etc. This mechanical energy is necessary to hold the aggregates in loose packing.

It is clear that the study of soil structure shows much similarity with the study of life. The living cell also is in an labile equilibrium; the living plant and animal cell also are heterogenous systems, but in which a definite order is to be seen. One even may say that the heterogenity is a conditio sine qua non for life. Thus it is necessary to bring a definite order in the heterogenous soil system, so that all reactions proceed harmoniously. This is done by bringing together the five above mentioned factors in suitable proportions, which automatically gives a crumb structure to the soil, in other words, gives the soil a good tilth. A good soil tilth or crumb structure is comparable to a sound, well functioning, living cell. If the harmony, in which the reactions are carried on, is disturbed in one way or another, the soil will loose its crumb structure and be ill, just as the cell does not function in that case and is ill also.

However, the soil cannot be quite considered as a living system, at least not the inorganic part of it; nevertheless the same processes, acting in the living cell, are observed already in action in a pure inorganic environment. But as to the latter these processes never produce any multiplication of matter. In the mean time a lot of living cells (such as micro- and macroorganisms) is observed, that live in this remarkable medium, called "soil". So it can be said that in the soil system life starts and that it stands between death and life.

Because the five factors show an intricate interaction, it is clear, that the study of soil structure is very complicated. Thus far one has not come to a satisfactory qualitative treatment, so that a quantitative description is out of the question. In the nineteenth century already Davy (1813), Schuebler (1833), Schumacher (1864) and Wollny (1879—1900) had started to study the problem of soil structure. Wollny published the journal "Forschungen auf dem Gebiete der Agrikultur-Physik" and has done splendid work. But the study slowed down, in spite of the work of the scholar Ramann, of Mitscherlich and others. In recent years the study has been successfully renewed by Russian, English (Rothamsted) and American workers. Splendid work has been done by Dojarenko at Moscou, whose life has been devoted to the problem of soil structure.

An enormous amount of literature exists on the problem of soil structure. For the greater part these works form a chaos of different theories. The author has set himself the task of studying the problem of soil structure systematically, partly by his own experiments, partly by a study of existing literature. For that purpose he finds himself obliged: 1. to introduce some new definitions to separate the several factors sharply and 2. to give a schematical description of the problem; but it must be emphasized that gradual transitions occur between these sharply separated facets of the problem. He hopes that this systematical study will remove some of the confusion around this problem.

§ 3. *Definitions.*

In the preceding § it has been pointed out, that soil is a dynamic system. From moment to moment there are changes, originating from the continuous modifications of the five factors, that regulate the physical state of the soil by their mutual interaction. A description of these modifications requires the availability of a nomenclature to point out, which part or which unity of the complex phenomenon is meant with a given term. In soil literature in the Netherlands only one term can be found, viz. structure, that in some cases refers to a part, in others to the total of the phenomenon. Sometimes the momentary physical building up, that is the arrangement of the three phases in a definite space, is called structure. But soil structure also refers to a non-momentary state, thus, e.g., when comparing two plots being in a different state of structure. Moreover the term structure is used for the complex of phenomena, describing not only the physical, but also the biological state, their mutual interaction and the result of these reactions as a complex.

The use of the term structure to describe different parts of the problem is confusing. Therefore the complex phenomenon will be analysed a priori and it will be tried to give a nomenclature, that designates which part of the phenomenon is meant.

The structural phenomena, presenting themselves as physical or mechanical phenomena, will be denoted curtly with the term structure. It has been described already that these phenomena have a dynamic nature, that is, they are subject to many changes. A method of measurement, applied to determine one of the properties of the structure-complex, will always give a momentary state in the dynamic process. The characteristic, derived from one or more measurements and determining the physical building up of the particles at a given moment, will be denoted with the term actual structure. The actual structure is a directly measurable, but variable quantity. Yet, besides this variable quantity, every soil possesses, under natural conditions or under the influence of man, a number of permanent characteristics with respect to the structure-complex. With regard to the distribution of the three phases, the properties of sand-, clay-, or peaty soils — to mention some extreme cases — are so different that they bear specific characteristics, finding expression in the actual structure, it is true, but not characterized by the actual structure alone. These phenomena, intrinsic to the soil type, will be denoted with the term intrinsic structure, or, perhaps better, with the term structure-capacity.[1]) The intrinsic structure is not directly measurable. It is a function of the constant quantities of the soil (e.g. : sand-, clay-, humus content, etc.), whereas the actual structure depends on the variable soil factors (eg. : temperature, moisture content, base status, etc.), but at the same time on the structure-capacity.

The complex phenomenon of the mutual interaction, that leads to a definite activity of the soil in respect to itself and to the plant growth, is more than is covered by the term structure. It is strongly influenced by structure, but it determines the structure in its turn. It may better be described with the term structure-activity, as it is an activity, that regulates the structure. Here also an actual and an intrinsic structure-activity can be distinguished.

In this connection it may be remarked, that, when the intrinsic and actual structure-activity are suitable and result in a desirable actual structure, the state is attained, defined by the Germans as "Bodengare".

It is necessary (see also Chapter II) to split the actual structure in three parts, viz. :

1. floc-structure : the physical (or mechanical) building up of flocs, resulting from coagulating a soil suspension ;
2. micro-structure : the building up of soil aggregates by flocs or primary particles ;
3. macro-structure : the arrangement of soil aggregates in respect to one another.

It is necessary to do this, because differences in structure may be the result of differences in any of these „structure-factors" or combinations of them. Some chernozems form an example of soils with a compact micro-structure and a loose macro-structure, they have a good intrinsic structure but their structure-activity leaves much to be desired. Nevertheless, when the aggregates have a definite diameter (viz. : 1—3 mm) then a satisfactory plant growth is possible. Other soils are known, which are coagulated (have an open floc-structure), but they have a compact macro-structure. Here also the structure-activity is negligible ; e.g. in white alkali-soils. Finally soils are known with a compact micro- and macro-structure, e.g. the podzolic soils.

The problem of floc-structure is entirely a physico-chemical problem ; that of the micro-structure partly a physico-chemical, partly a bio-physical problem ; the macro-structure is determined by physical and bio-physical factors. It is on this scheme that the lay-out of this work is based.

After Chapter II, in which the author describes the nomenclature, morphology and the experimental determination of the actual

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[1]) The author is fully aware of the fact that both terms chosen are unsatisfactory, but he could not find another term to express the influence of the mechanical composition, the coarseness and shape of the sand grains the physico-chemical properties of the soil material, the humus content, etc. on the actual structure (see also Chapter V).

structure, the origin of the floc and its structure is discussed in Chapter III. Chapter IV describes the micro-structure and Chapter V the macro-structure. In this way the factors, that are responsible for the structure-activity, are divided, and the influence of each of them on the actual structure is traced.

Finally Chapter VI deals with the influence of soil structure on water- and air-conditions and on plant growth.

CHAPTER II.

MORPHOLOGY AND DETERMINATION OF STRUCTURE.

§ 1. *Morphology.*

In Chapter I the author emphasized that the structure of the soil changes from moment to moment, because of the fact that the soil is a dynamic system. Moreover study in the field teaches that it changes from place to place (on the same plot). Loose and dense structures alternate in various forms. Cloddy regions (horizontal variation), but more frequently "pans" (vertical variation) are observed. The vertical succession may be regular and in this way characterize the soil morphologically. This latter phenomenon is an important aid in distinguishing "soil types" (see also page 11).

It is necessary to investigate the soil at a distinct moisture content. Very moist soils are swollen and dry soils are shrunk, because of the behaviour of the colloids. Wet soils smear and are plastic (in most cases), dry soils may be very hard. Most soils have a range of moisture contents, in which they may be crumbled, because the soil particles release each other easily. In soils with a good structure it is wide and in soils with a bad structure it is narrow. Sometimes it may be so narrow, that the farmer can plough in the morning with success and crumble the soil, whereas in the afternoon, because of drying, the soils breaks up in clods. On the other hand, after a sudden rainfall the soil may smear in the afternoon. Because of the fact that most structures are recognizable after the cracking of the soil (see fig. 4), it is desirable to investigate it when rather dry.

page 29

Because soil structure manifests itself in different forms and nature, it is necessary to give a nomenclature, in which the nature and shape of the structural units form the basis. The magnitude of the aggregates is of less importance.

Floc-structure is difficult to characterize, because the flocs are too small to be seen with the naked eye. They may be loose or compact (see Chapter III) and because of the very narrow pores between the primary particles, they are always filled with water.

The different kinds of micro-structure can be described in the following way. 'Grains' (fig. 5) are the primary, fundamental, soil particles. Thus, a grain never is an aggregate. It may have microscopic or macroscopic dimensions and can have very different shapes, varying from minute plates to large globules. When the grains are united to larger aggregates, so that a system of cells with wide pores, or in other words, a honeycomb structure arises, the author speaks of crumbs (fig. 6). A crumb has no distinct dimensions and also not a distinct shape; they can never be large because the planes of contact between the grains and flocs are small. Therefore the forces, by which the grains stick together, are small; the cohesion is weak. They easily fall apart on handling and they feel like velvet. The crumb structure is the most desirable state of aggregation from the point of view of agriculture.

When the grains make contact along broad planes, a system results with extremely narrow pores or these pores may be absent entirely; this being the case when the several soil fractions fit exactly together. These aggregates are called clods in this work. In contrast to crumbs, they may be of very large dimensions, so that lumps (fig. 7) arise. The planes of cleavage of clods always have sharp edges at a definite moisture content and the fragments may have a typical form, e.g. cubical (fig. 8), when the units are equally developed in the three directions; prismatic (fig. 9), when they are equally developed in the two directions and more strongly in the third; they may have the shape of bricks (fig. 10), of plates (fig. 11) and of nuts (fig. 12). These latter units form the intermediate state between clods and crumbs. Fig. 13 shows cubical, prismatic and brick-like structures in the same profile.

It is necessary to correct some errors, that are sometimes made in practice. In the case of loose soils, the structural units of which are the grains or primary particles, in other words, soils in a complete grain structure, the pore space may be 24 to 30 %. With crumb structure the soil is also loose, but now the structural units are porous crumbs; the pore space has a value, that always exceeds 50 %. Now, when many clods are present in the loose crumb structure and a number of crumbs are present in the loose grain structure, these structures are easily mistaken one for the other. However the crumbs may be distinguished by their rapid water absorption. Fig. 14 gives the intake of water of a crumbly soil and of a cloddy soil. The difference is evident (see also page 25).

In this way the author has classified the structural units according to their shape and nature. Their dimensions are left out, because they are less important. The nomenclature is based on the classification, that is proposed in Russia by Zakharov (see: Joffe, 1936). This classification has been adapted to

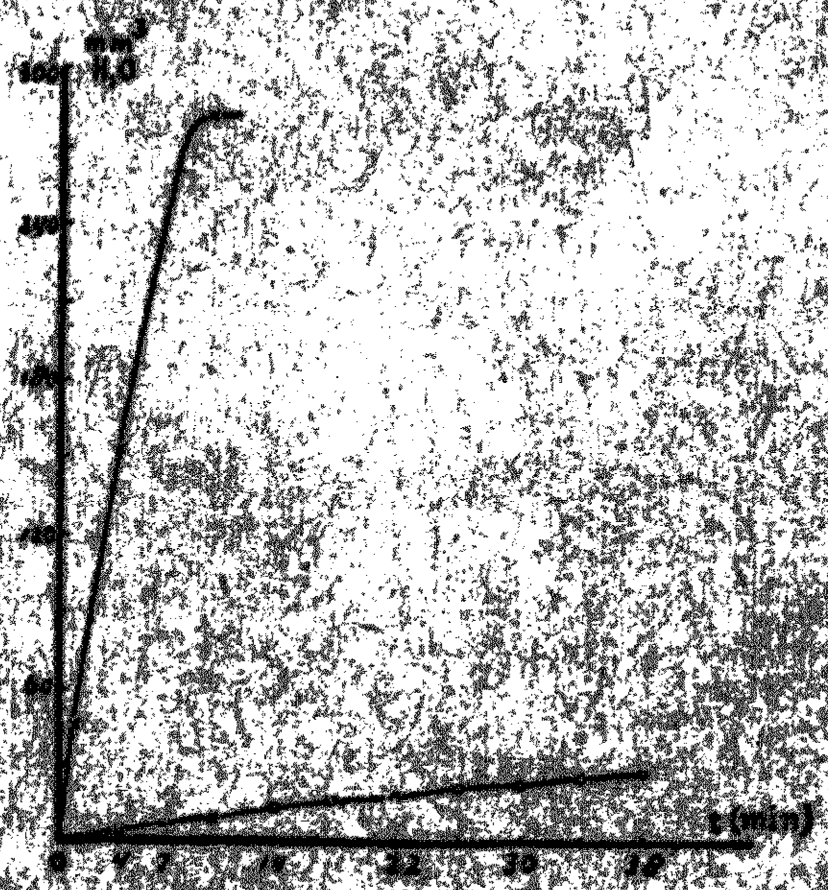

Fig. 14. Water absorption of crumbs (x-x) and clods (o-o) in mm³ water per g of soil after different times.

conditions in the Netherlands. For the sake of completeness it is given in table 1.

Table 1.
Classification of micro-structure

Type	Units	shape and nature
I. Crumb structure	1. crumbs	no specific shape. Soils feel like velvet and are spongy. Very rapid intake of water. Pores form a honeycomb system
II. Cloddy structure	2. nuts	nut-like shape. Transition between clod and crumb.
	3. lumps	faces and edges feebly manifested. Irregular shape.
	4. cubes	clearly manifested faces and edges. Equally developed in all directions.
	5. prisms	in one direction slightly better developed than in the other directions.
	6. bricks	units in the two horizontal directions well developed and in the vertical feebly.
	7. plates	only developed in the horizontal plane.
III. Grain structure	8. grains	variable.

Some additional remarks must be made here. First the author wishes to emphasize that one is wrong when considering the platy structures invariably as a result of aggregation of flocs or grains to aggregates. The platy structure and also the cube-like structure may be a consequence of the drying of a dispersed soil mass. They may be grain structures, although this is not always the case.

Secondly it has been mentioned on page 9 that the description of the structure is an aid to characterize "soil types", e.g. chernozems, podzols, etc. This is certainly true in the case of soil types, in other words, soils that are formed in the course of time under the influence of the climatic conditions in relation to the parent material, without man interfering with this process. In such systems an equilibrium is established between the constructive forces and the destructive forces. These soils behave as a more or less static system, and this is also true of the structure. But after the interference by man or after change of the climatic conditions, this equilibrium or apparent equilibrium changes and also the structure of the soil. In other words, a soil that is influenced by man cannot be characterized on the basis of its type of structure, as this would give an inaccurate picture of the soil. This structure will differ from moment to moment under the influence of the different treatments. In the Netherlands cases occur, that certain soils, that always crack into prismatic units after drying, e.g. the peaty clays, break in cubical or nutty units after a given treatment. So the different forms of structure may merge into one another. This being possible, the classification of soils with respect to morphological characteristics is not possible because it is very difficult, if possible at all, to classify on variable properties. It is known, that all cloddy structures may be changed into crumb structures by a suitable treatment and in these cases the morphological distinction of types disappears completely.

A nomenclature of the macro-structure has to reckon with the shape of the structural units and of the free spaces between the units. These spaces are important because, in the case of cloddy structures, they are the places, where the "life" takes place (see e.g.: Stöckli, 1946), and where all processes proceed, that are important to plant production. These free spaces may be formed in various ways; they may have the shape of capillaries, cells, holes, cracks, etc. and they are often determined by the shape of the aggregates. Examples are cloddy structures with prisms and horizontal and vertical cracks; cloddy structures with lumps and holes, etc.

The microscope may give a descisive answer here. Already Kamerling (1902, 1916) has used the microscope to classify structure. Also in Russia Pigulewski and Dojarenko (see: Krause, 1931) have used the microscope. The method of Pigulewski had been applied in Europe by Kubiena (1937) and in recent years by Redlich (1940), with some modifications.

To show, what may be attained with this method, a series of microphotographs follow now. In these photographs the transparent sand grains are light spots; holes, cracks and pores are light also. The clay and humus particles are dark on the photographs; in reality they are coloured, sometimes semi-transparent.

Fig. 15 shows a compact cloddy structure, in which only a few cracks exist. Fig. 16 shows a structure with holes with rounded and sharp boundaries; the solid phase has a cloddy structure. Thus it has a clod structure with holes. Fig. 17 is an example with distinctly separated clods, that have sharp faces, in other words, a clod structure with cracks. Fig. 18 shows a micro-clod structure, where the clods exist of spherical aggregates of a diameter of about 50 μ, which are packed so loosely, that they form large holes between them. A similar picture can be found in the chernozems, with this difference however, that the clods are larger in that case. Fig. 19 gives a crumb structure containing some clods. The crumbs are recognizable by the spherical boundaries and the clods by the sharp faces. A remarkable feature is the shape of the pores consisting of capillary canals and larger holes. The capillaries in the interior of the crumbs are visible only at higher magnifications. Fig. 20 is an example of a grain structure, in which pure sand and clay are deposited in layers in a compact structure.

§ 2. *Examination of the structure in the field, introduced and applied by* Goerbing *and* Cleveringa *(see:* Hudig, 1939; Sekara *and* Brunner, 1943).

The examination of the structure in the field plays an important rôle in the investigation of soil fertility. Soil structure can only be observed when the soil is in an undisturbed state; only in the laboratory structure may be defined in distinct characteristics. But both parts of the examination of the structure belong together. The most suitable samples for the determination of the structure in the laboratory are samples taken from the soil in situ and they have to be undisturbed when entering the laboratory. Furthermore they have to be provided with all data observed in the field. So it is clear, that samples, as usually taken for other purposes, e.g. to determine chemical characteristics such as lime or potassium content, are not appropriate to determine the structure of the soil. At most they can serve to the determination of distinct factors, influencing structure.

The fixation of the place of soil sampling has to be preceded by an examination of the field in question, viz. by digging small pits with a flat spade on several spots. The choice of the pits is made after a field-survey, noting e.g. differences in plant height or yields, the occurrence of plant diseases, the presence of weeds, etc. One has also to include the spots with good plant growth.

Some plant diseases are associated with typical structures. In this country very often eelworm-infested patches in rye crops are observed on very compact structures; as soon as the structure is ameliorated this disease disappears. Also lodging in cereals especially on compact structures is found and there are several examples more, indicating that given deviations in the crop coincide with differences in structure in the field. Hudig (1939) indicated, that large volumes of the soil are inactive in the case of compact structures and it may be computed, which part of the soil volume does not participate in the production of plant materials. In such cases e.g. Cu-hunger[1]) (reclamation disease), B-hunger (hart-rot in beets), Mg-hunger (Hooghalen disease), Mn-hunger (grey speck in oats) may occur.

The weed vegetation is reacting strongly on the water- and especially on the air supply of the soil, which in turn are determined by the structure of the soil. The weed flora is especially influenced by the depth of moist layers, that is, layers where the gas phase is in the minimum. When the surface layer is compact, then one often observes the following weeds: Musci, Apera Spica venti, Polygonum aviculare, Polygonum Convolvulus, Matricaria Chamomilla, Sinapis arvensis, Centaurea Cyanus, Atriplex-species (see fig. 21).

The drainage being insufficient, so that the soil is in very moist state during a long time, one may expect Holcus lanatus, Ranunculus arvensis, Anchusa arvensis, Geranium pusillum, Carex-species.

The occurrence of a pan in the subsoil, so that the water transport is impeded, favours the occurrence of Triticum repens, Equisetum arvense, Tussilago Farfara, Rumex acetosa, Sonchus arvensis, Sonchus asper (see fig. 22).

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[1]) Hunger in the meaning of pathological deficiency.

In the case that there is no plant growth on the field to be investigated, the external characteristics of the surface, that may be level, rough, crumbly, cloddy, lumpy, cracked, etc., determines the choice of the trenches to be dug.

The dimensions of the trenches differ from case to case. Generally a pit 50 cm wide and 80 cm length is sufficient. In some cases it is necessary to dig the pit to such a depth that the parent material is reached. Then a trench about 1 m wide and 2 m length is necessary. Both sides and one end of the trench are cut down to form vertical walls. The other end is then dug down to a slope with a step-like arrangement.

The digging should be done with a flat spade. The soil is laid down cautiously to one side of the trench, leaving the other side and the ends free from any extraneous materials. When the soil falls apart, then the rupture and the way of falling to pieces give important information about the structure. After having smoothened the walls with the flat spade without pressing the soil, the profile may be examined in several ways. One may probe the wall with the resistance meter of Oosting, a small steel cone pressed into the soil. In this way it is possible to trace hard and soft layers exactly. Furthermore the profile may be prepared by scraping the wall with a garden scratcher with 4 to 5 tines. In scratching, the crumbly zones fall down and the cloddy parts remain. At the same time the root development and the spots, where the roots function are observed. The shape of the roots may be very capricious. Sharp angles in the roots indicate, that they met clods; flat roots have grown in cracks. A wide root development indicates a good surface soil, a bluff root mass indicates a rigid and compact surface layer. Frequently an enormous mass of roots, unbrenched, "rope-like", like a beard is observed (Heyl, 1942). This indicates a compact structure, whereas thick roots with many root hairs indicate a crumbly structure.

Finally the "fall test" of Goerbing may be performed. A spadeful of the soil is taken and dropped from a height of about 1 m in such a way, that it falls with the broad side on the ground. When the soil is in a crumbly structure, it falls to uniform aggregates and it bursts to all sides. Hard layers remain in clods on the place where they have been fallen.

There is no soil, that cannot be characterized according to these simple principles. After having examined many profiles in this way, it becomes clear, that the factors, that are determining the forms of structure, have the same qualitative results in heavy as well as light soils. The natural processes, acting on the soil, tend to cause a close packing of the soil particles, in other words, cause a cloddy structure. Only the biological factors, that become active after supplying the soil with organic materials as food for bacteria act in the direction of crumb formation. To control the subjective observations described above, it is necessary to do laboratory measurements as well to establish objective data.

§ 3. *The determination of the structure in the laboratory.*

After having obtained an idea of the structure of the soil in situ by the clinical investigation of the soil described above, the question arises if it is possible to express this idea by a figure, that can be determined exactly.

Wollny, Kopecki, Ramann, Mitscherlich, Burger, and others have tried to make this possible. They determined mostly the pore space and the permeability of the soil to water. These methods were occasionally useful, but often failed. Therefore other investigators have tried to determine other characteristics of structure, e.g. the resistance against special forces, the aggregate-analysis, permeability of the soil to air, etc. In studying these investigations, it may be concluded that these methods give contradictory results in many cases. It appears soon, that the different methods, applied to the same object, give very different results. This is to be expected a priori for the following reasons.

The methods can be divided in two groups, viz. : I. Measurements of the porosity ; II. Measurements of the stability. The first group determines the pore space of the soil either in situ or in stirred samples, or of sieve fractions of the soil ; the second group determines the resistance of sieve fractions against the desintegrating action of water or mechanical forces. The results obtained with these methods do not necessarily agree, because the porosity may be determined by other factors than the resistance of soil aggregates against, e.g., water. The porosity is, for an important part, a physical, the resistance a physico-chemical or bio-physical quantity. Thus, the porosity of the soil is greatly influenced by cultivation. When cultivation takes place at the right moment, or, in other words, at a suitable water content of soil, a loose packing of soil aggregates results (so a loose macro-structure), by the fact that the water menisci, that are formed at the points of contact, bind the aggregates, so that the soil does not fall back into a state of close packing. Determining the porosity at that moment, one will get a large value and conclude, that the soil has a loose structure, that is desirable from the agricultural point of view. It must not be forgotten that the structure (macro-structure) is suitable for the moment. The resistance of the structure, especially the micro-structure, as always the resistance of the aggregates is determined, may be quite insufficient, because it is influenced mostly by the physico-chemical state of the particles, the nature and amount of the organic material and the activity of the micro-organisms and macro-organisms. It is possible to give dune sand a large porosity by mingling it with a suitable amount of water, but the resistance of this structure will be completely insufficient. On the other hand a soil in a coagulated state and with a proper content of organic materials, thus with a good resistance, may sometimes be found with a low porosity.

From Chapter I (structure differs from moment to moment) and the above mentioned facts and from the observation, that the structure of soil differs in a vertical direction as well as in a horizontal one, it is clear, that the only way is to collect several figures, obtained from several determinations in several ways.

It appears, that it is impossible a priori, to characterize soil structure with one figure, obtained by using one method. Determinations of porosity as well as of resistance must be done. Therefore the author will give a critical discussion of methods, that may be applied in the laboratory.

I. *Measurements of the porosity.*

These are based on the measurement of the pore space of the soil. This pore space, being the sum of the volume of pores between the aggregates and in the aggregates, must be determined in soil in situ, as the macro-structure of mixed samples differs sharply from that of soil in situ, because in the former the pores between the aggregates are changed appreciably.

The sampling may be done in two ways, either by preparing clods from the profile or by pressing a metal ring of a diameter of about 5 cm (Redlich, 1940) horizontally into the different horizons. Using the first method, as Sekara (1938) does, it should be stressed, that these clods are the most compact parts of the soil, so that the results obviously may be disguising. The second method is much better. The rings should not be too narrow to avoid compressing of the soil. Moreover it is essential that these rings be sharp at one end. Also it is necessary to take the samples at a suitable water content. Too low as well as too high a moisture content at the moment of sampling disturbs the structure appreciably.

There are several ways to measure the pore space:

1. Volume-weight determination. By determining the weight of a known volume of soil and the specific weight of the soil it is possible to compute the volume of the solid phase. The difference between the soil volume and the solid phase gives the pore space.

The volume determinations of the sample may be complicated by the shrinkage of the sample. (1) Samples of soils, that do not shrink upon drying, have the volume of the ring. It occurs that in the case of extremely heavy soils in a very compact structure, the shrinkage is considerable, and the soil volume is then not equal to the volume of the ring. (2) In those cases the samples may be surrounded by a thin layer of paraffin by plunging it into just liquid paraffin. The paraffin settles on the surface and after that the volume may be determined by plunging the sample into water. The volume of paraffin must be taken into account (Pigulewski: see Krause, 1931). (3) Also the soil can be saturated with water and determine the volume in a liquid immiscible with water, e.g. petroleum (Sekara, 1938). (4) Von Nitzsch (1938) tried to determine the volume of the soil in a direct way. He used to this purpose an "air-pressing-pycnometer". However, this method leads to conclusions (v. Nitzsch and Czeratzki, 1940), which are disputed thoroughly by Alten and Loofmann (1941). E.g. one of these results was, that water, first adsorbed by the soil particles, had a specific weight of about 0.2. After continued water adsorption the specific weight increased to that of free water. Thermodynamically this result is untenable (see also: Reinau, 1943), since, during the adsorption of water, heat (the heat of wetting) is developed, and Thermodynamics teaches that, when a change of volume takes place involving heat development, this must be a contraction and not an expansion. Therefore this method will not be described here.

The author determined the specific weight with the aid of CCl_4 in the following way; about 20 g of soil were brought into a flask of 50 ml. Under continued shaking CCl_4 is added from a burette till the mark is attained. The soil volume is then 50 ml minus the amount of CCl_4 added. The use of CCl_4 also has the advantage that soils not wettable by water may be investigated. This method gives very satisfactory results.

2. Suction method. It is known, that the rapidity of the ascent of water in capillary tubes is dependent on the inner diameter of these tubes. The author uses this fact as the base of a method for characterizing structure. He supposed that a cylindrical soil sample behaved as a bundle of capillaries of a definite diameter, and the laws of capillarity may be applied to the ascent of liquids in soil over small distances, this sample being brought into contact with a free liquid surface. If it is possible now to give a relationship between the height of ascent and the time, the number of capillaries present may be computed and their diameter with the aid of two equations, containing these quantities. In this way one has an important characteristic of soil structure.

The author arrived at the following two equations,[1]) viz.:

$$(1) \qquad (a_0h+b_0)\frac{d^2h}{dt^2} + a\left(\frac{dh}{dt}\right)^2 + (a_1h+b_1)\frac{dh}{dt} + a_2h + b_2 = o$$

where a_0, b_0, a_1 and b_1 are terms containing the quantity r (mean diameter of the pores) and h is the height of rise and t is time:

$$(2) \qquad Q = n\,\pi\,r^2 h\,,$$

where Q is the volume of the absorbed water and n is the number of capillaries.

Because the differential equation (1) could not be solved up to now, r and n cannot be computed. Yet it is possible to get an idea about structure with the method to be described in the following.

The measurements were done in the apparatus, represented in fig. 23 (see also: Burenkov, 1934). The apparatus consists of a vessel A, provided with a perforated plate and connected to a calibrated tube of a known diameter. This tube has a cock B and two flasks, filled with water, so that both parts of the tube can be filled. Vessel A is closed with a rubber stopper with a calibrated tube in which there is a drop of mercury. In this tube the volume

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[1]) see appendix I.

of air removed during the uptake of water is measured. The amount of the latter is measured in the tube below.

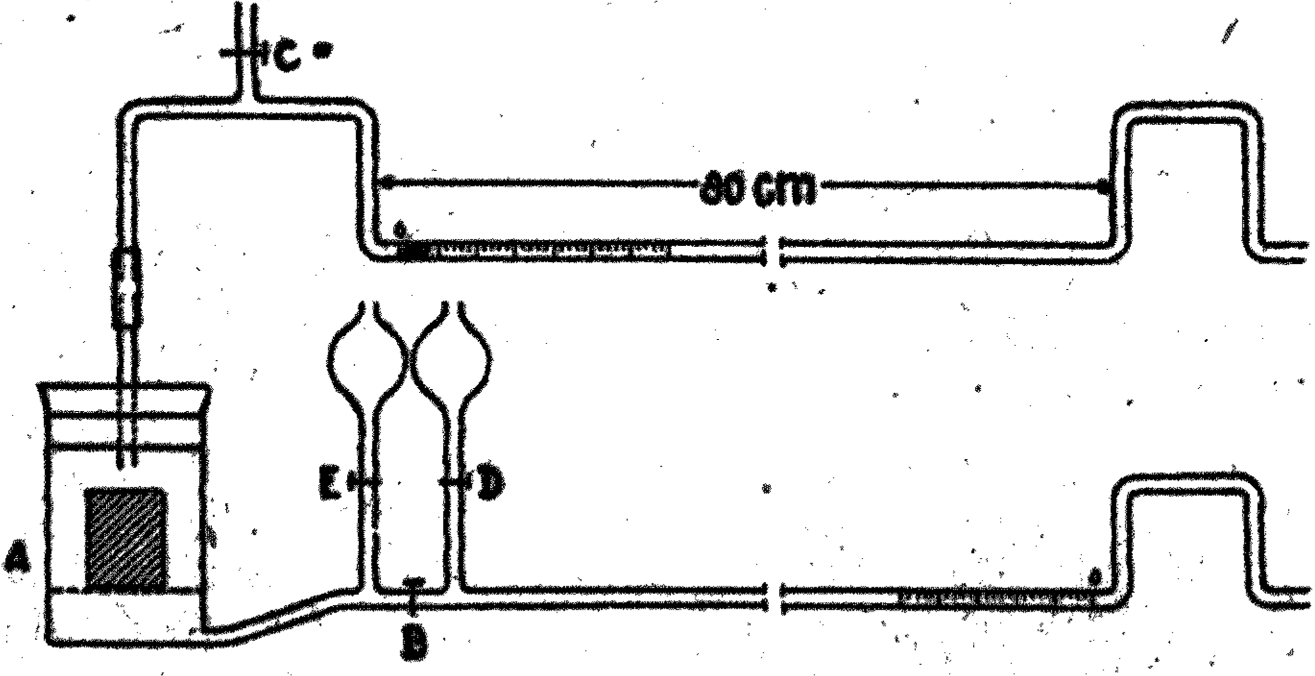


Fig. 23. Measuring apparatus.

The air dry sample (dimensions: height, 2.0 cm; diameter, 2.1 cm) is placed on the perforated plate. Now the vessel A is closed with the rubber stop and C is opened. After that D is opened to fill the tube with water and this being done, E is opened to fill the left part of the tube until the level of the perforated plate is reached. Then cock B is opened immediately and C closed at the same time. Now the amounts of water taken up and air displaced may be read.

Finding a rapid uptake of water in this way, it may be concluded that the soil in question has a loose structure; in the case of a slow water absorption the structure is compact. Some results are given at the end of this Chapter.

3. Determination of the capillary and non-capillary pore space. It appeared soon, that the determinations of the total pore space supplied insufficient information and that it was desirable to distinguish the pore space between the aggregates and in the interior of the aggregates. A soil with a definite pore space may consist of a few large aggregates, but the same pore space is possible if the soil is composed of many small aggregates. Agriculturally the soils behave quite differently (see also Chapter VI). Especially Dojarenko (see: Krause, 1931) and more recently Sekara (1938), have emphasized this fact.

Dojarenko allowed the soil sample to absorb water by forces due to capillarity. To this end the samples were placed on filter-paper, that hung with its edges in water. The water table was 5 cm below the samples. It is assumed that the pores within the aggregates are filled with water in this way. The total, capillary and non-capillary pore space can be computed from the volume, weight, moisture content after capillary saturation and the specific weight of the soil. The capillary pore space is then supposed to be the volume of the pores in the aggregates and the non-capillary pore space that of the pores between the aggregates, or, in other words, the air content of the soil, because the latter pores are filled with air usually.

Because the soil samples of Dojarenko had a height of about 10 cm and those of the author about 3 cm, the author allowed the samples to saturate capillarily with water under a suction of about 8 cm water.

It is clear, that the method is conventional, because the depth of the water table determines the amount of water that is absorbed and with this the computed capillary pore space.

4. Suction method of Sekara. If not being content with the division of the pore space in capillary and non-capillary pore space, the method of Sekarà (1938) may be applied, which allows a division to be made between any desired pore sizes. The method is based on the fact, that a suction tension, the value of which depends on the diameter of the pores, is required to remove water from pores of a definite diameter. This tension is given by the formula :

$$(3) \qquad p = \frac{4\sigma}{d} \qquad \text{dyn cm}^{-2}$$

where σ = surface tension and d = diameter of the pores.

This relation holds for cylindrical capillaries ; but these are not present in soil. Therefore d has the meaning of an equivalent-diameter. Applying a suction tension to a soil sample saturated with water and increasing this tension gradually, pores of decreasing diameters are emptied successively. The amount of the capillaries of equal diameter may be measured directly by determining the amount of water withdrawn from the soil sample. For this purpose Sekara uses the so-called capillarymeter, represented in fig. 24. A is an extremely fine porous sintered glass plate. B is connected to the water jet pump, with which the desired tensions are obtained.

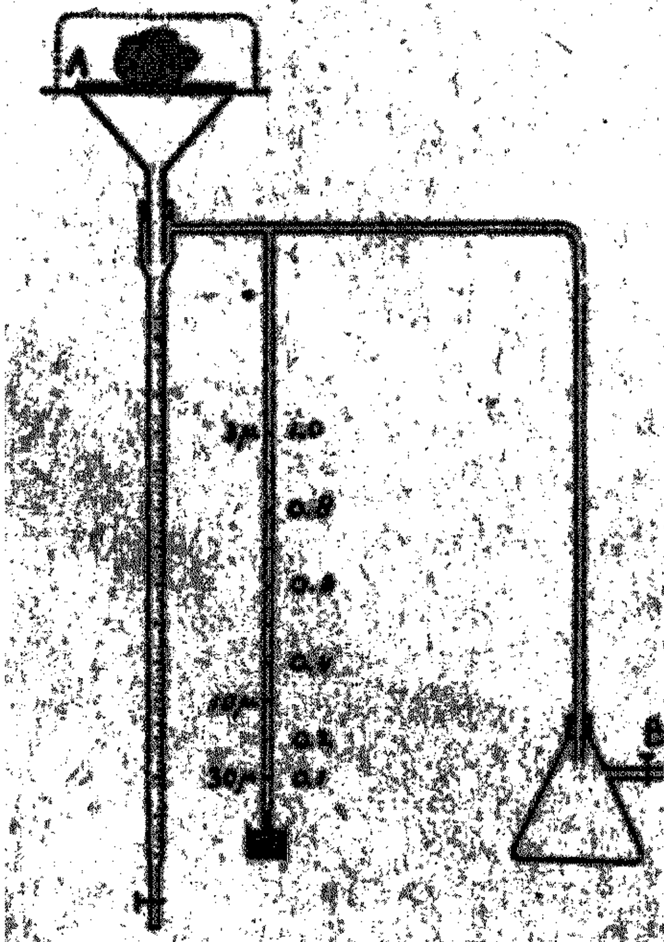


Fig. 24. Vacuum-capillary meter of Sekara.

The soil samples (Sekara uses clods, but it is better to work with ring samples) are saturated with water and placed on the porous plate. After that the sample is emptied gradually by applying different tensions. Because it is impossible to realise tensions larger than 1 atm. in this way, it is necessary to determine the amount of capillaries smaller than 3 μ in another way. The ~~samples) are saturated with water and~~ plate, weighed, dried at 110°C and weighed again. The decrease in weight is the content of pores with diameter smaller than 3 μ.

Because all figures about the content of water must be given in percentages of volume, it is necessary to determine the soil volume with one of the methods described (see page 16).

To divide the pores larger than 30 μ (belonging to a tension of 0.1 atm.) one may use the capillarimeter of Donath (1937), modified somewhat by Sekara (1938). The method of working is principally the same as that of the vacuum capillarimeter.

Modifications of the vacuum capillarimeter are given by Bradfield and Jamison (1938) and by Leamer and Lutz (1940). These methods being essential equal, differing only in their technical construction, they will not be discussed here.

5. Microscopical method. Finally it is possible to investigate the soil microscopically (Pigulewski, 1934; Kubiena, 1937; Redlich, 1940). Redlich impregnates the soil samples, taken in situ, with a resin (according to Kubiena, 1938), that is fluid at a distinct temperature and becomes hard after cooling. After that one side of the sample is polished. The samples are fixed with this polished side on a microscope glass and then the other side is polished in the same way, till a slice remains of about 10—20 μ thickness. Finally the preparates are covered with a cover slip and the arrangement of the particles may be observed microscopically.

A combination of this method with e.g. the method of Sekara gives an idea of the shape, arrangement and amount of the pores of different diameter in the soil.

II. *Measurement of structure stability.*

Here also a considerable variation of methods exists. The most important will be discussed here.

1. Aggregate-analysis. a. Keen (1933) screens the soil in air dry state to determine the distribution of the aggregates. A given amount of soil is placed on the uppermost sieve of a set with decreasing mesh and shaken during a given time. After that the various fractions are weighed. The resistance of dry soil against mechanical desintegration may be estimated in this way. The question, if it is permitted to transfer the result, obtained with this method, on the soil in situ, which is more or less moist, must be answered in the negative. When all soils react in the same way on a given amount of moisture, it would be allowed to do this, but this is not the case, as will be shown later.

b. Therefore Tiulin (1928) proposed a wet screening method: The soil is saturated capillarily with water during 30 minutes and then placed on a set of sieves, completely immersed in water. By moving these sieves up and down 30 times, the soil falls apart, according to their resistance into more or less fine aggregates. The weight of the fractions in each sieve is determined after drying. The lowest sieve of the set has pores 0.25 mm in diameter. There are several modifications of this method, but they all come to the same thing.

c. Agromeiko (1934) combined the methods a and b. First, he screened the soil when dry and each of the derived fractions is screened in water. The residu of the fractions is dried and weighed. The decrease in weight is a measure for the resistance of the aggregates.

The methods b and c determine the resistance of the aggregates against the desintegrating force of water. In other words they give a measure for the water resistance of the floc- and micro-structure.

d. Demolon and Hénin (1932/1933) performed the aggregate analysis in a 0.1 % $Ca(NO_3)_2$-solution. They supposed, that the flocs were maintained. A desintegration of the soil mass is a consequence then of a destruction of the micro-structure. So an idea of the resistance of the micro-structure is obtained with this method.

2) Determination of the resistance of aggregates against the impact of raindrops. a. Vilenski (1934) applied a very simple method. He took a sample of 50 aggregates and submitted each of them separately to the destructive force of water by allowing this to flow out by drops from a burette, so that they hit the aggregate, from a height of 5 cm, until it falls apart. The number of drops to attain this is a measure for the resistance of the aggregates (micro-structure). The author performed the determination on 20—30 aggregates of a diameter of 1—2 mm or 2—4 mm. This method is very simple and adequate and gives reproducable results.

b. Hudig and Siewertsz v. Reesema (1941) modified this method in order to manupulate with several samples at the same time. They worked as follows: The aggregates of a definite sieve fraction were filled in into Goochs crucibles of a diameter of 3 cm and a height of 6 cm. The bottom of these crucibles had 100 perforations. They allowed water to drop from pipettes on these soil samples. The volume of the pipettes was 10 ml. Three series of four cups were treated simultaneously (see fig. 25, page 32). The cups were placed above glass pots, on a platform performing a slight rotational movement, so that the drops were divided regularly over the whole surface in the cups. The pipettes could be adjusted to different heights, so that the hitting force might be varied. In this way it was possible to measure the resistance of the aggregates, because the drops destroyed them sooner or later and the permeability for water decreased. This latter fact comes to expression in the amount of drainage water per unit of time.

This method likewise gives the resistance of the micro-structure against the impact of water drops.

3) Elutriation method of Sekara and Brunner. Sekara and Brunner (1943) gave a very useful method to determine the water resistance of aggregates. The apparatus is given in fig. 26. Through a supply-tube (a), that is reaching the bottom of the

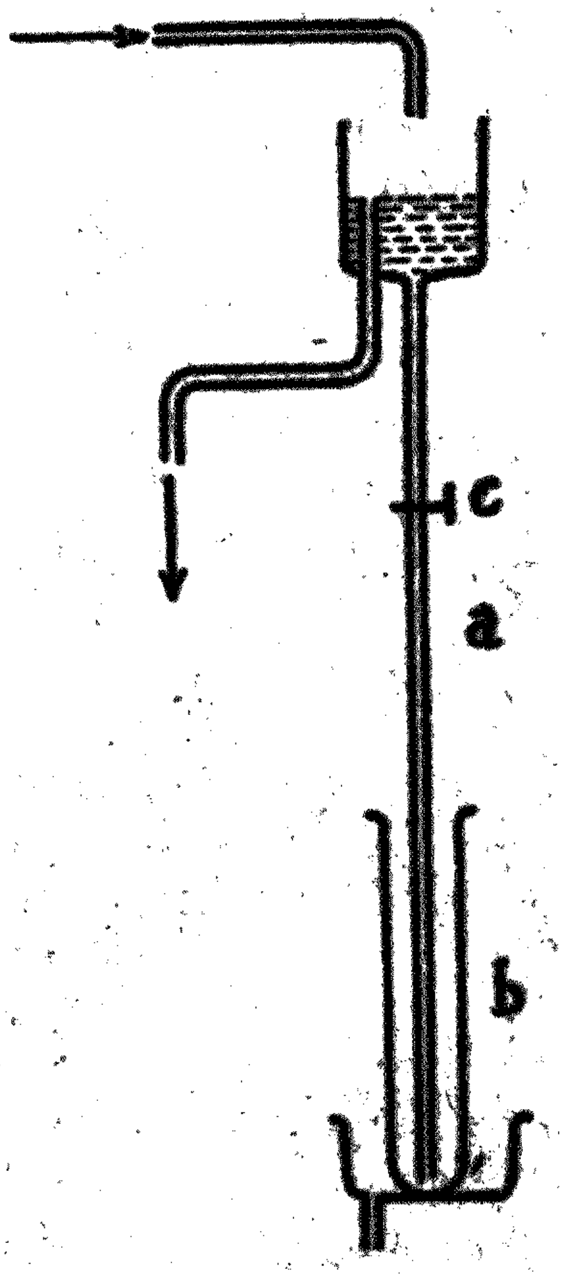


Fig. 26.

elutriation tube (b), in which a sieve fraction of the soil (10 g aggregates of a diameter of 1—2 mm), water is conducted with such a speed (by regulating cock c), that in the elutriation vessel a constant speed of flow of 2 cm/sec. is attained. This speed corresponds with the velocity of fall of particles with a diameter of 0.2 mm; in other words, particles with a smaller diameter are removed with the water flow. The soil sample is allowed to remain under water during night. After that the soil mass is elutriated and the aggregates are disturbed more or less, depending on the stability of the micro-structure. After some time (usually 10 min.) the ascending water is clear, which indicates that the separation is finished. The water resistent aggregates remain in the elutriation tube and are weighed after drying. This remainder consists of aggregates and sand. The separation of sand and the finer particles may be brought about by peptising the material with a 0.2 % solution of Li_2CO_3 and repeated elutriating. The difference between both remainders gives the amount of water stable aggregates. This amount is calculated on the basis of the weight of the samples minus the weight of sand.

This method may be critisized by remarking that the water flow is far from being laminar at this speed, so that Stokes' law cannot be applied to particles of a diameter as large as 0.2 mm and that peptisation with 0.2 % Li_2CO_3 alone is not sufficient. However, with respect to the first two remarks one may say, that particles below a definite diameter were elutriated, even if this diameter deviates from 0.2 mm. Working under the same conditions in all cases, these objections lose their force. The peptisation with Li_2CO_3 is insufficient in many cases, especially in soils rich in organic matter or $CaCO_3$. The organic matter has to be removed either by peptisation with 3 % NH_4OH or by oxidation with H_2O_2 and likewise $CaCO_3$ by treatment with HCl. It will appear from the measurements of the author that these measures are necessary.

4. Determination of the water permeability according to Sekara and Brunner. The permeability of the soil is a function of the resistance of the aggregates. The smaller this stability, the more the permeability decreases. In determining this permeability an impression of the resistance of the aggregates is obtained. 10 g of the sieve fraction 1—2 mm of a soil are saturated with water in a tube (a) (see fig. 27), after which the permeability is determined. The tubes have a length of 10 cm, a diameter of 2 cm, and are closed at the lower end with a piece of linen cloth. The tube with the water saturated samples is connected by means of a rubber ring (b) to a tube (c) of equal diameter. The upper rim of this tube is 25 cm above the bottom of tube (a), so that the permeability is determined at a constant pressure of 25 cm water. By opening cock (d) water flows in tube (a), this cock being opened so far, that small amounts of

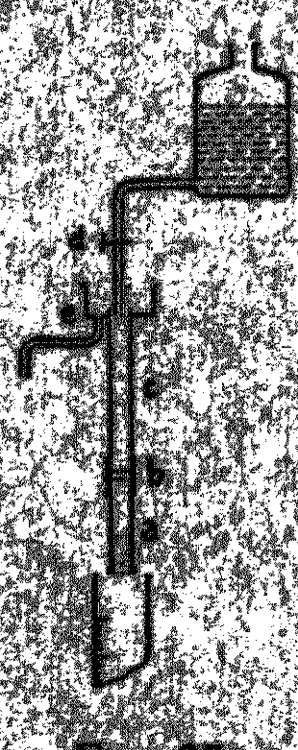


Fig. 27.

water flow away through the overflow (e). The water, percolating through the soil, is caught in a measuring glass, so that the amount of drainage water at different times can be determined. The more water percolating, the more resistent the aggregates are.

5. Structure-factor of Vageler. Vageler (1932) determines this factor to obtain a figure for the amount of water resistent flocs. He proceeds in the following way: 25 g of air dry soil are shaken in 500 ml CO_2-free distilled water, after which he allows the suspension to stand during 12 hours. Then the mass is shaken in an end-over-end shaker during 6 hours. After that a separation of the flocs is performed with the pipette method without adding a peptisation agent. Moreover a mechanical analysis is performed after the addition of a peptising agent. Now the structure-factor may be computed with the aid of the figures obtained, by using the following formula:

$$S = \frac{100 \times (\text{fraction} < 2\mu \text{ with peptisation} - \text{fraction} < 2\mu \text{ without peptisation})}{\text{fraction} < 2\mu \text{ with peptisation}} \tag{4}$$

By shaking intensively, the aggregates are broken down in their constituent flocs and so the stability of the flocs is measured.

The author worked with 10 g of soil in 250 ml distilled water. This mass is allowed to stand during the night and then shaken in an end-over-end shaker for 2 hours. After that the mass is brought in a sedimentation cylinder, 750 ml distilled water added and a mechanical analysis by the pipette method is done. An other sample of 10 g is freed from organic material by oxidation with H_2O_2 and peptized with $Na_2(COO)_2$. Once again a mechanical analysis is performed. The structure-factor is computed with the given formula.

It appears from the description of these methods, that in some cases the porosity (related to the macro- and (or) micro-structure) is determined, in others the resistance of the micro-structure or floc-structure. It is to be expected that these methods give different and often contradictory results (see p. 19 of this Chapter and p. 45 of Chapter III). As additional proof the author applied several of the methods described to the same objects. The results are given in table 2. This table shows that there is no correlation between the different measurements.

It appeared that the methods of Dojarenko and of the author in determining the porosity and those of Vilenski and of Sekara and Brunner (elutriation method) are most handy and suitable for routine work.

It is desirable to measure the porosity of the soil as well as the resistance of the structure. The latter indicates how and to what extent a given structure is maintained and it is related to the intrinsic structure of the soil. However, from an agricultural point of view, the porosity of the soil determines the plant production greatly, so that determination of the capillary and non-capillary pore space is most valuable for practice. The described methods of Dojarenko and of Sekara have the advantage of giving

TABLE 2.

Soil	Vagalar S	Vilenski Mean number ± σ_m	Elutriation (Sekara and Brunner) 1)				Porosity (Dojarenko)			(Sekara and Brunner) Permeability amount of water in ml after 20 min.
			1	2	3	% >0.2 mm	cap. %	non-cap.%	total %	
Heavy clay soil	80.7	27.5 ± 3.0				60.6	18.4	5.5	23.9	78.2
Clayey loam	82.1	6.3 ± 0.5				30.9				165.2
Loam (cultivated forelands)	68.6	72.4 ± 12.4				54.7				562.0
Profile: XV fig. 30		>100	2.034	1.107	0.292	37.0	42.1	13.0	55.1	
XVI fig. 30		14.0 ± 0.9	2.590	1.730	0.385	47.8	44.4	7.6	52.0	
XVIII fig. 30		25.0 ± 0.5	1.748	0.593	0.273	31.2	48.3	2.4	50.7	
XIX fig. 30		2.7 ± 0.2	0.073	0.053	0.050	0.4	38.0	19.6	57.6	
Clay soil 0-32 cm		>100	2.952	0.670	0.100	58.2	33.0	21.0	54.0	
> 32 cm		>100	3.620	1.150	0.015	72.3	34.0	8.0	42.0	
Dark coloured loam 0-20 cm		21.0 ± 0.8	1.371	0.941	0.941	19.4	34.2	16.6	50.8	
20-37 cm		6.8 ± 0.3	1.950	1.063	1.063	22.5	38.3	6.4	44.7	
Sandy soil 0-20 cm		4.5 ± 0.5	4.010	3.505	3.505	13.8	27.0	21.0	48.0	
20-25 cm		6.7 ± 0.9	3.161	2.885	2.885	13.0	24.5	18.5	42.0	
> 25 cm		5.5 ± 0.9	3.442	3.050	3.050	20.1	24.5	21.0	45.5	

1)
1: weight of the remainder after elutriation during 10 min.
2: " " " " " peptisation with Li_2CO_3 and elutriation
3: " " " " " oxidation with H_2O_2, peptisation with Li_2CO_3 and elutriation

figures for the volumes of the different pores; the method of the writer does not possess a quantitative character with respect to capillary and non-capillary pores; only the total pore space can be determined by it. However, it shows the way of absorption of water and the liberation of air, both important processes in practice, whereas the other methods fail with respect to these phenomena. Moreover it indicates that gradual transitions are found between soils in a crumb structure and soil in a cloddy structure. To show this, the author will discuss the suction-method in more detail.

Samples of soil in situ were taken with a brass tube of 2.1 cm diameter at such a moisture content, that no compression of the soil took place. After that the soil was removed from the sampler and a column of 2 cm in height was cut from the soil cylinder by means of a sharp knife; next the soil was air-dried.

The samples were taken from old clay soils in the Nude near Wageningen (V, VI, VII, table 3), from clay soils near Neerlangbroek (VIII, IX, X), from a profile in the forelands near Wageningen (XIV—XIX), from sandy soils of the Achterhoek (XI, XII, XIII) and from an irreversibly dried peaty soil of Utrecht (XX). The Nude-clay, having a very compact structure, was crumbled in the following way. The soil was moistened with water up to a suitable water content (up to the "crumbling point"), stirred and screened through a 2 mm sieve. A tube of 2.1 cm diameter was filled with crumbs and gently pressed. After that the mass was removed from the tube and again the height of the soil sample was made 2 cm.

The structure of the Nude clay soils was cubical to prismatic; the clay soil of Neerlangbroek possessed a nutty structure and the sandy soils had a grain structure, but the type of packing was not entirely close. The irreversibly dried peaty soils possessed the microclod structure (see: Hudig and Redlich, 1940, 1941). The profile of the forelands was as follows:

1. 0—9 cm: dark-grey clay with a 1 cm layer of sand at a depth of 1 cm below the surface. Many roots present.
2. 9—12 cm: coarse sand
3. 12—16 cm: light-grey clay with many roots
4. 16—18 cm: coarse sand
5. 18—30 cm: light-grey to brownish grey loamy clay with layers of sand a few mm in thickness
6. 30—70 cm: brown loam with sandy layers
7. > 70 cm: reddish brown loam with crotovinas.

The structure of the described layers was a crumb structure with many clods or from an agricultural point of view a fairly bad structure. There was a gradual increase in compactness to the deeper horizons, but layer 7 was crumbly and very loose. Samples were taken of the layers 1, 3, 5, 6 (two samples, viz. 50 and 60 cm below the surface) and 7.

The results of the measurements are given in table 3 and figs. 28, 29 and 30. Fig. 28 shows the absorption of water per g of soil in dependence of time. The lines divide the areas of loose, moderately loose and compact structures. A gradual transition is observed in the velocity of water absorption, passing from a soil in a crumb structure to a soil in a cloddy structure. Fig. 29 gives the "surplus" (volume air displaced minus the volume of water absorbed) in dependence of time. It will be seen, that the surplus is positive (negative only in one case) and further, that it is larger the more loose the structure is. Here also regions of loose, moderately loose and compact structures can be distinguished.

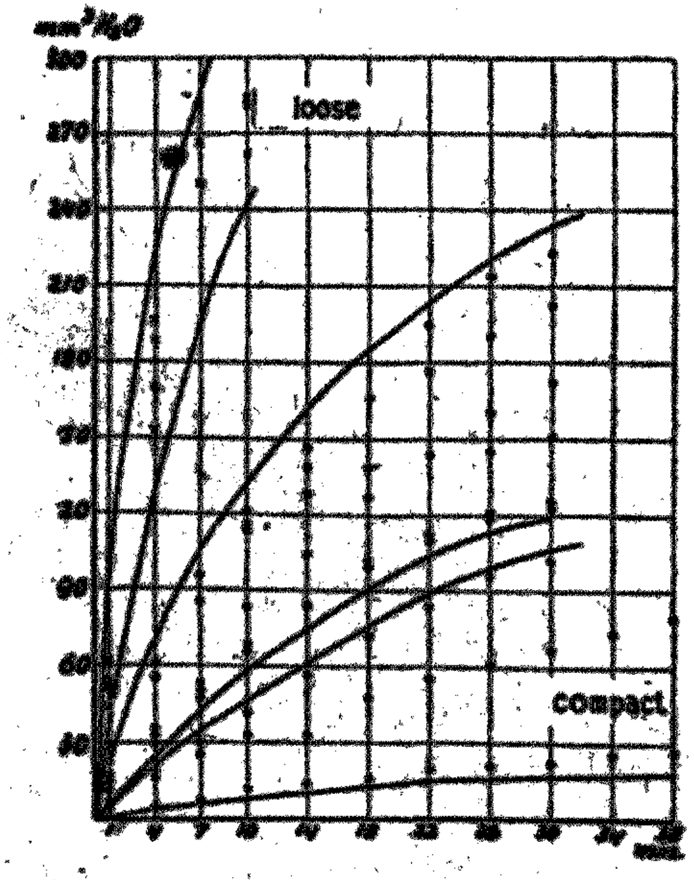


Fig. 28.

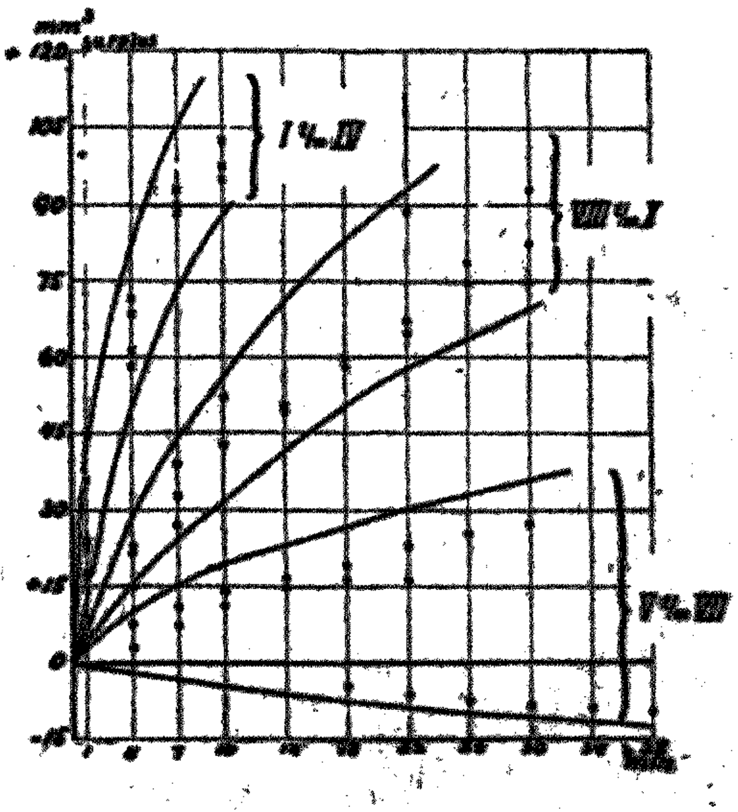


Fig. 29.

TABLE 3

		Water absorption and (removal of air) in mm³ per 1 g of soil after								surplus after							
		1 min.	4 min.	7 min.	10 min.	14 min.	22 min.	30 min.	38 min.	1 min.	4 min.	7 min.	10 min.	14 min.	22 min.	30 min.	38 min.
Clay soil; artificially prepared crumb structure	I	55.7 (77.9)	171.4 (241.0)	250.8 (358.9)	262.3 (350.5)					+ 22.2	+ 69.6	+ 88.1	+ 97.2				
	II	54.7 (91.1)	190.0 (248.0)	267.3 (361.7)	285.9 (381.0)					+ 36.4	+ 58.0	+ 94.4	+ 95.1				
	III	62.0 (85.3)	196.1 (267.0)	252.0 (342.0)						+ 23.3	+ 71·2	+ 90.0					
	IV	44.0 (62.7)	153.1 (214.8)	— (385.5)	284.3 (344.5)					+ 18.7	+ 61.7	—	+ 101.2				
Clay soil in moderately loose (nutty) structure	VIII	7.8 (10.8)	30.8 (45.8)	55.6 (83.0)	86.6 (116.9)	104.9 (156.4)	144.8 (211.9)	174.9 (255.9)		+ 3.0	+ 15.0	+ 27.4	+ 30.3	+ 51.5	+ 67.1	+ 80.7	
	IX	17.3 (19.4)	61.7 (82.4)	96.4 (130.1)	122.1 (164.7)	148.6 (199.3)	178.6 (243.6)	203.1 (277.3)		+ 2.1	+ 20.7	+ 33.7	+ 42.6	+ 50.7	+ 65.0	+ 74.2	
	X	17.0 (19.2)	55.4 (79.0)	85.1 (125.6)	114.0 (165.8)	— —	204.0 (293.4)	221.0 (314.0)		+ 2.2	+ 23.6	+ 40.3	+ 51.8	—	+ 89.4	+ 93.0	
Sandy soil in moderately loose structure	XI	30.1 (28.2)	71.5 (77.0)	99.8 (113.1)	117.7 (128.7)	130.2 (142.7)	142.5 (149.4)	152.5 (156.7)		— 1.9	+ 5.5	+ 13.8	+ 11.0	+ 12.5	+ 6.9	+ 4.2	
	XII	11.8 (10.9)	32.4 (33.6)	50.4 (54.1)	66.9 (72.4)	86.8 (92.3)	112.0 (114.5)	126.4 (124.5)		— 0.9	+ 1.2	+ 3.7	+ 5.5	+ 5,5	+ 1.6	— 1.9	
	XIII	13.1 (11.5)	35.9 (38.6)	54.0 (57.7)	69.5 (72.9)	86.9 (88.0)	111.5 (105.9)	123.3 (112.3)		— 1.6	+ 2.7	+ 3.7	+ 3.4	+ 1.1	— 5.6	— 11.0	
Clay soil in compact structure (cubical to prismatic)	V	1.8 (0.9)	3.3 (3.9)	7.7 (6.5)	10.5 (8.8)	13.6 (10.4)	18.8 (13.1)	23.6 (15.1)	27.4 (18.4)	— 0.9	— 1.6	— 1.2	— 1.7	— 3.2	— 5.7	— 8.5	— 9.0
	VI	2.8 (2.7)	17.2 (20.5)	30.5 (38.3)	43.0 (54.4)	57.6 (72.8)	85.0 (108.0)	105.7 (133.7)		— 0,1	+ 3,3	+ 7.8	+ 11.4	+ 15.2	+ 23,0	+ 28,0	
	VII	8.0 (5.0)	18.0 (25.4)	26.4 (37.5)	34.0 (48.2)	41.9 (58.0)	55.3 (71.4)	68.3 (81.8)	81.4 (92.0)	— 3.0	+ 7.4	+ 11.1	+ 14.2	+ 16.1	+ 16.1	+ 13.2	+ 11.5
Profile of the forelands	VIII	11.1 (15.8)	57.3 (82.8)	109.6 (156.7)	161.6 (228.8)	210.0 (305.5)	259.8 —			+ 4.7	+ 25.5	+ 77.1	+ 67.2	+ 86.5	—		
	XV	15.1 (19.6)	52.9 (72.6)	80.7 (112.3)	107.7 (148.0)	137.8 (188.8)	187.0 (256.4)	211.6 (286.0)		+ 14.5	+ 20.3	+ 31.6	+ 40.4	+ 51.0	+ 69.4	+ 74.4	
	XVI	15.4 (19.4)	51.1 (68.7)	80.5 (105.0)	101.4 (136.9)	128.1 (174.2)	173.5 (234.6)	199.0 (265.9)		+ 4.0	+ 17.6	+ 24.5	+ 35.5	+ 46.1	+ 61.1	+ 66.9	
	XVII	20.4 (30.8)	54.5 (80.1)	77.5 (111.3)	96.9 (137.6)	118.3 (166.6)	— —	161.9 (218.6)		+ 10.4	+ 25.6	+ 33.8	+ 40.7	+ 48.3	—	+ 56.7	
	XVIII	9.6 (13.2)	42.0 (58.2)	62.9 (86.7)	76.6 (110.6)	94.1 (138.4)	116.3 (174,1)	127.0 —		+ 3.6	+ 16.2	+ 24.8	+ 34.0	+ 44.3	+ 57.8	—	
	XIX	26.8 (41.3)	132.2 (181.7)	217.4 (285.6)	246.9 —					+ 14.5	+ 49.5	+ 68.2	—				
Irreversible dried peaty clay (micro-clod structure)	XX	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)								

To explain these peculiarities the author supposes that the pores of the soil behave like a bundle of capillary tubes of an equivalent radius. It is known, that the velocity of capillary rise of liquids depends firstly on the capillary pressure, which is inversely proportional to the radius of the capillary tube, and secondly on the internal friction of the liquid, that is inversely proportional to the square of the radius and proportional to the length of the capillary tube and the velocity of flow (Poiseuille). It is to be expected that the speed of rise of water in crumbly soils is higher than in cloddy soils, because the former behave like a bundle of capillary tubes with larger diameter than the latter. This actually was found as shown in fig. 28.

The fact, that the surplus usually is positive, may be explained by the mechanism of the transfer of air from the adsorbed state into the free state.

When a gas is adsorbed, its density will be larger than that of the gas in free state. After the addition of a liquid some of the adsorbed gas will be removed. As a consequence, the gas will expand. Applying this to the described phenomena and remembering that soils do adsorb air (see: Alten and Loofmann, 1941), the volume of water, penetrating the capillaries, will be smaller than the volume of air removed by the water. So the surplus must usually be positive. The question remains, why this surplus in cloddy soils is smaller than in crumbly soils. The probable explanation is the following: A crumbly soil possesses pores, that form a honeycomb system, or in other words, all pores are connected with one another. When water penetrates the soil, the air can evade easily and no air-bubbles are formed. This causes a large positive surplus. In the case of a cloddy soil, however, in which the pores do not from a honeycomb system, air spaces may be sealed off by the water. Then the water enters the capillaries due to the capillary pressure, so that the air in them is compressed. So the number of air spaces, that are sealed off, determines the magnitude of the surplus. In case this number is very large, the surplus may become negative. In fairly loose soils the number of these pores will be small and in consequence the surplus is rather large.

In table 3 it is shown, that the surplus in the case of sandy soils is smaller than in the clayey soils of the same structural class. This can be explained by the fact, that the total surface of the particles in sandy soils is much smaller than in clayey soils. Therefore, in the former case, the amount of adsorbed air will be smaller than in the latter.

It might be remarked, that the surplus could be ascribed to the swelling of the soil colloids. Yet this phenomenon is not so important as to account for the surplus. In table 3, the soil of sample V, that gives a negative surplus, had been brought artificially in a crumb structure (sample II, table 3); in this state it showed a large positive surplus. The rate of swelling will be slightly greater in sample V (compact structure), because the experimental samples were of equal volume. In spite of this, the difference in surplus is in favour of sample II. For an exact determination of the porosity of soils in air dry condition, it is necessary to use apolar liquids, e.g. CCl_4. The swelling process is then eliminated. In the described method the use of CCl_4 gives difficulties, that can not be overcome.

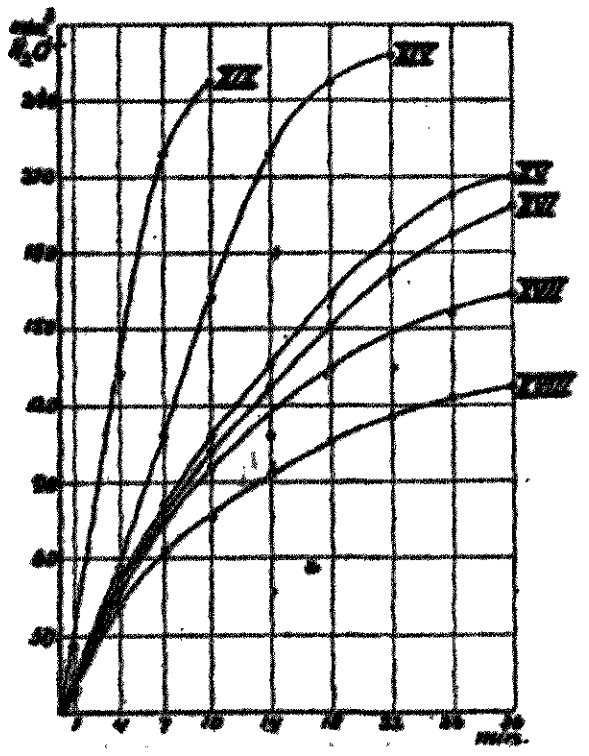
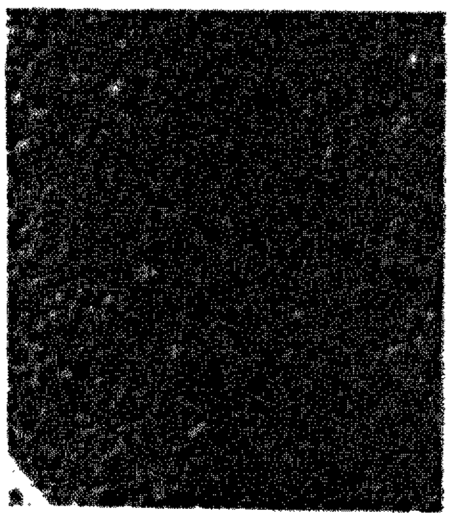


Fig. 30.

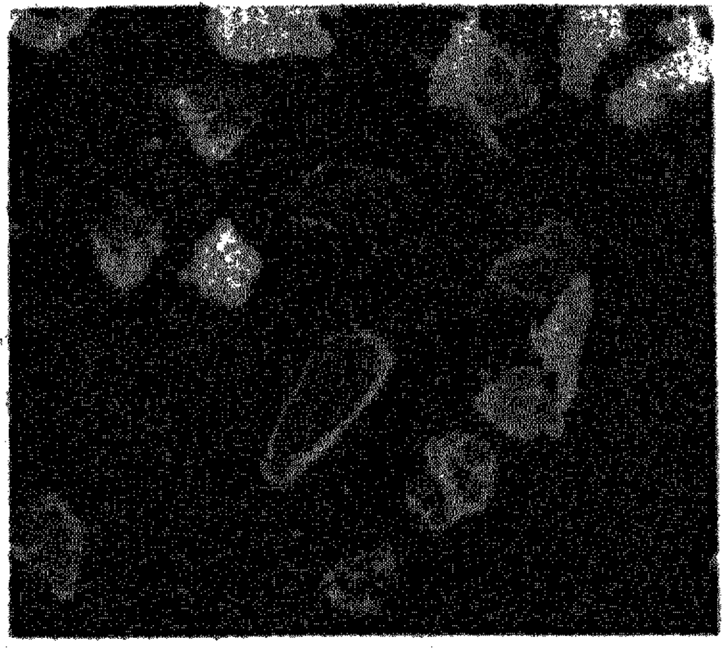
To measure the structure of a given soil, samples of the described dimensions are taken (see p. 24). The absorption of water and removal of air are determined and the results can be classified with the aid of figs. 28 and 29. As an example, results obtained with soils from the forelands (washlands along the Rhine, near Wageningen; composition of the profile described on page 25) are given in fig. 30. The graphs show, that the samples of this profile have a fairly loose structure except those of the layers 1 and 7, which are in a loose structure. Furthermore fig. 30 shows, that going down from layer 1 to 6 the structure becomes more compact, since the velocity of water-uptake is becoming smaller. So field observations and experiments correlate well. Therefore the author concludes that the suction-method makes it possible to detect differences in actual structure.

x Fig. 4. Soil in wet and dry state. Type of structure (platy) only to be observed in dry state of the soil.



x Fig. 6. Crumbs.

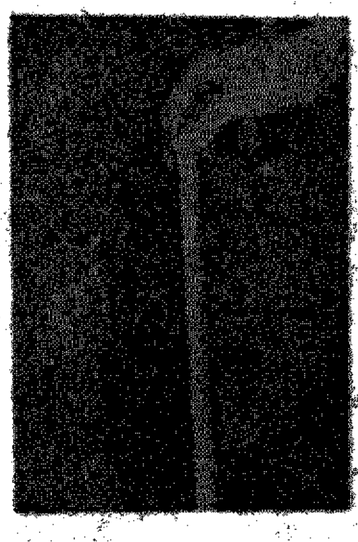
o Fig. 7. Lumps.



x Fig. 5. Grains.

o Fig. 8. Cubical structure.

o Fig. 9. Prismatic structure.



o Fig. 10. Bricklike structure.

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Fig. 11. Platy structure. x

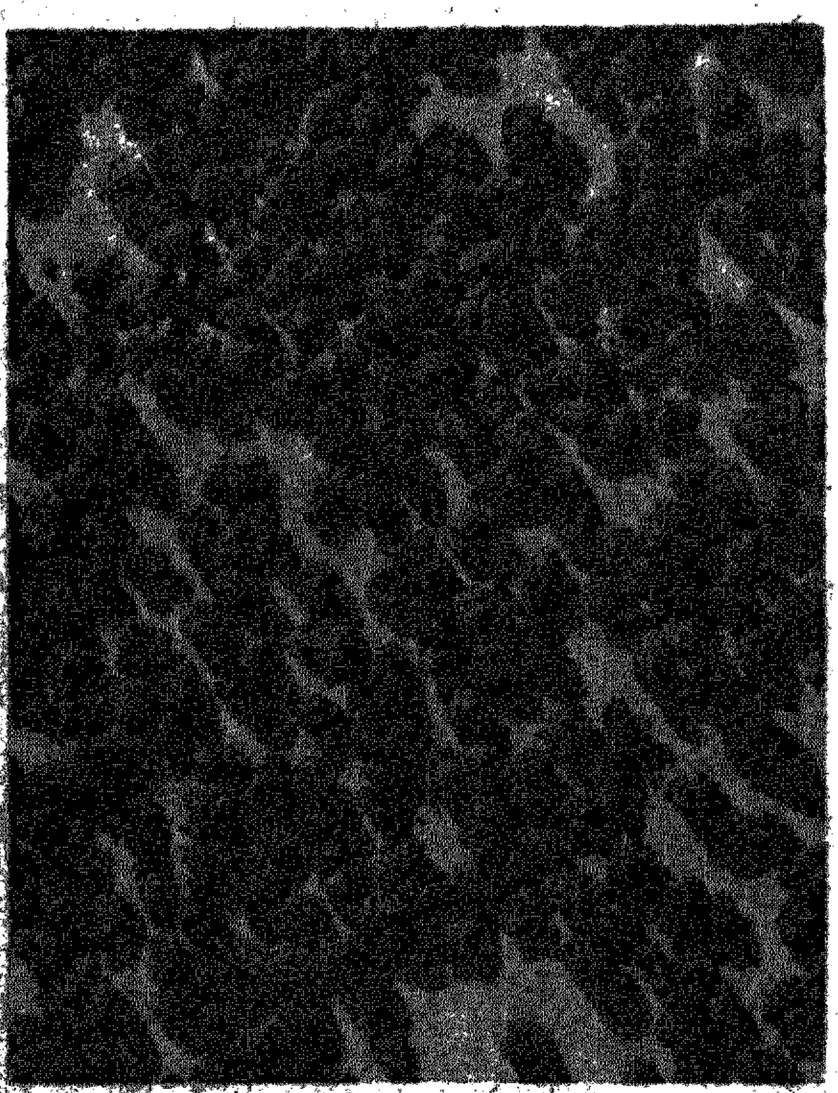
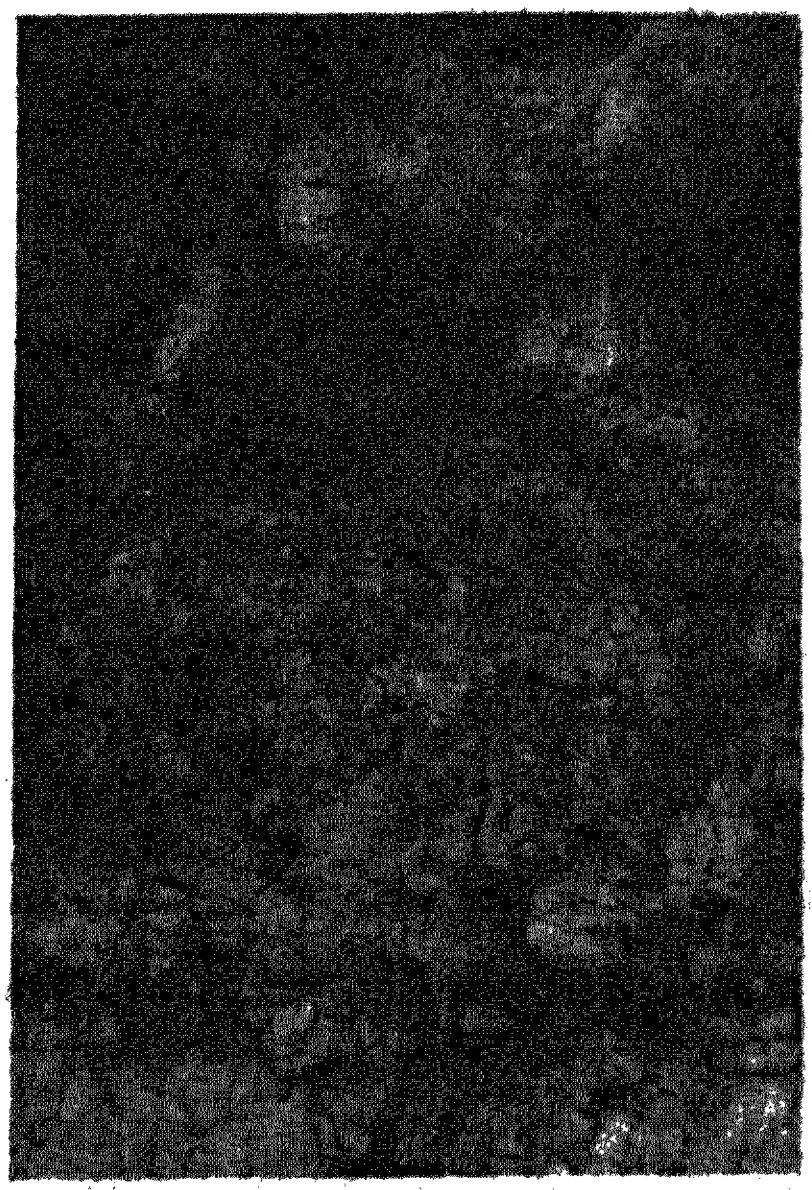


Fig. 12. Nutty structure. x



o Fig. 13. Profile with cubical, prismatic and brick-like structures.

Fig. 15. Compact structure. o

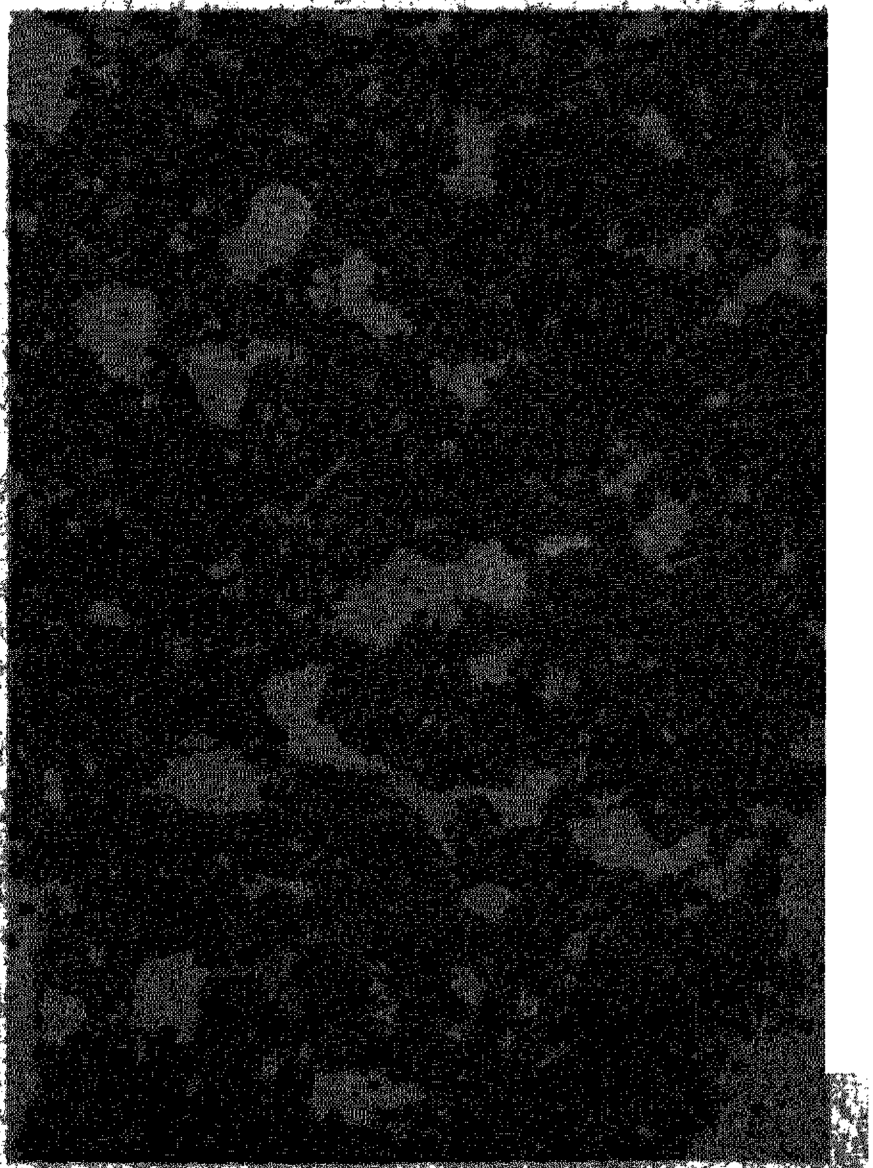


Fig. 16. Cloddy structure with holes. o

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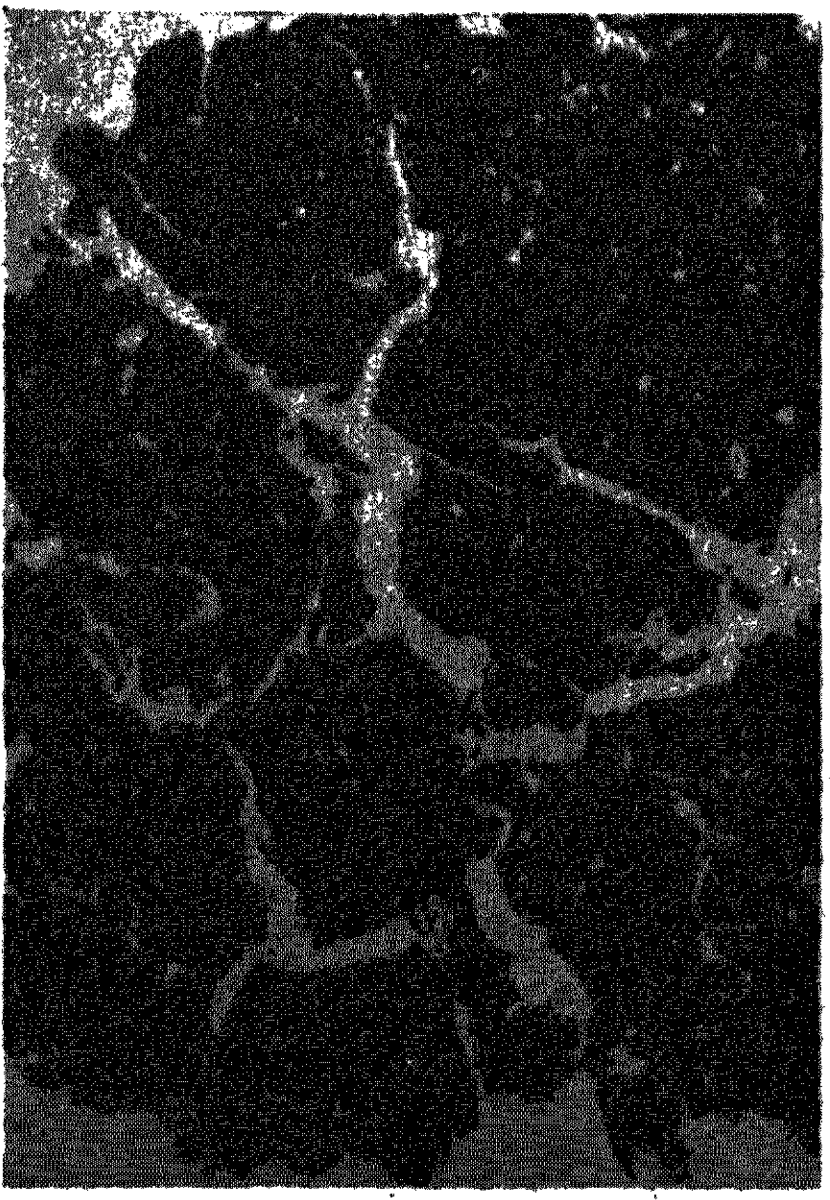


o Fig. 17. Cloddy structure with cracks.

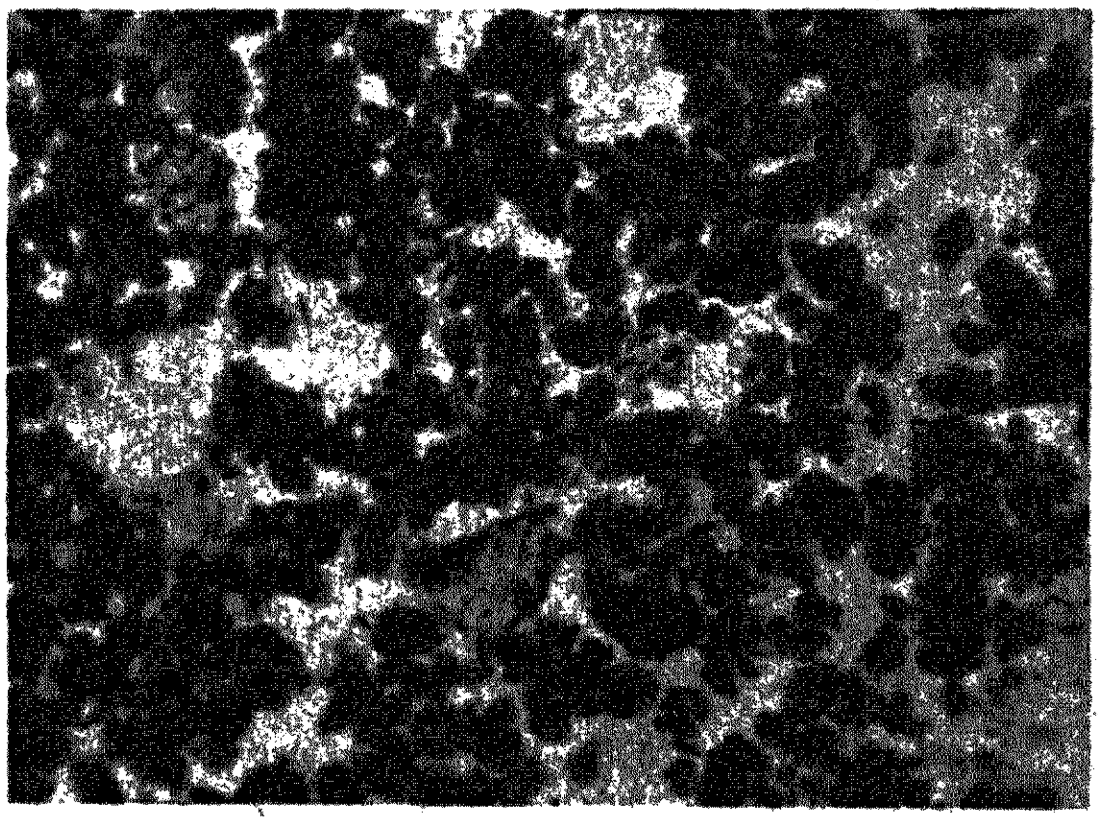
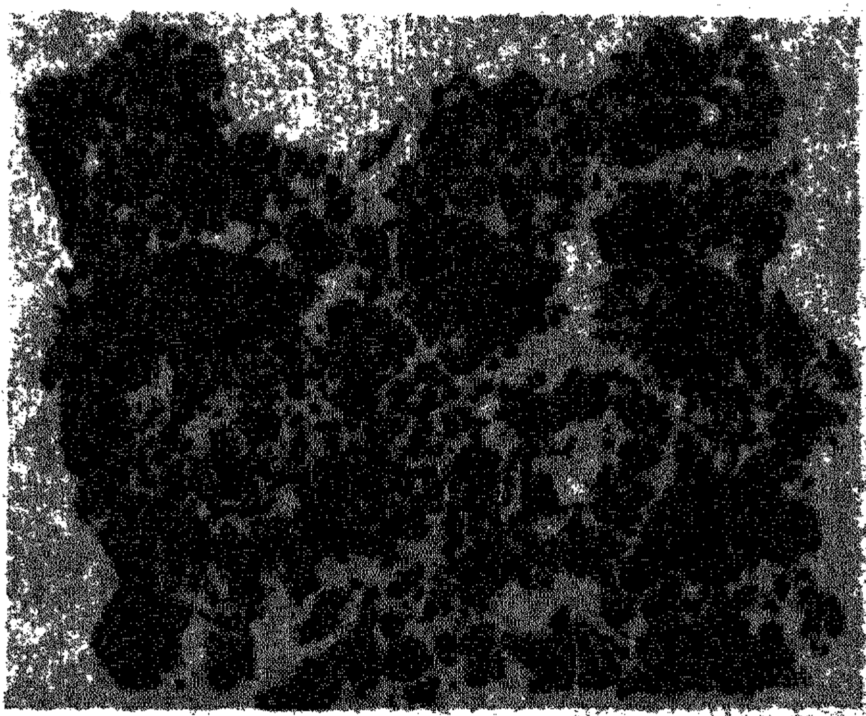


Fig. 18. Micro-clod structure. o



o Fig. 19. Crumb structure with some clods.

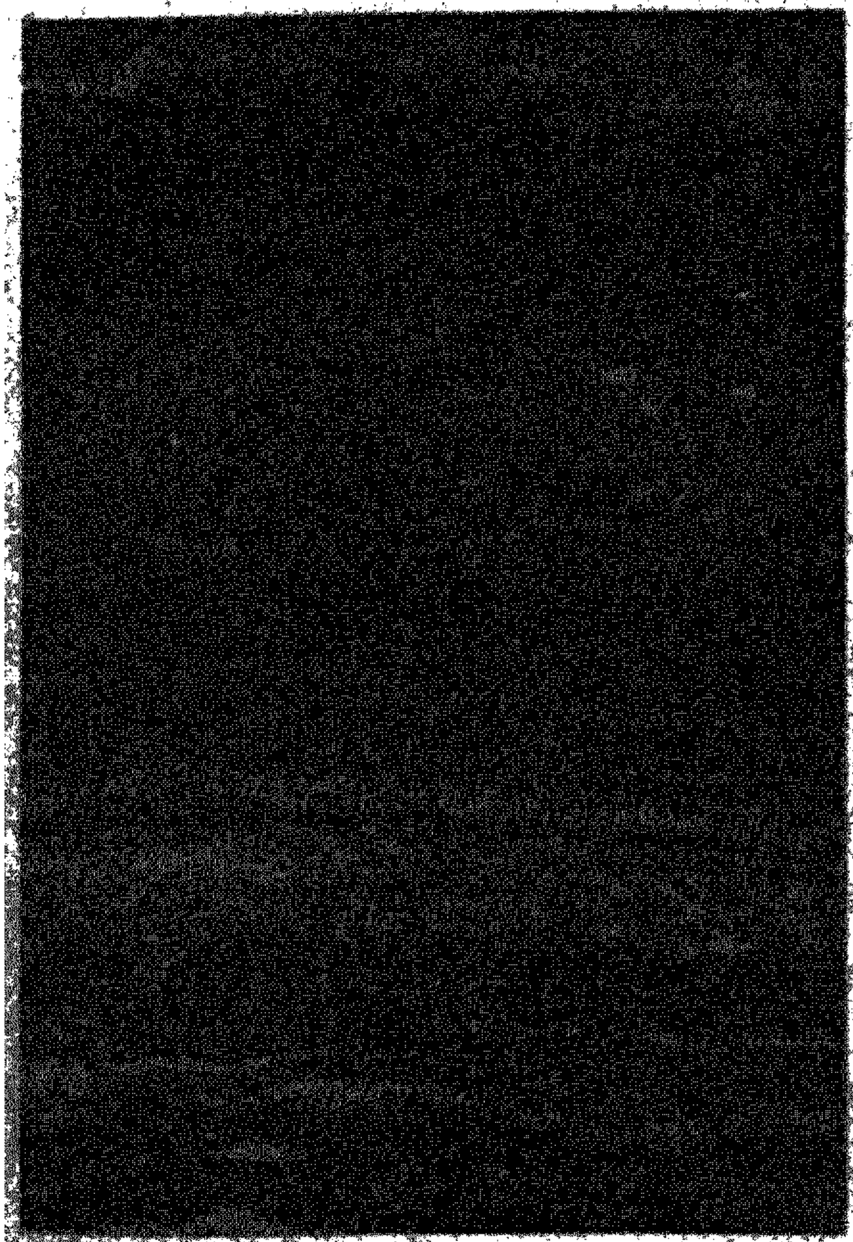


Fig. 20. Grain structure. o

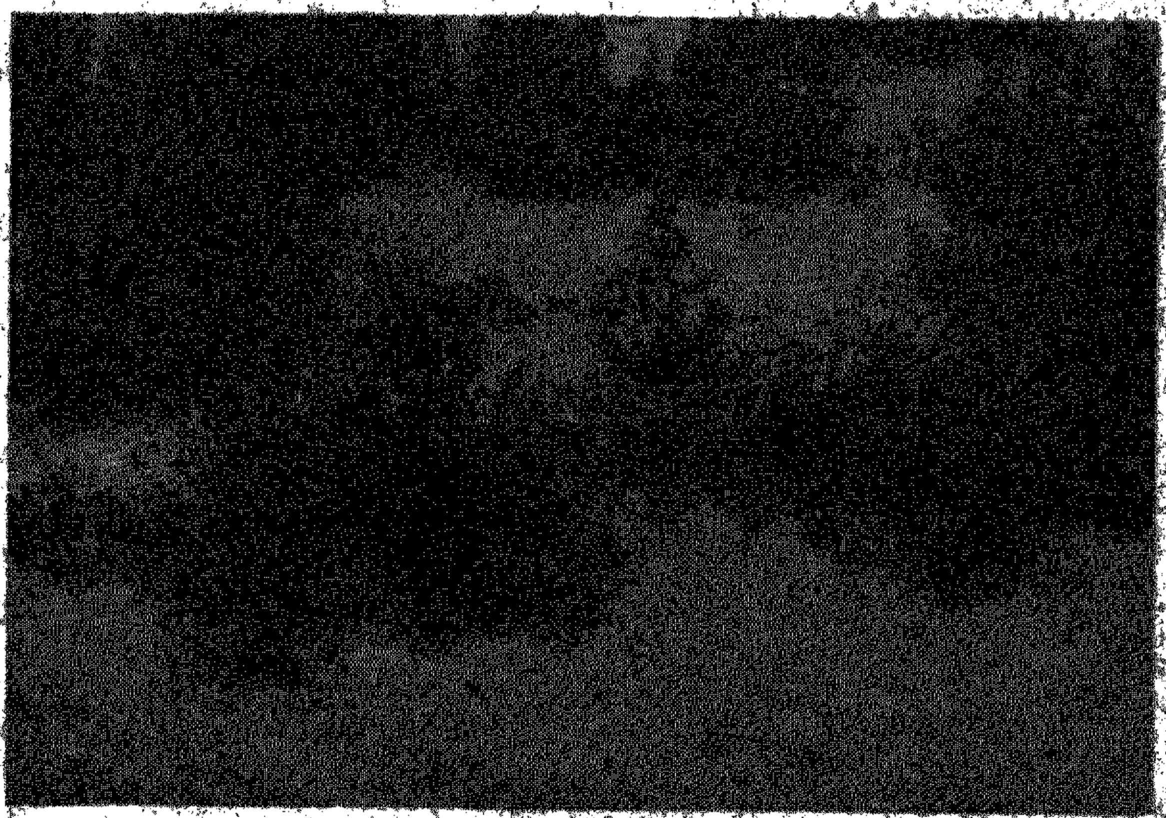


Fig. 21. Compact surface layer with weeds x
(Polygonum, Matricaria, Atriplex.)

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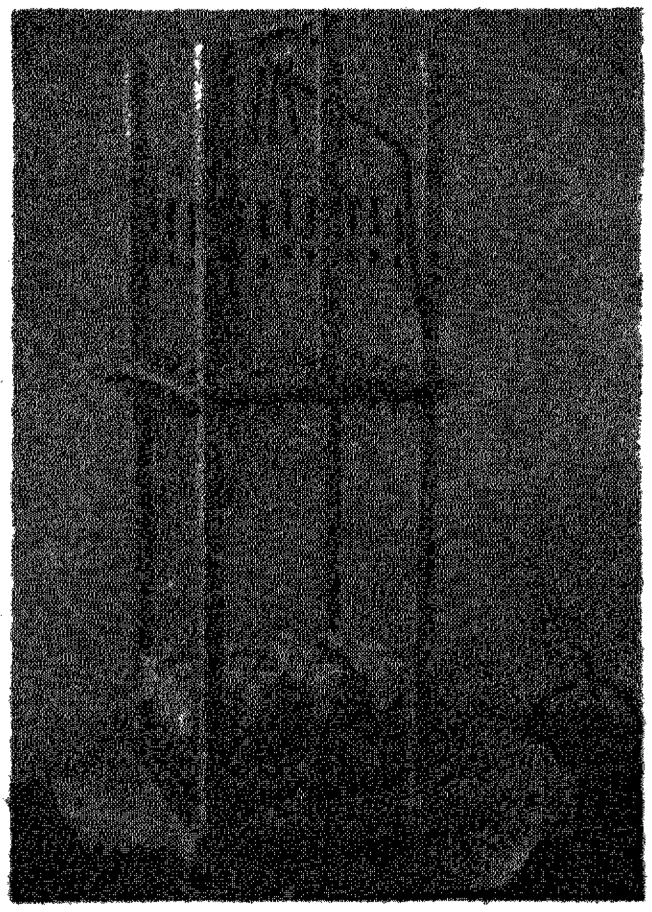
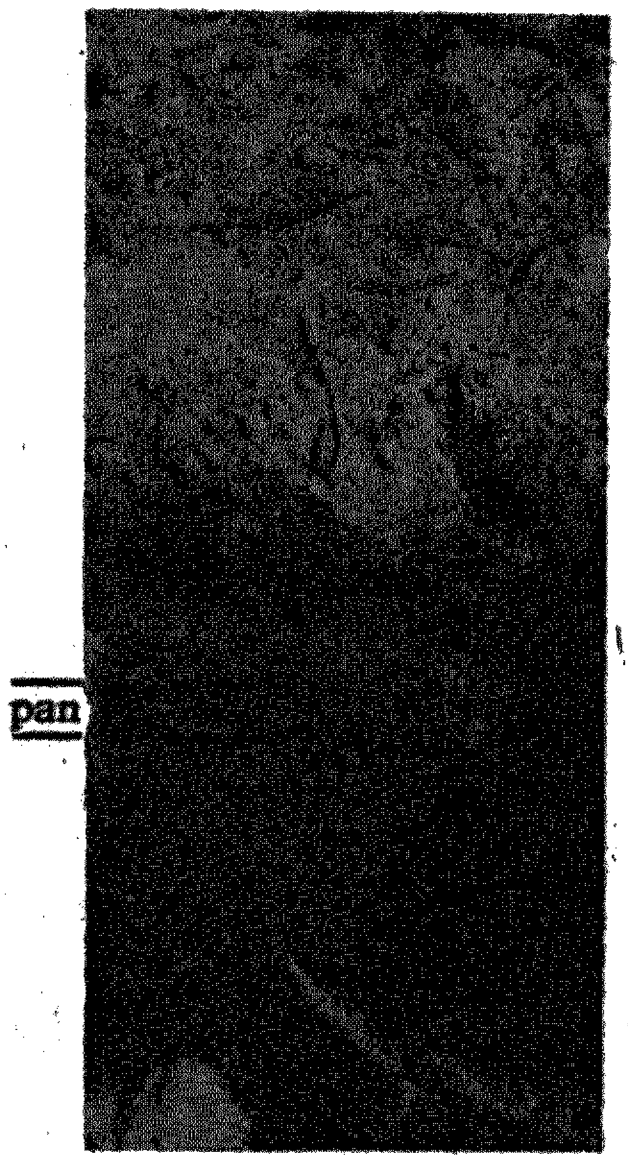


o Fig. 25.



x Fig. 22. Pan in subsoil.
Weeds: Triticum, Equisetum.

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CHAPTER III. THE FLOC-STRUCTURE.

§ 1. *General discussion.*

Because flocculation is a property of colloidal solutions or suspensions, it is clear, that flocculation phenomena play a part, that is becoming the more significant, the more colloidal materials are present in soil. The flocs resulting from coagulation of suspensions may have a different structure, this depending upon the way the flocs have been obtained. Therefore, in clay soils, the nature of the floc is of greater importance in soil structure than in sandy soils. In these latter other forms of aggregation prevail.

The flocculation of colloidal systems has been the object of extensive research. The problem has been treated in two ways, viz.: 1. Several investigators tried to elucidate the flocculating mechanism and to formulate it quantitatively (v. Smoluchowski, 1916, 1917; Comber, 1920, 1921/22; Wiegner and Tuorila, 1926; Tuorila, 1926, 1927; Wiegner and Marshall, 1929; Wiegner, 1932; Russell, 1936); 2. others tried to establish the structure of the flocs formed (Hilgard, 1879; Ehrenberg, 1918; Mattson, 1922; Freundlich and Sachs, 1929; v. Buzágh, 1931; Kovalevskaja, 1937; Moisseiev, 1937; Troelstra, 1941).

As the quantitative part of the flocculating mechanism is not to the purpose here, only the qualitative part will be discussed.

In the course of years it has been established that the properties and reactions of colloidal solutions may be brought back to properties and reactions, that are taking place in the interface of the disperse phase and the dispersion liquid. The interface is the place of an electrical double layer of the following origin: At the surface of the dispersed phase there are charged centres, resulting either by dissociation of ionogenous groups or by „adsorptive" attachment of special ions to the lattice; often it is impossible to distinguish between those cases exactly. Therefore the dispersed phase will be either electrically negatively or positively charged and consequently it will have a definite potential. The consequence is that ions of opposite sign of charge are attracted. Moreover a repulsion force, viz. the diffusion (as a consequence of the heat motion) acts on these ions. By the interaction of these forces the counterions will be arranged partly as a diffuse layer of ions some distance into the liquid (Gouy-layer), but partly also more firmly bound in the immediate vicinity of the surface (Stern-layer). The potential at different distances from the surface will be different therefore. The greater the distance the more the potential will approach the potential-level of the liquid (see fig. 31, drawn line). In reality the structure of the double layer is somewhat more complicated, but this does not matter for our purpose. The outer boundary of the water, inherent to the colloidal particle (v. Smoluchowski-layer) is a critical partition-plane. The potential at this point (ζ-potential) is of great importance in electrokinetic phenomena. (It has to be remarked, that the ζ-potential has been never measured directly, but has always been computed from theoretically derived electrokinetic formulae.) The ζ-potential determines the stability (in colloidal sense) of colloidal solutions and is determined in its turn by the shape of the potential-curve.

The shape of the potential curve is controlled by:

a. the surface potential;
b. the concentration (better: activity), valency, size, polarisability of the ions;
c. the nature of the adsorbing material, the cation exchange capacity, the site of adsorption;
d. the dielectric properties of the medium.

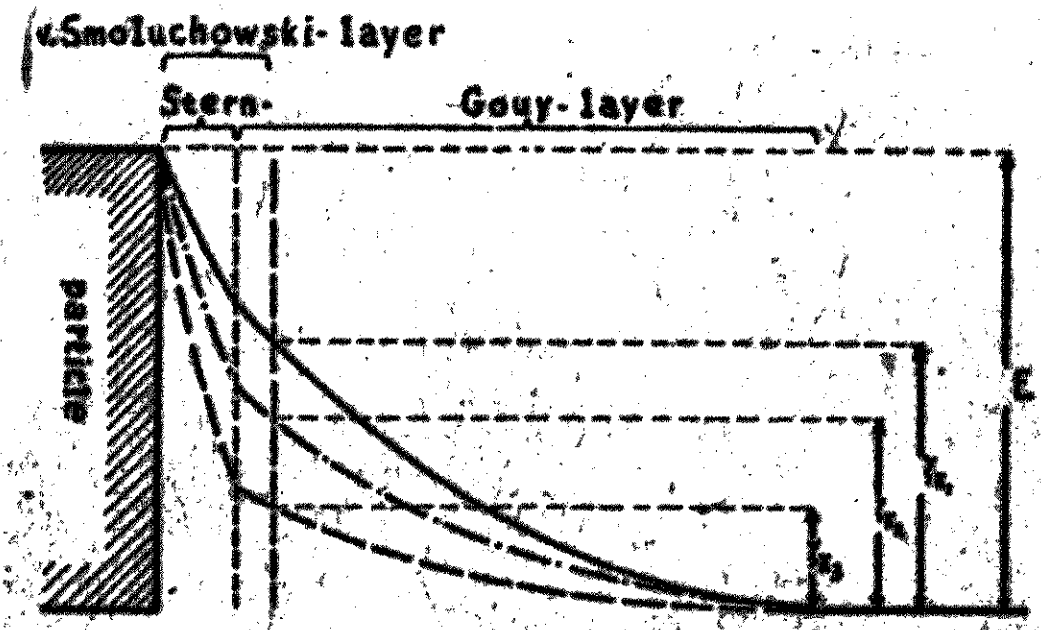

Fig. 31. Potential curves

In some cases the surface potential is dependent on the concentration (activity) of the potential determining ions (in the case of AgI-sol: Ag-, halide-, related complex ions) and has the character of a Nernst-potential. With respect to suspensions of clay minerals, the theoretical considerations of Vervelde (1946), building on the work of Mattson (1929a and b, 1940) and of Tendeloo, Vervelde and Zwart Voorspuy (1944a and b), seem to lead to the conclusion that the double layer potential in clay suspensions is controlled by practically all ions.

It is stated that all ions change the ζ-potential. The rate of this change depends on the adsorption. A divalent ion is electrostatically more strongly attracted than a monovalent ion. The concentration of both ions being equal, the potential curve, belonging to the divalent ion, will be more steep than that belonging to the monovalent ion (—·— and —··— line, respectively in fig. 31).

Now, these facts account for the mechanism of flocculation. Consider two particles of colloidal dimensions with equal charges and equal temperature. These particles are subjected to two forces: a. the electrical, repulsive, forces; b. the specific forces of attraction (London-v. d. Waals-forces). The former are the Coulomb-forces and are inversely proportional to the square of the distance between the particles and directly proportional to their charges; the latter are inversely proportional with the third to eighth power of the distance between the particles.

By decreasing the repulsive forces to such a degree, that the attraction forces dominate, there is a great chance, that, when the particles approach each other or collide as a consequence of the Brownian motion, they stick together and behave as an unity. The decrease of the repulsion forces may be attained by lowering the ζ-potential and this, in its turn, by e.g. increase of the concentration of electrolytes or replacing the counter-ions by ions of higher valency. The more the ζ-potential is lowered, the more firm the bond between the particles of the resulting floc will be.

§ 2. *The structure of the floc.*

Now the question arises: Is there any difference between the structure of a floc, resulting from coagulation of a colloidal solution under different conditions, e.g. performed with 1—1 electrolytes and with 2—1 electrolytes of different concentrations?

It was Ehrenberg (1918), who put this question theoretically and gave a hypothesis. Mattson (1922) elaborated the ideas of Ehrenberg experimentally. But it was Troelstra (1941), who investigated this problem exactly and directly. Though his conclusions, obtained with the AgI-sol, cannot be applied entirely to the suspensions of clay minerals, as the author could prove, it is nevertheless desirable to consider the work of Troelstra.

Troelstra investigated the structure of the floc in two ways, viz.: 1. by performing measurements of the extinction in flocculating systems; 2. by determining the sedimentation volumes.

The extinction exists in the absorption of light in the mass of the particles and the scattering of light (also called radiation) by the particles. The latter component prevails in the extinction by the AgI-sol.

By combining Rayleigh's law, indicating, that the percentages of light scattered is proportional to the number of particles and to the square of the volume of those particles (thus $I_s = Knv^2$, where I_s = the intensity of light scattered; n = the number of particles per unit of volume; v = the volume of the particles) with the theory of v. Smoluchowski, giving a quantitative estimation of the rapid coagulation, viz.: $T = \frac{1}{4\pi\varrho D n_0} = \frac{1}{\alpha n_0}$ (where T = the "specific coagulation time"; ϱ = the radius of the sphere of attraction; D = the velocity constant of the primary particles and n_0 = the number of particles originally present in the unit of volume), Troelstra obtained the relation:

$$(5) \quad \text{radiation}_t = Kn_0 v_1^2 (1 + 2\alpha n_0 t),$$

where radiation$_t$ is the scattering of light of a rapid coagulating system at time t, $Kn_0v_1^2$ the radiation of the sol at the moment of beginning coagulation and $2\,\alpha n_0 t$ is the relative increase of radiation, apparently proportional to t.

He was able to give a similar relation with respect to the extinction.

The derivation of these formulae is based on the suppositions, that : a. the particles are spherical ; b. they do not surpass a certain magnitude ; c. the primary particles fuse to a homogenous aggregate during coagulation ; d. the wave length of the incident light is large in respect to the particle diameter.

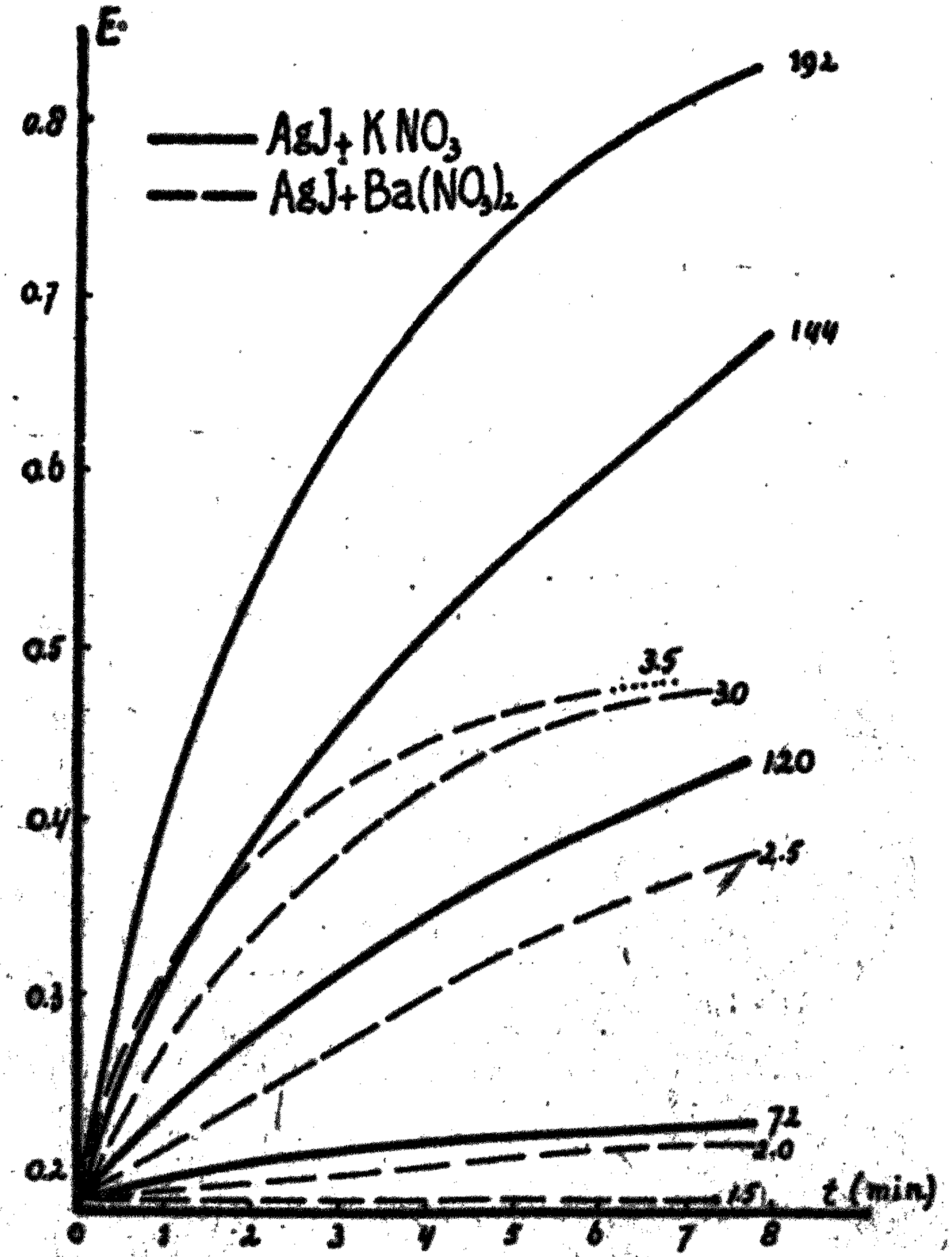

Fig. 32. E-t curves of the AgI-sol
Figures at the curves give the number of mmol of the electrolyte used. (Troelstra, 1941).

As indicated by equation (5) extinction will increase linearly during rapid coagulation. Thus the inner structure of the floc is not considered by this equation. However, it appears, that the E (extinction) — t(time) curves (figs. 32 and 33) are far from being linear, especially so in the case of a high concentration of electrolytes (rapid coagulation). In the case of slow coagulation (low electrolyte concentration) the extinction sometimes increases linearly with time. The cause of this phenomenon is the fact, that, during rapid coagulation, the aggregates have become so large after a very short time, that supposition b does not hold any longer. Therefore the linear relationship cannot be expected. Figs. 32 and 33 (where the extinction after a coagulation time of 5 minutes is plotted in dependence of the electrolyte concentration) show, that the optimal

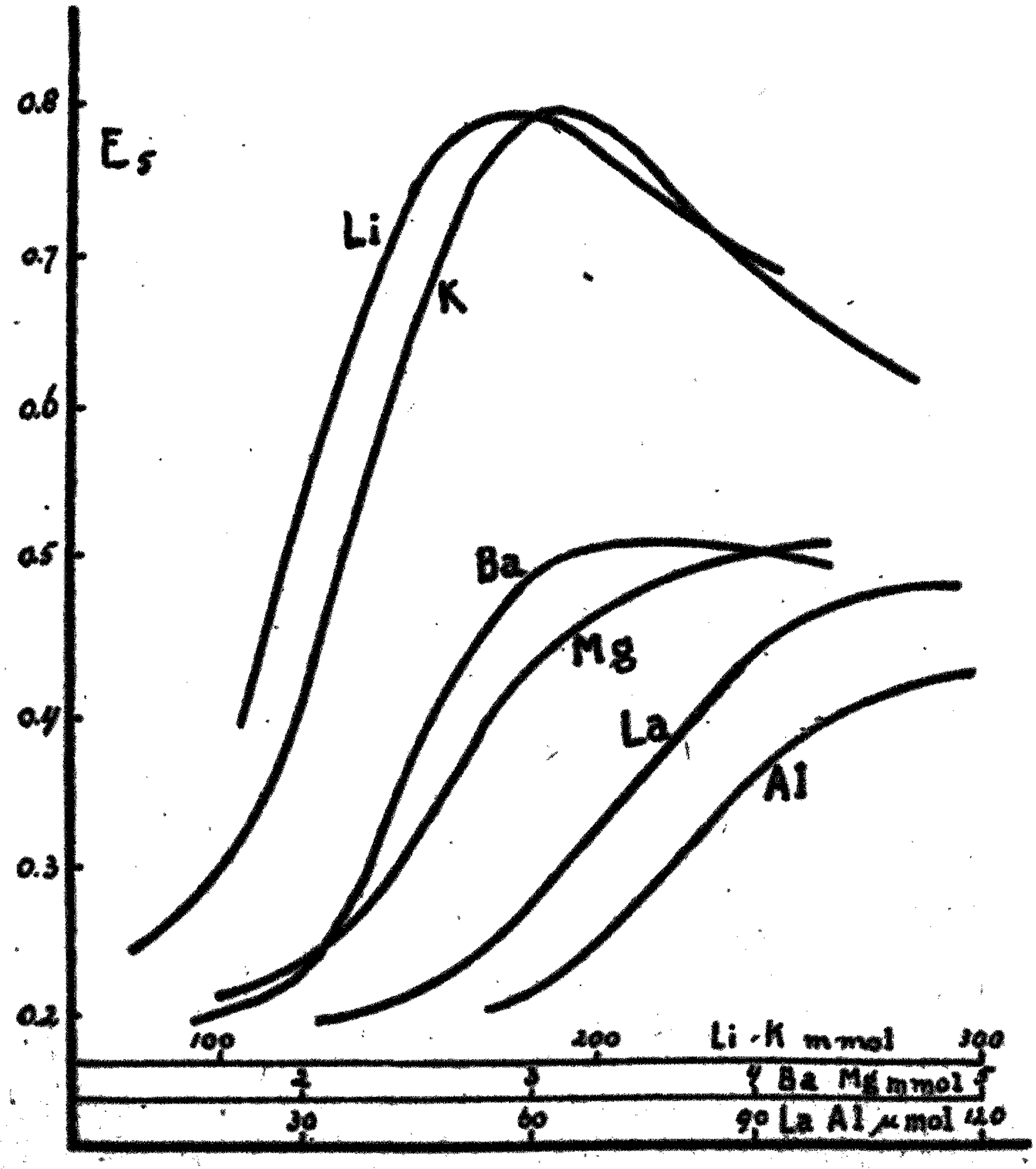

Fig. 33. E-c-curves. E after 5 minutes (Troelstra 1941)

extinction of the systems coagulated with monovalent ions is much larger than that of the systems flocculated with divalent ions. It is here that the structure of the floc comes into play.

According to Rayleigh it would be expected, that a k-fold particle (resulting from complete fusion of k primary particles) scatters k times more energy than k primary particles. However, flocs are things neither fused nor completely loose. They are intermediate between an entirely fused aggregate and the separate particles. Hence the floc has a smaller scattering capacity than has been derived in the theoretical considerations. Thus a closely packed floc should have a greater scattering capacity, and also a greater extinction capacity, than a loosely packed one. As shown by figs. 32 and 33, the flocs, obtained by coagulation with monovalent ions, have a greater extinction than the flocs obtained by flocculation with bivalent ions. Apparently, the former are more closely packed than the latter.

Troelstra verified his conclusions with measurements of sedimentation volumes. In the case of K-flocs the structure appears to be more compact than in the cases of Ba and Al flocs (see table 4).

Troelstra gives the following explanation with respect to these different floc-structures: Addition of electrolyte to a sol compresses the sphere of ions around each particle and this allows mutual contact. After coagulation, a very loose structure results by adherence of the primary particles, especially when the particles of the original sol are small. The firmness of this structure depends on the attractive forces, responsible for the adherence of the particles. In the case of flocculation with monovalent ions the cementation is a result of the specific (London-v. d. Waals-) forces and on many places shifting is possible.

TABLE 4.

Sedimentation volumes. A: height of the sediment after 20 min.; B: after centrifuging weakly; C: after centrifuging strongly.

150—300 mmol KNO$_3$		2—5 mmol Ba(NO$_3$)$_2$		1.5 mmol Al	
A	61.4	A	71.2	—	—
B	18.2	B	21.7	B	31
C	11.3	C	12.4	—	—
C in % of A	18.4	C in % of A	17.4	—	—

In the case of coagulation with polyvalent ions, these act — accumulated in the molecular condensator (Stern-layer) — as centres of attraction between particles and in this way they supply a supplementary force, that ensures cementation at all points of contact. The polyvalent ions act like "bridges" between the particles.

Ehrenberg and Mattson gave as early as 1918 and 1922 respectively, after flocculation experiments with quartz and clay suspensions, an explanation, that was principally the same.

It is clear, that, when the suspensions of clay minerals behave in a similar way as the AgI sol, a saturation of the adsorption complex in the soil with polyvalent ions will produce a porous structure. Yet, there are some experimental facts, that dispute this conclusion. Bradfield (1936) and Baver (1936) showed, that soils rich in Ca had a less favourable aggregate-analysis than soils poor in Ca; the Ca rich soils had a less resistant floc- and microstructure then the Ca poor soils. Further Visser (1941) reported in one of his statistical investigations that, by plotting out pore space volumes against the lime content of the soils, a larger pore space occurred in soils rich in lime than insoils poor in lime. Although this latter investigation is not so reliable as the former works, these statements are supported by several investigations, e.g. of Cleveringa, of Tyulin and Birjakowa (1933), indicating that liming gives an optimal result only when combined with organic manuring. This question will be discussed at page 47.

The experiments of the author, conducted with systems of clay minerals and with systems of pure sand and clay minerals, in some cases with addition of humates, are able to explain these discrepancies.

Two experimental methods were used: 1. measurement of the sedimentation volumes of the flocs; 2. measurement of the resistance to the impact of rain drops on aggregates, composed of mixtures of sand and clay minerals. Here the method of Vilenski (1934) was applied.

Method 1. The clay minerals used were kaolinite (Zettlitz), bentonite (Tixoton) and illite (Winsum), that had been dialysed. Of these minerals Na, K, Ba systems were prepared by suspending a definite amount in 2 ml water in haematocrits and flocculating with HCl, NaCl, KCl and $BaCl_2$ respectively in different concentrations and in mixtures of these electrolytes. The flocs settled in the calibrated, standardized part of the haematocrits and the volume was calculated from the height. Four hours after flocculation, the volume was determined. After that the haematocrits were centrifuged[1] and again the volume was measured. In this way the voluminosity and the resistance of the flocs against this pressure could be determined. The results are given in table 5 and 5a. Moreover, with bentonite and illite the same experiments were done with the addition of Na-humate (obtained by extracting a sandy soil with NH_4OH, dialysing the extract and adding NaOH up to a pH of 7). The results are given in table 5c.

Table 5 shows, that the figures (means of duplicates) fluctuate rather strongly (due to the difficult experimental technique) and that the concentration of the flocculating electrolyte has little influence on the volume of the floc (agreeing with the data of Troelstra, 1941). The latter phenomenon is to be expected, because the ζ-potentials of the particles in the different salt solutions are practically equal, except in the salt concentrations of 0.005 n or less (see fig. 34: the electrophoretic velocity of the

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[1] The flocs were centrifuged: a. during 1 min. at 750 r.p.m.; b. during 1 min. at 1850 r.p.m. and c. during 1 min. at 2750 r.p.m. with a radius of rotation of 12 cm. The centrifugal force was therefore: 0.12, 0.71 and 1.0 kg/cm^2 resp. The last force corresponds with the force exerted by a horse of 700 kg and a hoofsurface of 200 cm^2.

TABLE 5

mm^3 floc after	Na-kaolinite (5 mg/ml)						
	flocculated in NaCl solution of					Mean	II, III, IV in % of I
	0,005 n	0,015 n	0,03 n	0,04 n	0,05 n		
I	?	46.4	39.6	45.3	42.4	43.4	
II	?	19.7	18.5	18.5	16.5	18.2	41.7
III	?	16.9	15.4	16.3	15.3	16.0	36.9
IV	?	13.1	12.5	12.2	11.5	12.3	28.3

mm^3 floc after	K-kaolinite (5 mg/ml)						
	flocculated in KCl solution of					Mean	II, III, IV in % of I
	0,005 n	0,015 n	0.03 n	0.04 n	0.05 n		
I	46.6	50.3	44.0	45.4	51.5	47.8	
II	17.1	18.5	17.2	17.6	19.6	18.2	37.9
III	16.5	17.8	16.5	17.2	17.9	17.3	36.0
IV	12.5	12.9	12.3	12.9	12.8	12.7	26.7

mm^3 floc after	H-koalinite (5 mg/ml)						
	flocculated in HCl solution of					Mean	II, III, IV in % of I
	0.005 n	0.015 n	0.03 n	0.04 n	0.05 n		
I	48.6	49.7	51.1	50.7	47.1	49.6	
II	16.2	17.3	16.5	16.5	16 6	16.7	33.7
III	15.6	16.2	15.1	14.7	15.4	15.3	30.8
IV	11.3	11.3	11.3	11.0	11.5	11.3	22.9

mm^3 floc after	Ba-kaolinite (5mg/ml)						
	flocculated in $BaCl_2$ solution of					Mean	II, III, IV in % of I
	0.005 n	0.015 n	0.03 n	0.04 n	0.05 n		
I	46.6	47.5	44.8	43.5	49.4	46.3	
II	15.3	15.7	14.9	14.5	15.1	15.0	32.3
III	14.0	14.2	14.3	14.3	13.7	14.1	30.4
IV	10.6	10.9	10.9	10.7	10.1	10.6	22.8

mm^3 floc after	Na-bentonite (3 mg/ml)						
	flocculated in NaCl solution of					Mean	II, III, IV in % of I
	0,005 n	0.015 n	0.03 n	0.04 n	0.05 n		
I	?	8.6	8.2	6.9	9.8	8.4	
II	?	7.5	7.3	6.1	8.7	7.4	88.1
III	?	7.3	7.1	5.7	8.7	7.2	85.7
IV	?	7.0	6.3	5.3	7.9	6.6	78.6

mm^3 floc after	K-bentonite (3 mg/ml)						
	flocculated in KCl solution of					Mean	I IV in % of I
	0.005 n	0.015 n	0.03 n	0.04 n	0.05 n		
I	x	x	x	x	x	x	
II	x	x	x	x	x	x	
III	18.0	17.5	19.2	19.9	20.1	29.1	
IV	15.3	15.2	16.0	16.1	15.4	15.7	81.8

TABLE 5 (continued)

mm3 floc after	H-bentonite (3 mg/ml)						
	flocculated in HCl solution of					Mean	II, III, IV in % of I
	0.005 n	0.015 n	0.03 n	0.04 n	0.05 n		
I	7.2	10.9	10.3	12.1	10.6	10.9	
II	6.2	7.8	8.1	8.5	7.3	7.9	72.0
III	6.1	6.9	7.0	7.7	7.3	7.2	66.0
IV	5.8	6.3	6.7	6.9	6.5	6.7	61.0

mm3 floc after	Ba-bentonite (3 mg/ml)						
	flocculated in $BaCl_2$ solution of					Mean	II, III, IV in % of I
	0.005 n	0.015 n	0.03 n	0,04n	0,05 n		
I	17.6	17.2	17.6	18.2	16.0	17.2	
II	11.2	9.9	10.5	9.9	10.0	10.1	58.0
III	9.4	9.9	10.3	9.8	10.0	10.0	57.0
IV	8.7	8.5	8.5	7.8	7.3	8.0	44.0

? means that the first series appeared to be peptised, so that the volume could not be measured

x means that the flocs were so large, that theen did not settle in the calibrated part of the haematocrit. But after centrifuging they do.

I : the floc volume after 4 hours ; II : the floc volume after weak centrifugation during 1 min. (750 r.p.m.) ; III : the floc volume after stronger centrifugation during 1 min. (1850 r.p.m.) ; IV. the floc volume after strong centrifugation during 1 min. (2750 r.p.m.).

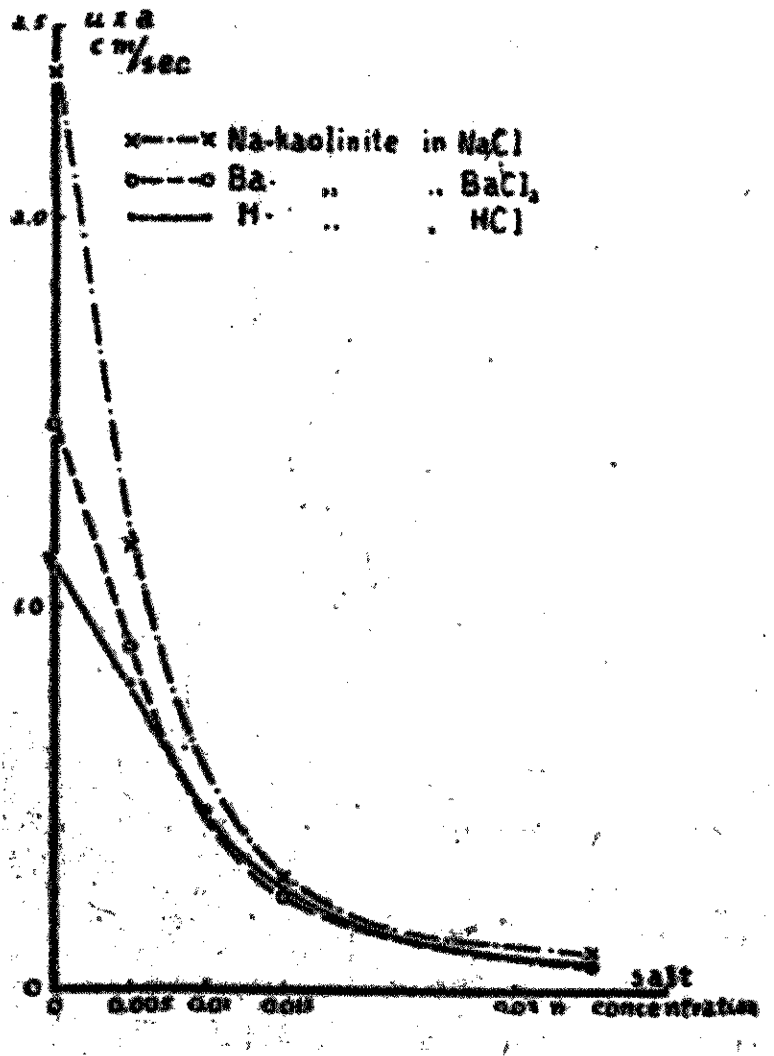

Fig. 34. Electrophoretic velocity of kaolinite in different electrolyte solutions.

particles is directly proportional to the ζ-potential). Therefore the means of the last four figures of each row are given in the last but one column of table 5. Moreover, in table 5a, the mean volumes with the mean errors are presented. It appears, that the results are sufficiently reliable for our considerations.

Secondly table 5 and 5b show, that the differences between the volumes of the Na-, K-, H-, and Ba-kaolinite flocs are much smaller than those of the corresponding bentonite flocs. The explanation of these phenomena will be given later on (see p. 48—51).

Thirdly it may be noted, that the Ba-flocs of bentonite, after centrifugation, have a greater volume than the Na-flocs, whereas in the kaolinite systems, the relation is reverse. This is possibly a result of the size of the particles (see p. 48—51).

Comparing the data of table 5 furthermore and also the figures

TABLE 5a

	Mean volumes ± mean errors	
	before centrifugation	after centrifugation
Na-kaolinite	43.4 ± 1.0	12.3 ± 0.2
K-kaolinite	47.8 ± 0.8	12.7 ± 0.1
H-kaolinite	49.6 ± 0.4	11.3 ± 0.1
Ba-kaolinite	46.3 ± 0.6	10.6 ± 0.1
Na-bentonite	8.4 ± 0.3	6.6 ± 0.3
K-bentonite	> 19.2	15.7 ± 0.1
H-bentonite	10.9 ± 0.2	6.7 ± 0.1
Ba-bentonite	17.2 ± 0.2	8.0 ± 0.1

given in table 5b (that gives the reliability of the differences between the sedimentation volumes), the volumes of the flocs of Na-, K-, Ba-, and H-kaolinite, before centrifuging, can be arranged in the order:

$$\text{Na-} \leqslant \text{Ba-} \leqslant \text{K-} \leqslant \text{H-floc};$$

but after centrifugation:

$$\text{Ba-} < \text{H-} < \text{Na-} \leqslant \text{K-floc}.$$

TABLE 5b

Reliability of the differences of the sedimentation volumes

kaolinite systems			
differences of the sedimentation volumes			
before centrifuging		after centrifuging	
Ba- minus Na-floc	2.9 ± 1.2	H- minus Ba-floc	0.7 ± 0.14
K- „ Ba-floc	1.5 ± 1.0	Na- „ H-floc	1.0 ± 0.22
H- „ K-floc	1.8 ± 0.9	K- „ Na-floc	0.4 ± 0.22
K- „ Na-floc	4.4 ± 1.3	Na- „ Ba-floc	1.7 ± 0.22
H- „ Na-floc	6.2 ± 1.1	K- „ Ba-floc	2.1 ± 0.14
H- „ Ba-floc	3.3 ± 0.7	K- „ H-floc	1.4 ± 0.14
bentonite systeems			
differences of the sedimentation volumes			
before centrifuging		after centrifuging	
K- minus Ba-floc	> 2.0	K- minus Ba-floc	7.7 ± 0.14
K- „ H-floc	> 8.3	K- „ H-floc	9.0 ± 0.14
K- „ Na-floc	>10.8	K- „ Na-floc	9.1 ± 0.3
Ba- „ H-floc	6.3 ± 0.3	Ba- „ H-floc	1.3 ± 0.14
Ba- „ Na-floc	8.8 ± 1.3	Ba- „ Na-floc	1.4 ± 0.3
H- „ Na-floc	2.5 ± 0.4	H- „ Na-floc	0.1 ± 0.3

Although Troelstra (1941) considers the values of the volumes after the last centrifugation to be a measure of the resistance of the floc-structure, the author of this work believes, that this is not quite correct and that it more exact to consider the

TABLE 5c

	Na-bentonite (3 mg/ml) in							
	0.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0375 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	10.1						26.0	
II	8.8	87.1					13.6	52.0
III	8.8	87.1					8.8	34.0
IV	7.9	77.9					7.3	28.0

	Na-bentonite (3 mg/ml) + 0.1% Na-humate in							
	0.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0375 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	169.0		170.0		173.5		190.0	
II	110.0	65.1	111.5	65.6	101.5	58.5	116.5	61.3
III	58.0	34.3	54.5	32.1	—	—	53.5	28.2
IV	—	—	—	—	—	—	—	—

	Na-illite (3 mg/ml in)							
	0.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0375 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	10.3		20.6		24.9		25.6	
II	9.0	86.0	12.2	59.2	12.4	50.0	13.3	52.0
III	7,4	71.0	9.8	42.2	8.7	35.0	8.6	33.4
IV	6.4	62.0	6.6	32.0	7.1	28.4	7.4	28.4

	Na-illite (3 mg/ml) + 0.1% Na-humate							
	0.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0375 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	66.0		90.5		105.0		104.0	
II	48.5	73.5	56.0	61.9	68.0	64.8	72.0	69.2
III	30.0	45.5	34.5	38.0	37.5	35.7	37.0	35.6
IV	—	—	—	—	—	—	—	—

	Na-soil (mg/ml) in							
	9.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0375 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	23.6		36.0		37.4		35.3	
II	18.2	74.0	22.1	61.3	20.7	55.3	20.6	58.0
III	10.6	44.0	10.3	28.6	10.1	27.0	9.9	28.0
IV	7.4	31.0	7.4	20.6	7.4	20.0	7.4	21.0

	Na-soil (3 mg/ml) + 0.1% Na-humate							
	0.05 n NaCl		0.0375 n NaCl 0.0125 n $BaCl_2$		0.0125 n NaCl 0.0373 n $BaCl_2$		0.05 n $BaCl_2$	
	mm^3	%	mm^3	%	mm^3	%	mm^3	%
I	59.5		72.5		76.5		78.0	
II	43.0	72.2	45.0	62.0	48.0	62.7	48.5	62.1
III	23.5	39.4	26.0	35.7	27.5	36.0	28.5	36.4
IV	—	—	—	—	—	—	—	—

I: sediment volume after 4 hours; II: that after weak centrifugation; III after strong centrifugation; IV after very strong centrifugation. % means II, III, IV in percentages of I.

values, obtained by expressing the sedimentation volumes after the last centrifugation as a percentage of the original volume, as a measure for the resistance of the floc-structure, provided this last volume is not the smallest possible one. Therefore, in the last column of table 5, the percentages after the first, second, and third centrifugation are given. It appears, that the corresponding values can be arranged in the same order; thus, the last percentage can be considered as a measure of the resistance of the floc-structure. Doing this, the same order is obtained as mentioned above, with the one exception, that now the Na-floc seems to be more resistant than the K-floc.

With respect to the volume of the Na-, Ba-, K-, and H- bentonites, the order is, before centrifugation:

$$\text{Na-} < \text{H-} < \text{Ba-} < \text{K-floc},$$

and after centrifuging:

$$\text{Na-} \leqq \text{H-} < \text{Ba-} < \text{K-floc}.$$

Taking the percentages as a measure of the resistance, the order

$$\text{Ba-} < \text{H-} < \text{Na-} < \text{K-floc} \qquad \text{results,}$$

this agreeing with the order, found in the kaolinite systems.

Summarizing, and leaving the K-systems out of consideration, it appears, that the volumes of the Ba- and H-flocs are larger than those of the Na-flocs, or, in other words, that the particles in the Ba- and H-flocs are more openly packed than in the Na-flocs. However, the resistance of the Ba- and H-flocs is smaller than that of the Na-flocs.

Again omitting the K-systems, the results before centrifugation agree with those of Troelstra (1941). Although Troelstra believes, on the basis of his centrifugation experiments, that he may conclude, that the Ba-flocs are built more firmly than the Na- or K-flocs in the case of AgI, this is questionable in the case of clay minerals. But even when the results of Troelstra are expressed as percentages, as is done by the author of this work in table 4, last row, it appears, that the Ba-floc is slightly less resistant than the K-floc (the K-systems behave like Na-systems in the case of AgI-sols), so that the agreement is now still more evident. Therefore the author thinks to be justified in believing that the conclusions of Troelstra are not quite correct as far as the firmness of the flocs is concerned.

Considering the flocculation experiments in mixtures of electrolytes and those with the addition of Na-humate (table 5c), the same tendencies can be observed as described above. Here also the Ba-flocs have a greater volume than the Na-flocs (e.g. Ba-bentonite, 26.0 mm^3, Na-bentonite 10.1 mm^3; Ba-illite 25.6 mm^3, Na-illite 10.3 mm^3; Ba-soil 35.3 mm^3, Na-soil 23.6 mm^3). Further it appears, that the greater the Ba$^{\cdot\cdot}$-concentration in the mixtures the greater the sedimentation volumes, in other words, the looser the floc-structure. The resistance against pressure also decreases. Furthermore it is notable that the volume of the soil systems, flocculated in 0.05 n $BaCl_2$ is a little smaller than in the mixtures of 0.0125 n NaCl and 0.0375 n $BaCl_2$. A great difference exists between the sediment volumes of Na-bentonite in 0.05 n $BaCl_2$ (viz. 26.0 mm^3, table 5c) and of Ba-bentonite in 0.05 n $BaCl_2$ (viz. 17.2 mm^3, table 5 and 5a). The conclusions may be drawn, that a small amount of Na is favourable to give a more porous structure to a Ba-floc and that appreciable amounts of Na-ions did not disturb the porous structure of the Na-Ba-flocs considerably.

The humate affects the floc-structure strongly. The volumes of the flocs are increased as compared with the systems without humates (e.g. Na-bentonite in 0.05 n $BaCl_2$ 26.0 mm^3 and Na-bentonite + Na-humate in 0.05 n $BaCl_2$ 190.0 mm^3; Na-illite in 0.05 n $BaCl_2$ 25.6 mm^3 and Na-illite + Na-humate in 0.05 n $BaCl_2$ 104.0 mm^3; Na-soil in 0.05 n $BaCl_2$ 35.3 mm^3 and Na-soil + Na-humate in 0.05 n $BaCl_2$ 78.0 mm^3). Also the sediment-volumes after centrifugation are larger than the volumes of the systems without humate after the corresponding centrifugation (e.g., Na-bentonite in 0.05 n $BaCl_2$ 8.8 mm^3 and Na-bentonite + Na-humate in 0.05 n $BaCl_2$ 53.5 mm^3; Na-soil in 0.05 n $BaCl_2$ 9.9 mm^3 and Na-soil + Na-humate in 0.05 n $BaCl_2$ 28.5 mm^3). The differences in the stability percentages are in the case of the mineral-humate-flocs much smaller than in the case of the mineral-flocs alone. This means that humus has a stabilising effect on the structure of the floc. The explanation of these results will be given later on (p. 50).

Method 2. The above mentioned results are supported by other experiments. The author prepared aggregates by mixing pure sand (diameter 250—500 μ and 105—150 μ) with Na-bentonite or with H-kaolinite; in some cases $Ca(NO_3)_2$ was added to flocculate the system and in other cases $NaNO_3$ (see table 6). These aggregates can be compared completely with the above mentioned flocs, because the same forces are active in the flocs as in the systems in discussion now. So there is an essential difference between the natural aggregates and these synthetic aggregates. Therefore these aggregates will be termed floc-aggregates.

TABLE 6

	resistance (mean number of drops)	number of aggregates
sand (250-500μ) + 30% Na-bentonite	17.3 ± 2.0	20
„ + 30% „ + $Ca(NO_3)_2$	7.0 ± 0.7	20
sand (105-150μ) + 30% Na-kaolinite	8.8 ± 0.3	20
„ + 30% „ + $Ca(NO_3)_2$	4.0 ± 0.2	20
„ + 30% H-kaolinite	4.0 ± 0.2	20
„ + 30% „ + $Ca(NO_3)_2$	4.5 ± 0.2	20
„ + 30% „ + $NaNO_3$	7.4 ± 0.2	20

The resistance of the floc-aggregates was determined with the drop method of Vilenski (1934). The results of some experiments are given in table 6.

It is evident that the Na-floc-aggregates have a greater resistance than the Ca- and H-floc-aggregates, both in the sand-bentonite and in the sand-kaolinite mixtures. Moreover this table shows that the sticking power of bentonite is larger than that of kaolinite. These results correlate perfectly with those of the floc experiments, supposing that the divalent Ca- and Ba-ions have an equal influence on flocculation.

Summarizing it may be concluded, that the Ca-, Ba- and H-floc-aggregates have a smaller resistance against mechanical forces than the Na-floc-aggregates, and therefore, according to the flocculation experiments, the Ca-, Ba-, and H-floc-aggregates have a more porous structure than the Na-aggregates.

The experiments of Peterson (1946), apparently performed in the same time with those of the author, lead to the conclusion, that seems to be opposite to those mentioned above. Peterson finds, that Ca-aggregates are more resistant than Na-aggregates. This discrepancy can be explained however from the difference in the experimental technique.

Peterson puddles his materials and so forces the particles into close packing. In other words he does not allow the systems to get a structure that is the result of the addition of electrolytes alone. That is, the Ca-systems are brought into a state, that the Na-systems have got directly. Peterson surely tries to undo the influence of the puddling process by alternately wetting and drying of the mass, but he cannot succeed in his trials, as will be shown in Chapter IV. Peterson only measure the attractive forces between the particles and it appears that these are in agreement with the theory.

On the other hand the writer of this work mixes the sand and the clay minerals in dry state, after which water is added gradually, under continuous stirring, until a kind of crumbling point is reached. Then, either the humate solution or $Ca(NO_3)_2$, $NaNO_3$ or both are added, so that the water content becomes so high, that the system flows. After that the water is evaporated at a temperature of 40° C, again under continuous stirring. Care is taken, that the stirring is stopped as soon as puddling is noticed. Then the evaporation of water is continued. When the systems are in a different structure, this is due to the electrolytes added. In this way the difference in resistance may be referred to a difference in the structure of the aggregates.

The second point, that contributes to the apparent contradiction of the results is the difference of the methods of measuring the resistance of aggregates. While Peterson uses the wet sieving method, the author applies the method of Vilenski. In the former case the dispersing action of the water prevails over the mechanical action and in the latter case mechanical forces prevail over the dispersion. Now it is more difficult for Ca-aggregates to be dispersed by water than for Na-aggregates. But Ca-aggregates are more sensitive to mechanical desintegration than Na-aggregates.

With respect to the systems, supplied with humates, the experiments of the author appear to give opposite results. The above mentioned mixtures were supplied with NH_4-humate (obtained in the same way as at the sedimentation experiments) in an amount of 0.1 % of the weight of the clay minerals. The aggregates are tested by the drop method of Vilenski. The results are shown in table 7.

TABLE 7

mixture	resistance
sand (250-500μ) + 30% Na-bentonite + 0.1% NH_4-humate	14.2 ± 1.2
„ + 30% „ + 0.1% „ + $Ca(NO_3)_2$	18.0 ± 0.4
sand (150-200μ) + 30% Na-bentonite + 0.1% NH_4-humate	19.4 ± 1.0
„ + 30% „ + 0.1% „ + $Ca(NO_3)_2$	33.2 ± 1.8
sand (105-150μ) + 30% Na-kaolinite + 0.1% NH_4-humate	5.7 ± 0.2
„ + 30% „ + 0.1% „ + $Ca(NO_3)_2$	8.4 ± 0.3

This table shows that, when a humate solution is added, the Ca-floc-aggregates are firmer than the Na-floc-aggregates, agreeing to the results of the flocculation experiments.

Before trying to explain these results, the author wishes to draw attention to the investigations of Bradfield (1936) and of Baver (1936). In the light of the experiments described it is understandable that under certain conditions the structure of soils rich in Ca is less resistant than the structure of soils poor in Ca and yet when the above mentioned workers had done porosity measurements, then perhaps they had found results to the effect that soils rich in Ca had a more open structure than those poor in Ca. This shows clearly once more how necessary it is to measure structure in several ways, because then alone it is possible to get a view in the different factors, controlling the structure of the soil.

Also the fact, emphasized by Cleveringa many times, that liming should be accompanied by organic manuring, and the experiments of Myers (1937) and Hudig and Siewertsz v. Reesema (1940) are supported by the experiments of the author. These results are important with respect to the grounds in the Netherlands, that have been inundated with sea water. This will be discussed in § 3 of this Chapter.

But also from a biological point of view the addition of organic matter to the soil is important. The activity of the biological factor is significant in structure formation (see Chapter IV), and, in its turn, the activity is influenced by the organic matter content of the soil and by the base status. Ca is the most important of the bases to regulate the pH, so that it is concluded, that organic matter and Ca stimulate the structure-activity of the soil; and the increased structure-activity leads to an amelioration of the actual and intrinsic structure of the soil.

With respect to the explanation of the results, it must be emphasized that there are three factors, that may determine the values of the sedimentation volumes, viz.:

a. difference in swelling of the clay minerals in the electrolyte solutions;
b. difference in ζ-potential;
c. difference in structure of the floc.

Because kaolinite does not swell or shrink appreciable, only in the bentonite and illite systems the swelling can play a rôle. Puri (1934) and Sideri (1936) have shown, that the saturation of the adsorbing complex of the soil with different cations does not effect the swelling of soils. However, Mattson (1932) and Falconer and Mattson (1933) mention, that the swelling of bentonite was larger in water than in solution of electrolytes. Furthermore they show that the swelling-decrease is increased with increasing valency of the cations. This being so, the case is imaginable, that the sedimentation volume of the Na-systems is larger than that of the Ba- or H-systems. This never is found by the author. When there is a difference in swelling, the difference in structure of the sedimenting flocs overlaps this phenomenon. This conclusion is supported by swelling data of bentonite in different salt solutions, given by Freundlich, Schmidt and Lindau (1932). According to these data, the difference of swelling of the bentonite systems, used by the author of this work, cannot exceed 0.8 mm^3.

The ζ-potential can influence the floc-structure. It determines the mutual repulsion of the particles. The greater the ζ-potential the greater the repulsive force between the particles and the smaller the resulting attractive force. The latter is the resultant of the specific attractive forces and the electrical repulsion.

When the remaining force is small, the structure of the floc is weak and will break down already under the weight of the primary particles. Because it is known, that the electrokinetic potential of Na-systems differs from that of Ba- or H-systems, it seemed appropriate to determine this potential in the electrolyte solutions, used in the flocculation experiments. Therefore the electrophoretic velocity of the kaolinite particles was measured and the results have already been given in fig. 34. This figure shows, that the electrophoretic velocity of the particles is very different. The velocity of the Na-kaolinite particles is greatest, followed by the Ba-kaolinite, in its turn followed by the H-kaolinite. The velocities are less in the salt solutions and approach to nearly equal values in the highest concentrations. Hence, the ζ-potential of the different particles is also equal in the higher salt concentrations; therefore, the difference in sedimentation volumes cannot be ascribed to a difference in ζ-potential.

The third possibility, viz., the difference in floc-structure remains.

With respect to this, the picture, as given by Troelstra (1941) is quite useful (see p. 38).

Probably, the remarkable action of K-ions on floc-structure can be explained by the adsorption of K by active surfaces, this being in an intermediate position between Na and Ba. A mixture of Na and Ba-salts should then have a similar influence on floc-structure; this is partly true (see p. 43). Further experiments are needed to elucidate this peculiarity.

The resistance of the flocs may then be interpreted in the following manner. The structure of the Na-floc is more compact than that of the Ba- or H-floc. Because clay minerals are platy materials, one may perhaps represent these structures in the way, shown in fig. 35. In the case of a Na-floc the plates are neatly arranged in packets (because the plates easily glide past each other), whereas the packets as a whole are fixed in more or less accidental positions by their weight. But in the case of Ca-flocs also primary particles may be fixed in random positions, so that a more open structure is obtained. Now it is understandable that the Na-flocs, having a more compact structure and larger frictional planes, may be more resistant against pressure and mechanical disruption than the Ba-flocs with only points of contact, i.e. small frictional planes.

Fig. 35.

The influence of the humus on the floc-structure is more difficult to be understood. It is possible to change the floc-structure by coagulating the systems with different ions, but also by changing the surface of the particles. Now it is known, that quartz and clay particles adsorb proteins (Lindau and Rhodius, 1934/35; Mattson, 1931; Ensminger and Gieseking, 1939), after which, a sufficient amount of protein being present to cover the particles completely, they behave like pure protein. It is known, that humus is also adsorbed by clay minerals (e.g. Demolon and Barbier, 1929; Myers, 1937; Sideri, 1938; Tyulin, 1938, 1942). The way in which humus is adsorbed is still obscure, because the structure of humus is unknown. However, it is an established fact for the adsorption of humus, that it is necessary to add humus in peptised state, so that it is mixed with clay homogeneously. After that the electrolyte concentration must be increased so far, that humus coagulates in a film around the clay particles. Only a very slight amount, viz. 0.1 % of the weight of the clay fraction (Hudig and Siewertsz v. Reesema, 1940), is required to surround the clay particles completely. Thus in this way the surface of the mineral particles can be changed. Now, Schachtschabel (1941) established that humus coated clay minerals adsorbed the cations quite differently. Percolating humus preparates and clay minerals with mixed solutions of Na- and Ca-salts and determining the ratio $Ca_{adsorbed}/Na_{adsorbed}$, it was found that this ratio was much larger in humus than in clay minerals. Thus, Ca is more strongly adsorbed by humus than by clay, or, in other words, the adsorption energy increases more in the case of divalent ions than in the case of monovalent ions. Likewise it is acceptable, that the "coagulation bridge" between particles coagulated with polyvalent ions, will increase to a higher degree than that between particles, flocculated with monovalent ions. So it may be imagined that a structure, as presented in fig. 35 (right) might bear a definite pressure now. Thus the result is obtained, that the Ba-floc has a firmer structure than a Na-floc and so will remain more open (see table 5c).

To this action may be added the one, resulting from the possible combination of humus with Ca, so that the bond between the clay-humus particles become very firm. Also the possibility, that the number of charged centres per unit of surface in the case of clay-humus particles is larger than in the case of the clay particles, so that Ca can form a larger number of "bridges" between the clay-humus particles, may contribute to a firmer structure of the floc.

For practice, the following conclusions can be drawn. One of the most important factors, that realize a good plant growth, is the loose structure of the soil with a high resistance against disruptive forces (see Chapter VI). This loose structure can only be obtained, when the soil colloids are in a flocculated state. Since, in practice, the Ca- and H-ions are the most strongly coalugating ions, it is necessary to supply the soil with these ions, in which Ca is preferred to H, because it gives a more open structure; moreover in the most cases Ca-salts are used to regulate the pH of the soil in a stage that is desirable for a good plant growth. From the viewpoint of floc-structure, it was shown that, as a rule, an acid soil has an open structure. Also with the aid of Na-salts a flocculated state of the soil colloids is possible, but then a very high salt cencentration is required, in which case plant growth is not possible. In this connection the ratio of, and the amounts of the ions present in the soil must be regarded too. It is an established fact, that this ratio is of great importance for several phenomena in and on the soil (Hudig, 1940; Schuffelen, 1940, 1944); this will probable be true in structure formation too; an indication may be found in the flocculation experiments in mixtures of electrolytes.

However, the resistance of the structure of Ca- and H-flocs is smaller than that of the Na-flocs, so that the conclusion seems to be obvious, that an open and resistant floc-structure cannot be realized at the same time. But here the organic matter of the soil can realise the apparent impossibility. The organic matter acts in two ways: 1. a part of the organic substances can surround the soil particles, if the conditions are favourable. In that case the structure of the Ca-flocs was more open than the Na-flocs and at the same time the Ca-flocs were the firmest ones; 2. moreover a part of the organic matter can feed, and therefore stimulate, the living soil organisms, that, in turn, affect soil structure in a desired direction (see Chapter IV).

These considerations lead to the conclusion, that liming in order to improve soil structure should always be accompanied by organic manuring. Or, in other words, if the manuring of the soil is neglected, this always deteriorate soil structure, also in soils rich in Ca. But also the danger exists, that after liming, causing a too high Ca-content, some humus substances become autoxidable and therefore disappear (**Hudig** and **Siewertsz v. Reesema**, 1940).

Finally the author will discuss the theories of **Russell** and of v. **Nitzsch** and **Czeratzki** with regard to crumb formation. According to the theory of **Russell** (1934, 1935, 1936) the crumb structure would only be obtainable in the case of a high ζ-potential. **Russell** supposes that water dipoles act like bridges between the negatively charged centres of the clay particles and the cations; therefore this theory requires the presupposition of a high ζ-potential because in that case the distance between clay particles and cations is large. This is given schematically in fig. 36. This picture probably holds in the case of cloddy structures. But a crumb structure can only be obtained when the soil is in a flocculated state, as is discussed in the preceding pages, or, in other words, when the particles have a low ζ-potential. Hence, the theory of **Russell** does not fit our vision.

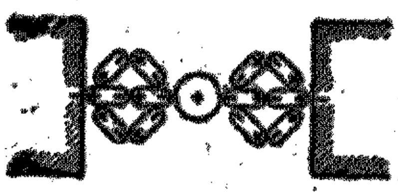

Fig. 36. Formation of aggregates according to Russell.

The theory of v. **Nitzsch** and **Czeratzki** (1941) is based on three "facts", these authors claim they have established, viz.: (a) water is not only adsorbed around ions, but is adsorbed also on the surface of the clay particles. This water would be packed loosely and have a low specific weight, viz. 0.2 to 1, according to the increasing distance from the wall of the particles; (b) the presence of positively and negatively charged centres on the clay particles is supposed, according to **Mattson** (1931); (c) large very polarisable anions may be adsorbed and may ameliorate structure, e.g. the phosphate-ion. The bond between two clay particles may be considered as follows: positive centre on clay particle — phosphate ion — positive centre on clay particle; but also: negative centre on clay particle — cation — anion — cation — negative centre on clay particle. Water dipoles may be included in these chains. In addition to the fact, that (a) is certainly erroneous (see p. 17) and point (b) is questionable in the case of clay minerals under natural conditions, it may be said that this theory as a whole is very unsound.

§ 3. *The saline soils.*

The reclamation of the saline soils is a major problem in many countries and it may be solved on the base of the principles, discussed above. With respect to their amelioration the saline soils may be separated in three groups: 1. alkali soils rich in $CaCO_3$ and Na_2CO_3, containing large amounts of water soluble salts (Na_2CO_3 and Na_2SiO_3) and also $CaCO_3$ in the upper layers. The content of exchangable Na is larger than 10 % ; the soil reaction is alkaline ; 2. alkali soils poor in $CaCO_3$, containing small amounts of $CaCO_3$ and water soluble salts in the upper layers. The soil reaction is nearly neutral ; 3. saline soils, containing much NaCl ; the reaction is weakly acid to neutral.

Generally the saline soils are in a very poor physical state. The very poor water conditions and the compact structure of the soil are the most important characteristics. The soils become pitch-like at a small water content, whereas, the water supply becoming larger, they swell enormously. Being under water the soil colloids peptise. On drying they become very hard and the dehydrated soil colloids shrink, so that broad and deep cracks are the result. Such a soil is represented in figs. 37 a and b.

Fig. 37a. Walcheren after the inundation. x

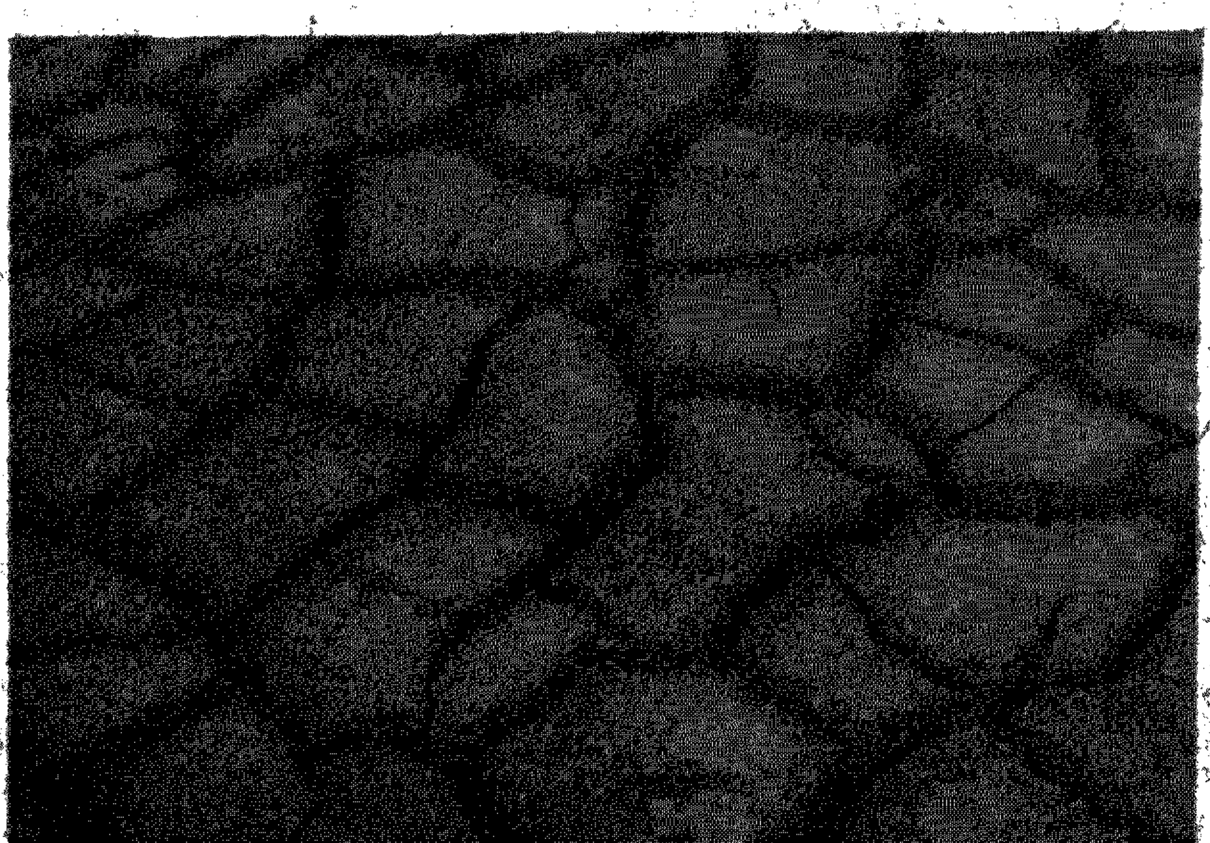

Fig. 37b. The soil in detail. x

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x Photo author.

The reclamation of the saline soils embraces the three following points:

1. Regulation of the ground water level. In order to allow the soluble salts to percolate through the soil the ground water level must be lowered and the soil well drained. An excess of precipitation over evaporation is required; in arid climates (evaporation larger than precipitation) irrigation is the only remedy.
2. Maintenance of the possible flocculated state of the soil colloids. This flocculated state being absent, the soil colloids must be coagulated. Here, the Ca- and H-ions play the most important rôle, because they coagulate already in small concentrations and give the most porous floc-structure.
3. Application of organic manure, leading to a more loose and more resistant structure. The addition or organic matter requires tillage of the soil. This has the danger that a possible open structure may be destroyed (Mayer: see Ehrenberg, 1918; Swaving, 1899) and that soil rich in salts is ploughed up. However, this danger can be reduced by the sowing of lucern. Then only shallow tillage operations are necessary in order to prepare the seedbed. The soil lays down in lucern during a few years, thus bringing organic matter in the soil (roots and falling leaves) without the requirements of tillage operations. These facts could be observed clearly in our province Zeeland. The secondary, favourable effects of the lucerns are the breaking of the shock by the impact of raindrops, the decrease of dessiccation by the shadowing leaves, etc. (see Chapter IV).

Point 2 can be realized in several ways. The first group of saline soils should be treated with sulphuric powder (de Sigmond, 1927; Thomas, 1927; Kelley and Arany, 1928; Kelley, 1937; Arany, 1943). By microbial activity H_2SO_4 is formed, that reacts with Na_2CO_3 of the soil and forms Na_2SO_4 and $NaHCO_3$. The alkalinity is decreased in this way. $CaCO_3$ is converted into $CaSO_4$ and $Ca(HCO_3)_2$ and the Ca-ions enter the soil solution. After-that the Na-ions are displaced by Ca in the adsorbing complex, so that the soil particles flocculate.

In some cases H_2SO_4 or HNO_3 is added to the soil, since the conversion of S into H_2SO_4 by microorganisms is rather slow.

Also ferric or aluminium sulfate may be added. Hydrolysis occurs and free sulphuric acid is liberated. This H_2SO_4 again reacts with Na_2CO_3, etc.

$$Al_2(SO_4)_3 + 6Na_2CO_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3Na_2SO_4 + 6NaHCO_3.$$

The aluminium and ferric hydroxides may give the disadvantage in some cases, that they clog the pores in the soil, thus hindering the percolation of the other substances. This difficulty is only important in heavy soils.

Dressings of $CaSO_4$ are very commonly used. $CaSO_4$ also decreases the alkalinity:

$$Na_2CO_3 + CaSO_4 \rightarrow Na_2SO_4 + CaCO_3.$$

Moreover Ca of the $CaSO_4$ may replace Na in the adsorbing complex.

A method, only used in Hungary, is the following : Primarily the water table is lowered. Then the soil is covered with a layer of pure sand and this sand is mixed with the upper layer of the soil. After that a considerable amount of farmyard manure is added and ploughed in. By lowering the water table and mixing the soil with sand better percolation, better aeration and decrease of the salt content result. Then the farmyard manure can be oxidized easily, so that HCO_3- and H-ions are formed. The alkalinity decreases in this way and $CaCO_3$ may dissolve, etc.

The amelioration of soils of the second group may take place by adding farmyard manure and limestone or melasse. The organic matter forms HCO_3- and H-ions, so that Ca dissolves, thus improving the physical properties of the soil.

The third group includes soils formed by flooding with sea water. The inundated soils in the Netherlands are examples. Analysing the behaviour of the seawater flooded soils according to the conceptions, developed in this Chapter, the following remarks can be made. During the inundation, an important part of the adsorbed Ca-ions were exchanged for Na- and Mg-ions of the seawater, thus giving rise to an easily peptisable Ca-Na-Mg-soil. However, the process takes place at high salt concentrations, that is, at a low ζ-potential. Therefore, peptisation does not occur directly, and it is to be expected, that the floc-structure does not change materially, because, generally, there are no mechanical forces destroying the soil system. After the running dry of the soils a well flocculated system is found. However, the washing out of the salts results in a lowering of the salt concentration, so that the ζ-potential of the particles increases ; the soil becomes peptisable. Moreover, the Na-soil hydrolyses thus increasing pH and, in turn, peptising the soil still more. The mechanical force of the beating raindrops and the percolating water are now sufficient to destroy the structure. In order to prevent this, addition of $CaSO_4$ is most suitable. It is sufficiently soluble to maintain the flocculated state and, on the other hand, it solves so slowly, that a continuous exchange of Na-ions by Ca-ions is possible ; moreover, the change of being drained off is very small. In this wayt it is possible to restore the original floc-structure of the soil before inundation. It is clear that tillage operations during these processes should be avoided.

CHAPTER IV.
THE MICROSTRUCTURE.

After the discussion of the factors determining the floc-structure, the author will describe the factors influencing soil micro-structure, defined in Chapter I as the structure of the aggregates.

§ 1. The factors mentioned in Chapter III may be of importance for the formation of micro-structure. In floc formation the following forces were found to be important: a) the specific attraction forces (in the case of of Ca- and H-flocs enlarged with the extra sticking force, see p. 38) and b) the weight of the primary particles. When the former are small and/or the latter large, a dense floc results. Now, because the weight of the flocs will be much larger than the attractive forces (influenced by the coagulating ions), these latter do not play a rôle in the formation of aggregates (micro-structure). Probably they are of importance if humus is present around the mineral particles because in that case the attractive forces have a considerably higher value, as has been shown in Chapter III.

§ 2. *Tillage.*

The tillage of the soil influences the micro-structure in an indirect way. However, since these tillage and cultivation operations are intented to reduce the larger clods and to increase the non-capillary pore space, these manipulations play a more important rôle in the formation of the macro-structure. Nevertheless they may be important with respect to the micro-structure, especially when a proper water content is chosen for the moment of the tillage operations. This factor will be discussed not here, but in Chapter V.

§ 3. *Frost.*

Frost influences the micro-structure directly. Given (1915), Wiegner (1927) and others emphasize the indirect action, viz. the increase of the concentration of the soil solution by the freezing of the water; whereas Mitscherlich (1913) and Jung (1931, 1932, 1937) think that the frost acts only mechanically on soil structure. Ehrenberg (1928) considers both aspects of this factor.

Already in 1915 Given stated, that soils, that had been frozen with liquid air had a more compact structure (had very fine capillaries) than soils, that had been frozen with a cold producing mixture, particularly if Ca-salts were added previously. Wiegner

(1927) studied the frost action too. He traced the decrease of dispersion of soil suspensions, either freed from electrolytes or not, after freezing. It appeared, that a decrease of dispersion occurred only in the case of the original soil suspension. In the electrolyte-free suspension freezing did not cause any decrease of dispersion, but it did after re-adding electrolytes. Wiegner concluded that the cause of the frost action had to be sought in the increase of the concentration of electrolytes in the soil solution.

Mitscherlich (1913) considered the frost action from another point of view. It is known, that soil water is held longest and firmest in the more narrow capillaries and pores, as here the smallest and most strongly curved menisci occur. In very compact clods the water is held longest. When this water freezes, the pores become larger because of the increase in volume of water, when it is changed from the liquid into the solid state. To make this favourable expansion possible, room must be made beforehand. Therefore the soil should be ploughed before the frostperiod. The mechanism proposed by Mitscherlich is, according to Jung, too simple, as will be shown in the next section. Moreover another mechanism is possible. Freezing results in a solidification of the outer wall of the aggregates. As a consequence, the interior of the aggregates is compressed and the aggregate may break up into smaller units.

It was Jung (1931, 1932, 1937) who established this mechanical action of the frost exactly. To eliminate the influence of electrolytes he washed the soil with water. After that he frose the soil samples at different temperatures, viz. from —10°C to —190°C (liquid air) and stated that at the highest freezing temperatures (0 to -10°C) the best desintregation was attained. But from —78°C Jung did not find aggregation at all. So the aggregation is not based on the expansion of soil water by the transition into the solid state alone, for this change in volume occurs at all low temperatures. The explanation can be found in the speed of cooling. If the cooling is rapid (below — 10°C) the water solidifies in large numbers of small crystals; the soil mass becomes rigid throughout. Slow cooling (0 to —10°C) brings about large crystals, pressing, according to their size, the soil grains to larger or smaller aggregates. These observations led to the conclusion, that the change in aggregation of the soil by freezing is dependent on the way and nature of crystallization of soil water.

The water content at the moment of freezing plays a rôle also. The larger the water content, the larger the crystals may be and the more the soil mass is pressed. Jung showed, that at full water capacity of the soil sample and at —78° C just visible crystals are formed. This can be explained from the binding intensity of the liquid molecules since the forces of attraction between the soil grains and the water molecules are greatest on the surface of the grains. They decrease with increasing distance from the surface and cease to exist at the point, where the adsorption forces and the forces brought about by heat motion are in equilibrium. Upon cooling the soil slowly, the "tension-free" water will crystallize first and not before lower temperatures are reached, the more firmly bound water will crystallize ; the crystallization of ice proceeds until the attraction forces are in equilibrium with the forces, that press the water molecules into the ice crystal. So at a slow rate of freezing the crystallization originates from the relatively small numbers of growth centers, that are formed in the tension-free pore space. These factors do not play a rôle in the case of rapid freezing ; the bulk of the water, just because of the high rapidity of cooling, solidifies in its entirety. In the case of water being present in a quantity, representing half of the water holding capacity, the loosely bound water disappears, so that a considerably smaller number of water molecules have the possibility to escape from the binding forces of the soil grains and to crystallize.

So Jung concluded, that the aggregation of the soil grains by the frost action is connected closely with the crystallization mechanism, which in its turn is determined by the rapidity of cooling, the water content of the soil and the surface of the soil particles (see also: Erikson, 1942, and Torstensson and Erikson, 1942).

Because temperatures lower than —10°C are rare in our countries, the action of slow cooling is of most importance in practice. According to Jung when considering an aggregate, in which relatively large and small pores are present, one may say, that the ice crystals found in the larger pores compress the soil mass between them and may cause a breaking of the aggregates into smaller units.

From Jung's experiments, the author of this work concludes, that :

1. in the most favourable case, a cloddy structure of lumps may be changed into a structure of smaller clods, while the micro-structure of these clods will be denser than of the lumps. In other words, the macro-structure has been ameliorated and the micro-structure has deteriorated ;
2. the resistance of the micro-structure against pressure increases ; because the aggregates are compressed by the growing ice crystals, possible points of contact (weak points in the aggregates) become planes of contact, resulting in a larger friction when it is tried to disturb the aggregates mechanically and, as a consequence, in a larger resistance ;
3. a cloddy micro-structure can never be transferred into a crumbly micro-structure by frost action alone.

Because in the Netherlands soils are known, which are not influenced by frost, the author emphasizes, that only soils, having the capacity to get into more favourable structure, can be brought in a better structure by frost. Or, in other words, when it would be possible (and it really is) to determine some structural properties of a given soil, it can be predicted, whether frost will improve soil structure or not.

Furthermore, it must be remarked, that thawing can nullify any favourable action of frost, this particularly being the case when a thick layer of snow has fallen on the ground (dispersing action of water).

§ 4. *Swelling and Shrinking.*

The alternate wetting and drying of the soil influences microstructure strongly. Bouyoucos (1924), Haines (1923), Puri (1934), and Sideri (1936) have studied this mechanism.

Bouyoucos (1924) puddled soil samples with water and allowed them to dry. The result is very dense, hard clods. After rewetting of the soil and drying again, it is not so hard as originally. Often cracks are formed in the compact mass during the remoistening. Repeating this wetting and drying a few times, the hard mass breaks up into several small clods or crumbs. In some soils this crumbling takes place already after the first wetting and drying and these always are soils, that were in a flocculated state originally. It is impossible to bring a soil, that originally had a cloddy structure, in a crumb structure by alternately wetting and drying alone. Hudig (1940) gained the same experiences with similar experiments.

Swelling and shrinkage of the soil colloids are the causes of the crumbling or pulverisation in this case. When taking up water, the particles diverge more or less, unequal strains arise during wetting and drying because these processes cannot be uniform throughout the soil mass and cracks are brought about. The grains do not come back in the original state of drying. This causes an increase in volume after rewetting,as was shown by Haines (1923) by measuring the volume of soil samples under mercury. He kneaded the soil at optimum moisture content into balls and determined their volumes. After that he allowed them to dry at the air and measured the volume during the drying process. Plotting the data as a function of the volume of water removed, curves are formed as given in fig. 38. It is to be noted, that in the beginning of the drying process the decrease in volume of the soil balls is equal to the volume of the water lost. As dehydration proceeds, there is a distinct break in the curve at a certain point and the change in soil volume becomes less than the volume of water lost. This is the point at which water is removed from the soil colloids and the pores, and air enters the soil. The skeleton of the soil closes more and more, but slower than before this point.

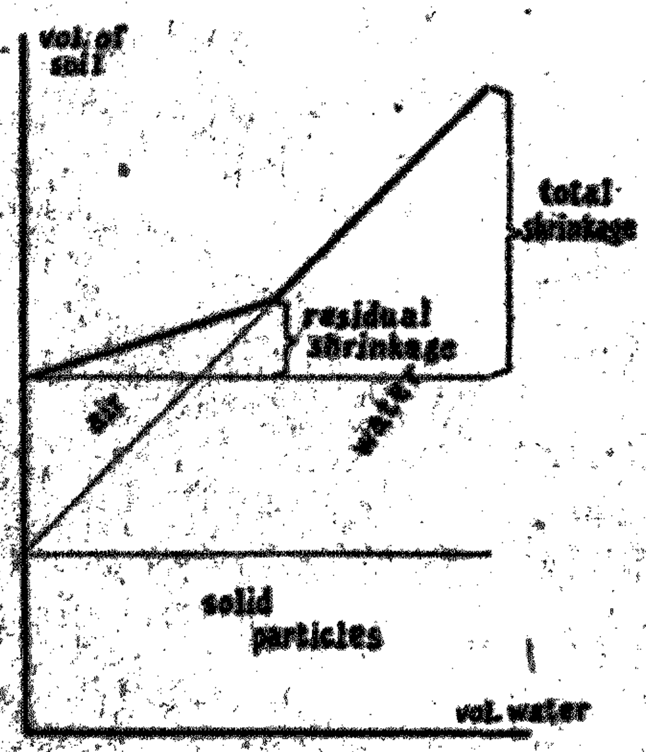

Fig. 38. Shrinkage curve (Haines).

It is significant to compare the drying and wetting curves (fig. 39). It may be concluded then, that the volume of rewetted soil sample is larger than the original volume. Drying again shows that this increase in volume is permanent.

The saturation of the adsorbing complex of the soil with different cations has no effect on the shrinkage of the soil (Puri, 1934). Puri worked in a similar way as Haines and could not establish any significant influence.

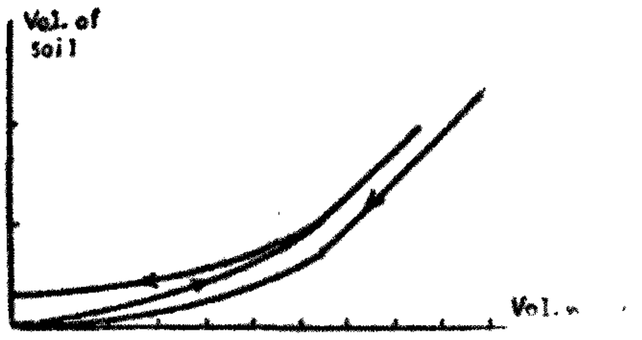

Fig. 39. Effect of alternative drying and wetting on volume of soil. (Haines).

Sideri (1936) has formulated in more detail the effect of the swelling process on soil porosity. According to Sideri the water is absorbed in two ways: 1. in the capillaries and pores of the soil (capillary imbibition) and 2. in the lattices of the minerals (swelling water). The former amount, according to Sideri, equals to K_Δ-r, where K_Δ is the amount of water absorbed in percentages of the volume of the swollen soil, and r the correction factor according to the increase in the volume of the soil and equalling to $\frac{K_\Delta Q}{100}$, where Q is the value of the volume increase. Further the relation holds $K_\Delta - r = K$, in the case that there is only capillary imbibition, where K is the amount of an apolar liquid absorbed by the soil, expressed in percentages of the volume of the air-dry soil. In all cases where $K_\Delta - r > K$, there is swelling, accompanied by a change in the structure (see also fig. 39). Therefore the quotient $S = \frac{K}{K_\Delta - r}$ gives an expression of the changes during the absorption of water. Sideri designates S as the "structure coefficient". The smaller this coefficient, the greater the change in soil structure. The "swelling water" may be calculated from the equation $W_q = (K_\Delta - r) - K$.

In the case of a fine loamy sand chernozem Sideri found: $S = \frac{29.47}{29.62} = 1$ and $W_q = 0.15$, so practically 0. In this case there is merely capillary absorption and no change in structure. In the case of an alkali soil he found: $S = \frac{28.22}{31.38} = 0.58$ and $W_q = 13.16$, so a considerable amount of imbibition water; the structure changes to a high degree.

§ 5. *Capillary compression of air.*

Another phenomenon, that is caused likewise by the uptake of water, is the compressing of air in capillaries and pores. Considering a capillary tube with both ends in water, water will try to penetrate with a pressure $\frac{2\sigma}{r}$, where r is the radius of the capillary tube and σ the surface tension of water. As a consequence, the air in the tube will be compressed and therefore a pressure is exerted on the wall of the capillary tube. This being the case in the pores and capillaries of the soil, a pressure results on the particles and this force being large enough, the soil grains will be pressed aside. The mentioned capillary forces are of the same order of magnitude as the centrifugal forces (see table 8) applied in the flocculation experiments and, as a consequence, of the same order of magnitude as forces, exerted on soil in practice (see p. 39).

TABLE 8

radius of the capillary tube in μ	capillary pressure in kg/cm^2	centrifugal force applied kg/cm^2
10	0.15	
5	0.30	0.12
2	0.74	0.71
1	1.5	1.0

The phenomenon in question can be shown by determining the resistance (according to Vilenski) of dry aggregates and aggregates cautiously saturated with water by capillary absorption. During this wetting the air is allowed to escape, so that the aggregates are filled with water. In the former case the falling apart of aggregates is chiefly determined by the destructive action of the beating water drops and the pressure exerted by the air on the walls of the pores, whereas in the latter case the resistance is determined only by the impact of the waterdrops; so it is to be expected that the wet aggregates are more resistant than the dry aggregates. This holds for all soils examined by the author; some results are given in table 9.

TABLE 9

Soil	Resistance according to VILENSKI	
	dry	wet
Sandy soil (Eng)	2.3 ± 0.1	14.7 ± 1.4
Dark coloured loam ("Moor"-soil)	6.3 ± 0 3	14.4 ± 2.2
Clayey loam (forelands)	25.0 ± 0.5	> 100
Clay soil (Nude clay).	27.5 ± 3.0	> 100
Heavy clay soil (Neerlangbroek) .	72.4 ± 12.4	> 100

(The figures are means of 20 measurements.)

The wetting properties of the soil material is an important factor in the processes of water absorption by soil. When the spreading of water on the solid mass of the soil is not complete, then for instance the capillary tension is:

$$(6) \qquad p = \frac{2\sigma}{\text{[illegible]}} \cos \alpha$$

where α is the angle of contact between the water surface and the interface soil-water. α may vary between 0° and 180°. In the case of a = 180°, which may exist at extreme dehydration of the irreversible drying peat soils in the Netherlands, there is [illegible] capillary ascent at all, but capillary depression ($\cos \alpha = -1$). This is the reason, why these soils have a very water resistant structure. The low spreading coefficient, defined by Harkins (1924) as $S = W_{ad} - W_{co}$ (W_{ad} being the work of adhesion [illegible] W_{co} the work of surface cohesion of water) is caused undoubtedly by the nature of the organic matter in these soils, this being present in the form of Fe-humates (Hudig and Redlich, 1940). There are several indications in literature, that suggest Fe-humate is the cause of the non-spreading. Tyulin (1940) for instance pointed out, that at a definite ratio of hydrophilic organic colloids to Fe-hydrosol a hydrophobic precipitate arises, that, after drying at room temperature, cannot be wetted. Also Mattson (1931), Falconer and Mattson (1933), Myers (1937), Puri (1938) and Hénin (1938), suggest, that in certain conditions hydrophobic materials may be derived [illegible] after drying, are wetted with difficulty.

§ 6. *Mechanical composition of the soil.*

The mechanical composition influences especially the resistance of the micro-structure and as a consequence the porosity too. In literature there are known few exact data about this factor. Baver (1935) stated, that at low percentages of organic matter the correlation between aggregates larger than 0.05 mm and clay ($< 5\ \mu$) content is 0.506 to 0.947 (0.347 and 0.456 being significant resp.). At high humus percentages the correlation becomes insignificant. Also Baver stated that the correlation between aggregates larger than 0.05 mm and organic matter content becomes larger, the smaller the clay ($< 5\ \mu$) content. The author of this work has done experiments showing, that the mechanical composition of the soil strongly influences the resistance of the micro-structure against break-down by water.

In the same way as indicated in Chapter III, mixtures were made of different coarse fractions of pure sand and different amounts of Na-bentonite. Part of the mixtures were coagulated with $Ca(NO_3)_2$. Aggregates of a diameter of 2—4 mm were obtained by screening the dried mass through a 4 mm and 2 mm sieve. The resistance of these aggregates was determined by the drop method of Vilenski. The results are given in table 10.

This table shows that the resistance of the aggregates becomes higher at increasing clay content and decreasing diameter of the sand grains. The same tendencies are found when $Ca(NO_3)_2$ is added, however in a smaller degree. These results agree well with those of Erikson (1942), who showed, that the structure of a clay soil was more resistant than that of the same clay soil mixed with pure sand.

In practice one has to keep in mind these results. A sandy soil will have to be treated in a different way from a clay soil (see also Chapter VI).

From the above mentioned results it must be concluded, that the computation of correlation coefficients between e.g. the clay fraction < 2 μ and aggregates of a definite diameter is very difficult, because various factors influence this correlation, e.g. coarseness of sand particles, concentration soil solution, humus content, etc.

TABLE 10

mixture	resistance	heigt of fall of the drops in cm
sand (250-500 μ) + 5% Na-bentonite	3.1 ± 0.2	5
„ + 10% „	7.0 ± 0.5	5
„ + 30% „	17.3 ± 2.0	5
„ + 60% „	> 100	5 and 15
sand (150-200 μ) + 5% Na-bentonite	11.0 ± 1.2	5
„ + 10% „	18.1 ± 2.3	5
„ + 30% „	> 100	5 and 15
„ + 60% „	> 100	5 and 15
sand (105-150 μ) + 5% Na-bentonite	16.0 ± 1.5	5
„ + 10% „	32.2 ± 2.6	5
„ + 30% „	> 100	5 and 15
„ + 60% „	> 100	5 and 15
sand (250-500 μ) + 5% Na-bentonite + $Ca(NO_3)_2$	2.0 ± 0.1	5
„ + 10% „ „	5.0 ± 0.1	5
„ + 30% „ „	7.0 ± 0.7	5
„ + 60% „ „	10.4 ± 0.7	5
sand (150-200 μ) + 5% Na-bentonite + $Ca(NO_3)_2$	3.3 ± 0.2	5
„ + 10% „ „	5.4 ± 0.5	5
„ + 30% „ „	8.6 ± 0.5	5
„ + 60% „ „	14.2 ± 1.1	5
sand (105-150 μ) + 5% Na-bentonite + $Ca(NO_3)_2$	4.0 ± 0.3	5
„ + 10% „ + „	6.2 ± 0.7	5
„ + 30% „ + „	13.3 ± 1.8	5
„ + 60% „ + „	19.6 ± 1.8	5

Some remarks should be made here with respect to the intrinsic structure, defined in Chapter I. The experiments described in this section and the flocculation experiments described on pages 39—46 (table 5, 5c, 6, and 7) demonstrate clearly the influence of the structure-capacity on the actual structure. It was shown for instance, that kaolinite systems are less resistant than bentonite systems (table 6), but because the factors, affecting the actual structure, are equal in the mentioned experiments, the kaolinite- and bentonite systems have a different structure-capacity. Generalizing it may be concluded, that soils, differing in the nature of their clay minerals, have a different intrinsic structure and, under equal conditions, a different actual structure. The clay content and the soil skeleton influences the structure-activity too (table 10). Soils with different clay contents have a different intrinsic structure, because the actual structure was different under equal conditions.

Furthermore the flocculation experiments show that the flocs of clay mineral-humus-systems have a more porous structure than the flocs of the clay mineral systems and therefore, again because the conditions are equal, the difference in actual structure is the result of a difference in structure-capacity as a consequence of the humus content.

§ 7. *Biological activity of the soil.*

It appears that the most important factor in the formation of the micro-structure is the biological activity of the soil, that is the influence of the microflora and fauna on the physical state of the soil.

The influence of the fauna will be discussed first. Bornebusch (1932) divided the animals with respect to their activity and distinguished:

(a) animals, that feed on organic material, grind and digest it, but mingle it to a slight degree with the mineral soil particles (e.g. insects);
(b) animals, that digest organic material and mingle it at the same time thoroughly with the soil (e.g. worms);
(c) animals, that feed on individuals of (a) and (b) (e.g. centipedes).

The action of the animals of group (a) is restricted to the upper layers of the soil. They grind the organic material present and bring it in this way in a state, that it may be taken more easily by the animals of group (b).

The earthworms are of more importance with respect to soil structure than the animals of group (a). They move into the deeper layers of the soil and loosen the soil by their large number, so that a good air and water circulation results. The worm tracks in the upper layer of 10 cm may account up to 67 % of the volume (Stoeckli, 1928). The tracks are connected by the excreted slime of the intestines and the activity of the microorganisms is stimulated by virtue of the increased air-circulation.

During their moving the worms eat their way through the soil, so that a great part of the soil passes through the alimentary canal in course of time (Wollny, 1890). During that process the soil grains are blended with partly digested organic material and are united in such a manner, that the excrements are not larger than 2 mm in diameter (Blanck and Gieseke, 1924). In this way aggregates are formed, existing of soil firmly cemented with organic material, and ejected partly along the tracks, partly on the surface as "worm casts". The exrements contain 5 times as many bacteria as the original soil. Significant amounts of organic excrements are produced. Franz and Leittenberger (1943) found, that one individual of Lumbricus rubellus Hoffm. secreted 1—1½ g a year and that in one m^2 about 100 individuals are present in most mineral soils. Darwin (1881) estimated that these "worm casts" would form a layer of about 5 mm thick in the course of a year. So worms bring about a good mingling of the subsoil and surface soil. This may be made visible by adding a layer of organic material on mineral soil into a glass vessel and then bringing earthworms into it. After a lapse of time the two layers are mingled completely.

It is evident that the existence of animals in soil is very important and therefore it is desireable to consider under which conditions they thrive best. Primarily it is necessary that organic material be present to serve as food. Whereas Frenzel (1936) thinks, that in all soils sufficient food is present, Morris (1922, 1927) had shown previously that, on the Rothamsted fields continuously supplied with manure, considerable more, viz. 3—10 times as many, animal organisms are found than on unmanured fields. Secondly temperature and moisture content influence the presence of worms. They do not endure high temperatures and disappear to lower depths then. Also they require a suitable moisture content. Therefore it is important that, in farm practice, the soil be kept covered as much as possible. The crops shadow the soil so that temperature remains moderate and drying of the surface layer is checked. Thirdly the amount of air is important. Fortunately the worms need only a small amount of oxygen to live (Stoeckli, 1928), so that they may occur in soils with compact structures (low 0_2-content), where they are most needed for the amelioration of soil structure.

The importance of the fauna in the formation of structure may be taken together in two points : 1. They grind the organic material and digest it partly, so that it may be decomposed by the microorganisms more rapidly; 2. They „cultivate" the soil by their digging, so that an extensive mingling of the soil constituents results.

The influence of the flora on soil structure often is complicated and obscure. The higher plants influence the persistance of the macro-structure and they protect the micro-structure against destruction by the impact of raindrops. This action will be discussed in Chapter V.

The lower organisms that influence the micro-structure are algae, fungi and bacteria.

The algae-flora in soil consists of Chlorophyceae, Cyanophyceae and Diatomeae. Depending on the conditions (climate, soil cultivation, plant growth, etc.) the groups dominate alternatively. E.g. in temperate climate the Chlorophyceae are most abundant; in warm, humid climate the Cyanophyceae. Their action upon structure is little known. Sekara (1941) pointed out, that they bind the soil particles by their fibres.

According to Waksman (1916, 1917) the soil fungi belong chiefly to the Fungi imperfecti. The type of fungi which occur depend on climate, pH of the soil, etc. Their action is twofold: 1. They break down organic materials as cellulose, starch, pentosans, fats, fatty acids, etc. and form dark coloured decomposition products, which, according to Martin and Waksman (1940, 1941) have an aggregating action. Further Sideri (1938) shows, that autolysis products of Aspergillus niger, when mixed with soil, ameliorate its structure. The amounts necessary to bring about this aggregating action are very low. 2. The fungi fibres connect the particles into aggregates. Waksman (1937) describes a case, that a lump of sandy material with firmly connected particles was sent to him ; it could be crumbled only with difficulty. It appeared that a Zygorynchus species had caused the cementing of this lump by its long unbrenched mycelium. Peele (1940) inoculated sterile soils, supplied with sucrose, with a culture of fungi and found, that in twelve days the water-resistant aggregates larger than 2 mm in diameter increased from 0 % in sterile soil to 79 % in inoculated soil as a consequence of the development of mycelium, whereas the aggregates $<$ 0.02 mm decreased from 18.0 % in sterile soil to 7.2 % in inoculated soil. Also other fungi form an expansive mycelium, that binds together this soil grains. This process may be made visible by putting microscope slides into the soil and allowing them to remain for a year, so that the slide, soil particles and the organisms living on them, grow together in a natural way (Sekara, 1941). After having carefully removed these slides, fixed and stained the adhering material, a section of the soil with its organisms can be observed under the microscope. Sometimes a vegetation of fungal fibres grow on the surface of the aggregates and in this way protect them against the destructive action of water.

Bacteria play a very important rôle in structure formation. They occur in all soils and under all conditions. Bacteria are active : 1. in the decomposition of organic material ; 2. in the formation of mucus. (slijm)

Almost all organic compounds can be decomposed by bacteria. Under aerobic conditions this breakdown proceeds to the formation of the end-products such as CO_2 and H_2O. As intermediate products acids are often formed, that aggregate the soil. As by-products in the decomposition mucus is formed. The nature of this substance is often unknown, but definite compounds have been recognized, e.g. uronic acid and pentosans. However it may be considered as an established fact that these substances play an important rôle in structure formation by their sticking properties, binding the soil particles together into aggregates. Peele (1940) mixed bacterial mucus with dry soil (even sandy soil) and made small balls of this mixtures. After drying these balls, he placed them in distilled water. Even after 24 hours the balls did not fall apart. If balls were formed with distilled water then they collapse immediately when put in water after drying. Martin and Waksman (1940, 1941) found, that inoculation of soil with cultures of bacteria results in cementation of the soil particles by mucus formation and that 80 % of the unbound inorganic material was fixed.

Sekara (1941) proves this mucus formation microscopically. Sometimes soil spaces are observed entirely filled with bacteria. The mucus produced protects the structure against disruption after death of the bacteria. Soon the mucus becomes crowded by fungi and algae fibres, that take care of the further stabilizing of the structure. After the death of the fungi and algae, a rapid growth of a bacteria flore is observed on it. Here a succession of organisms ensures a definite state of aggregation.

Martin (1945, 1946) allowed several bacteria to grow in different media. During their growth these bacteria formed excretion products, from which Martin isolated several polysaccharides (fructosans and dextrans) with different uronic-acid content. These polysaccharides ameliorate the structure considerably. Further it appeared that the higher the uronic-acid content the more intensive the amelioration of structure.

Summarizing the action of the microorganisms on structure, one may state that the fungi bind the particles to aggregates and that both fungi and bacteria, but especially bacteria, in decomposing organic materials, produce by-products, small amounts of which already cause aggregation of the soil. This factor especially determines the structure of sandy soils.

Recapitulating it may be remarked, that the increase in porosity of the micro-structure is caused by tillage (indirectly), swelling and shrinking, compression of soil air and fauna and an decrease in porosity by the frost action. The resistance of the micro-structure against mechanical forces is increased by the frost action, fauna and flora and decreased by swelling and shrinking and compression of air. The mechanical composition of the soil influence the resistance of the micro-structure in an increasing or decreasing way.

CHAPTER V.

THE MACRO-STRUCTURE AND A SURVEY.

In Chapter IV the author has emphasized that tillage operations highly influence the macro-structure, or the arrangement of the structural units, but do not affect the micro-structure directly, as will be shown now.

Consider a soil in a definite state (cloddy or crumbly). Ploughing or otherwise cultivating this soil causes the soil mass to break up along the less compact regions as in these places the resistance is least. The more intensively the soil is cultivated, the greater the number of weak junctures giving way and the more compact the remaining aggregates are. In this way a soil results, which, when dry, consists of very hard clods. Realizing this, it may be concluded, that tillage operations do not change micro-structure, but the macro-structure has been undergone a considerable amelioration, as was shown by Dojarenko (see Krause: 1931), who traces the beneficial effect of ploughing and other manipulations on the air content (see table 12: Chapter VI); since the air content is determined chiefly by the non-capillary pore space, it is a measure of the macro-structure. In other words it is impossible to transfer a cloddy structure in a crumb structure by tillage operations alone and likewise it is impossible to maintain a loose crumb structure by tillage.

However, in an indirect way tillage may cause changes in micro-structure and macro-structure too. If these operations are accompanied by cultural treatments, e.g. organic manuring, it is possible, that, by the favouring of biological processes, because of better aeration, that micro-structure is effected in a desired direction, as pointed out in Chapter IV, since it is the biological activity of the soil, that can re-orientate the soil particles. It can be concluded, that the tillage operations may have a great indirect effect on soil structure and do have if these operations are done at a definite moment and followed by the most suitable cultural measures.

The direct effect of tillage upon soil macro-structure is determined by: a. the water content of the soil at the moment of tillage; b. the size of the particles; and c. the shape of the resulting particles.

a. This can be elucidated in the following way. Pure sand flows away when the water content is high. But when the water content is low so that menisci are formed between the sand grains, they are held together by forces due to capillarity. In this case a force is necessary to separate two sand grains. As early as 1898 Hellriegel has emphasized the occurrence of this phenomenon, but without giving a quantitative relation between the water content and the force needed to separate the sand grains.

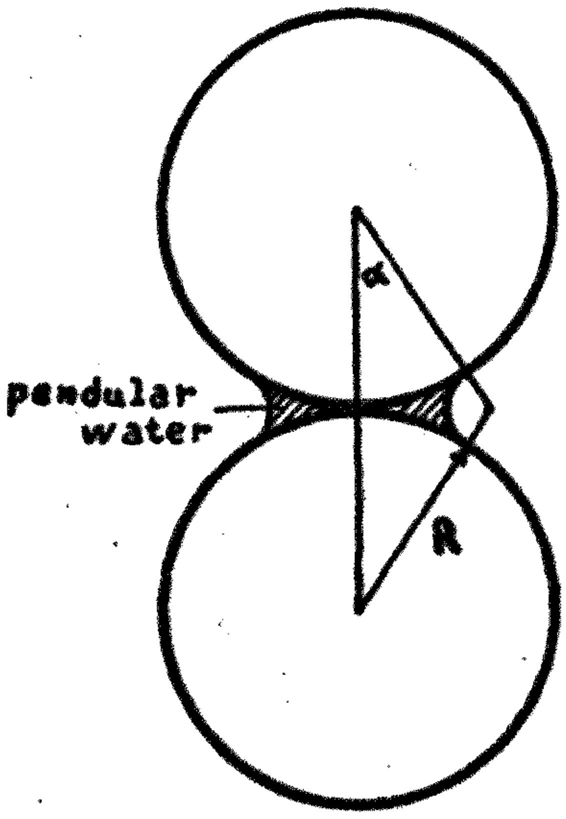

Fig. 40. See text.

It was Versluys (1916) who gave this relation. He considered the case when two spheres, surrounded with a water film, are brought together. Water will accumulate in the point of contact because then the interface water-air is reduced and the free surface-energy is decreased (see fig. 40). Now the question arises: What force (work) must be applied to separate the two spheres? The magnitude of this force is computed entirely theoretically by Versluys (1916) for the case that α does not surpass 30° (limit of the pendular water). It is

$$P = \sigma \pi R \left\{ 2 \sin \alpha - \sin \alpha \frac{\tan \alpha}{\tan {}^1\!/_2 \alpha} + \frac{\tan \alpha}{\tan {}^1\!/_2 \alpha} - \left(\frac{\pi}{2} - \alpha \right) \tan \alpha \right\}$$

where σ is the surface tension of water.

When the amount water is so small, that $\alpha <$ 20°, the formula can be simplified to:

$$P = \sigma \pi R \left\{ 2 - \left(\frac{\pi}{2} - \alpha \right) \tan \alpha \right\}$$

as in these cases $\frac{\tan \alpha}{\tan {}^1\!/_2 \alpha}$ approximates the value 2.

Kruyt and Van Selms (1943) give a somewhat differing derivation because they leave out of account the non-pendular water moistening the spheres.

As it is possible to give a relation between α and the amount of water, the force (work) can be computed. This relation is:

$$W = \left\{ \frac{3}{4} \sin^2 \alpha + \frac{1}{2} \cos^3 \alpha - \frac{1}{2} - \frac{3}{2} \sin \alpha \frac{(1 - \cos \alpha)^2}{\cos^2 \alpha} \left(\frac{1}{4} \pi - \frac{1}{2} \alpha - \frac{1}{4} \sin 2\alpha \right) \right\} \times 100\,\%$$

Now P can be calculated in dependence of the water content (expressed in α), when R is fixed. This has been done by the author and the result is given in fig. 41. This figure shows that P rapidly increases when the water content decreases to a level with α = 25°. The increase of P is slow at water contents corresponding with $\alpha <$ 25°.

Cultivating such a sand consisting of spherical particles, then this is allowed at a water content corresponding with $\alpha =$ 25° or below 25°, because of P being so large in those cases, that the grains are fixed in the state brought about by cultivation. If the water content is higher and thus P is low, then the grains fall back into a state of close packing, so that the desired effects of cultivation are not attained. Hudig and Siewertsz v. Reesema (1940) showed, that this phenomenon occurs actually in soils. In determining the distribution of the different pores in samples of really crumbly soils according to the method of Sekara (1938), they found, that, at a certain water content, it was not possible to remove the sample from the sintered glass plate without destroying it. It was supposed, that the pendular water at the points of contact between the crumbs had disappeared, so that the samples fall apart already under a light pressure of the fingers. Soils in a cloddy structure did not show this phenomenon, as a consequence of the small menisci.

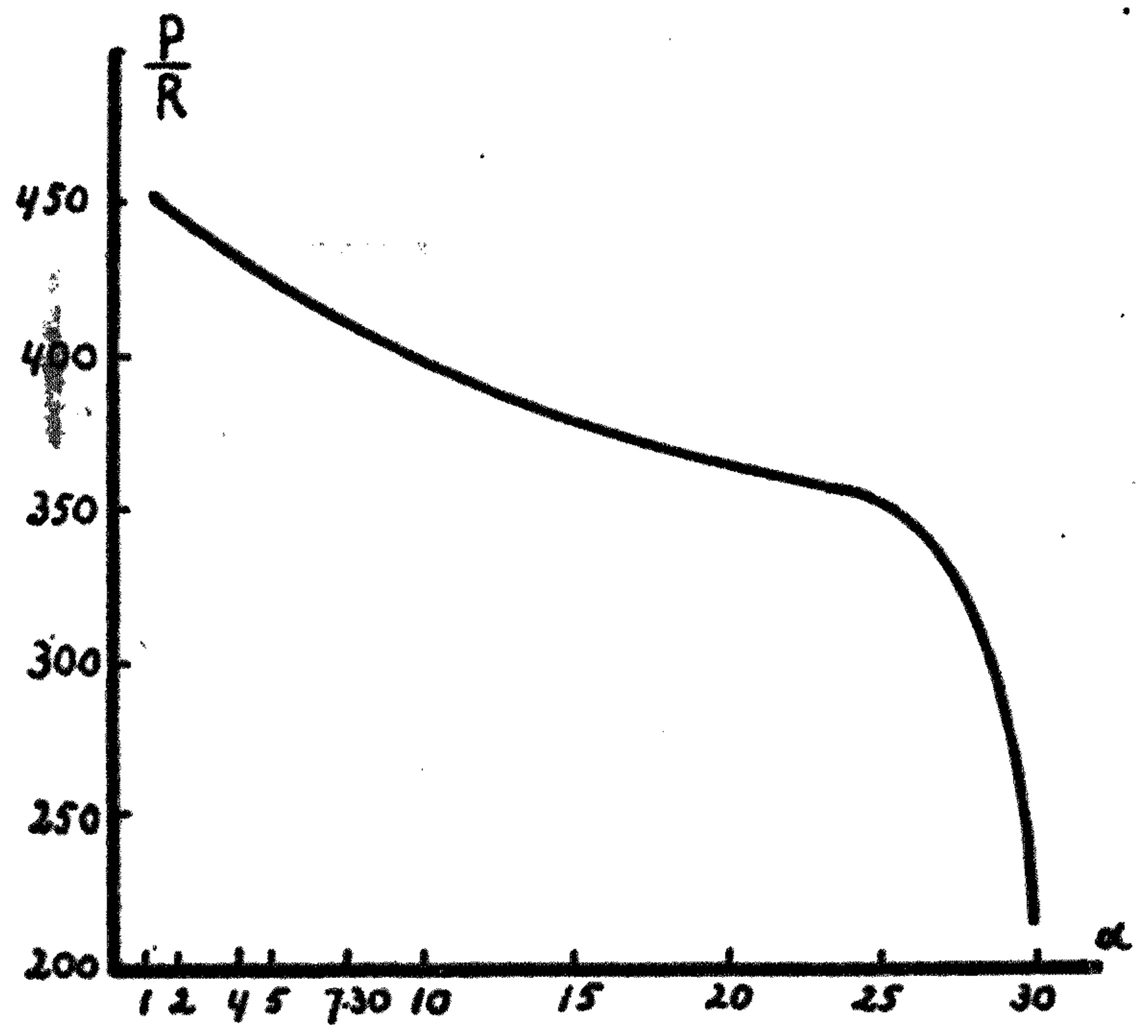

Fig. 41 P in dependence of α.

It is probable that the above mentioned findings are directly applicable to light sandy soils, but not to soils containing large amounts of clay and organic matter. Nevertheless the water content at cultivation time plays a significant rôle in the latter soils too. Any soil can be brought artificially into a more suitable physical state (small clods) by choosing a definite water content when working it. It is a well established fact, that ploughing or an other cultural treatment gives an optimal result only when this treatment takes place at a very definite water content. Slipher (1932) remarks with respect to this problem, that the water content is the key to structure formation in soil. Vilenski (1934) obtained experimental results, supporting the ideas of Slipher. He tilled several soil types with varying moisture contents. Afterwards samples are taken, air dried and the resistance of their structure determined in several ways. It appeared that at a tillage moisture content of 37 % chernozems had optimal structure resistance; the corresponding value for a solonetz was 30 %; for the illuvial layer of a podzol 19 % and the eluvial layer 10 %. The clay fraction of the soils decreases in this order.

b. The size or weight of the aggregates, prepared by tillage, is of importance when considering the possibility of the maintenance of an eventually ameliorated macro-structure. The weight of the aggregates increases with the third degree of the radius, considering the hypothetical case of spherical particles, whereas P increases with the first power of R, a being fixed. In other words, if ploughing or otherwise cultivating results in large aggregates, these latter will fall back into a state of close packing, because of the small increase of P compared with the weight of the aggregates. However, the falling back may be hindered by the friction forces, that increases with increasing weight of the aggregates. It is difficult to say, which of the factors: weight, P, or friction predominates, since this is influenced by the more or less accidental positions of the aggregates.

c. The friction forces become very great, if the aggregates are not spherical, but irregularly shaped. In the case of very irregular units, the macro-structure can be very resistant against disruptive forces.

It can be concluded from these considerations, that the tillage operations should result in small irregular clods, because in that case the stability of the macro-structure is greatest. Then also it is possible that secondary reactions (e.g. biological reactions), needing time, come into play and favour indirectly micro- and macro-structure.

The second factor that influences macro-structure is the growing plant. The direct action of plants on macro-structure lies in strengthening the network of aggregates because the plant roots follow the wider capillaries between them. In this way the aggregates are protected from falling back into a state of close packing.

The indirect action of the plant is to protect the soil against sunshine and against the impact of raindrops. The great enemy of the living micro-flora and fauna is the sun, that gives the surface layer of the soil a high temperature and therefore dries it. The micro-flora and fauna chiefly influence micro-structure, but in its turn the micro-structure alters the macro-structure.

Finally the influence of moles and field-mice on macro-structure, by their digging and making holes, is a loosening one.

Surveying the analysis of soil structure, given in the preceding chapters, it can be summarized in the following way.

The division of the actual structure of the soil into floc-, micro-, and macro-structure appears to be useful for our purpose. It is possible to approach the problem of soil structure in a way but little developed up to now. The author is fully aware of the fact, that this is a first trial, but, on the other hand, he has the conviction that this method elucidates the problem better and sooner than the method, followed by other workers, that consists in doing many determinations, with very often contradictory results, because these determinations are related to different fields of the problem without stressing this limitation.

The flocculation, described in Chapter III, is the first aggregation process, occuring in the soil and forms the basis with respect to the building up of the aggregates. It appeared that the study of the floc-structure can be treated experimentally and has the advantage that it is related to the physicochemical work, done by many colloidchemists. It is a rather sharply limited part of the problem and therefore can be investigated thoroughly.

The micro-structure, or the aggregation of flocs into larger units, appears to be a well limited part of the problem too, so that it gives the same possibilities of studying as the floc-structure. It can very well be studied experimentally, although not in the same exact way as floc-structure.

The macro-structure, investigated in most cases, remains a field of qualitative research. The methods, applicable in this field, were not developed in useful form. The fact, that no good interpretation can be given of many data, obtained from the clinical investigation of the soil, is the best proof.

The activity of the factors, influencing the floc-, micro-, and macro-structure of the soil under natural conditions are summarized in table 11.

TABLE 11. Factors affecting the actual structure of soil

Factor	soil structure						Importance
	floc-structure		micro-structure		macro-structure		
	porosity	resistance	porosity	resistance	porosity	resistance	
Cations: monovalent	compacting	increasing	—	—	—	—	×
polyvalent	loosening	decreasing	—	—	—	—	×××
Humus	loosening	increasing	loosening	increasing			×××
Frost	(compacting)	(increasing)	compacting	increasing	loosening	decreasing	×
Swelling and shrinking	(loosening)	(decreasing)	loosening	decreasing	—	—	××
Compression of air	—	—	loosening	decreasing	—	—	×
Fauna	—	—	loosening	increasing	loosening	decreasing	×××
Flora	—	—	—	increasing	loosening	increasing	×××
Tillage	—	—	—	—	loosening	decreasing	×

×××: very important; ××: important; ×: less important.

It appears that, generally, the factors are specific with respect to the different parts of soil-structure, but it must be emphasised that gradual transitions occur. This means, that, in the case of a poor structure, after analysis of the soil, it is possible to indicate the measure leading to an improvement of soil structure.

In table 11 some factors, e.g. mechanical composition and soil skeleton, are not mentioned, because these factors effect the structure-capacity of the soil. Their influence is rather obscure; generally it may be said that, up to definite values, the larger the clay content, the better the structure-capacity, this depending strongly of the coarseness of the sand grains present. Also the nature and content of humus (stabile part of the organic matter) influence soil intrinsic structure mostly in a favouring way.

In practice, it is often the structure-capacity that determines which agricultural treatments have to be performed in order to improve the actual structure. By subdividing the problem of soil structure in different fields, the author believes to have given the way, along which this question must be studied. Also he believes to have shown, that it is absolutely necessary to approach this problem with the aid of several methods of structure determination, because each of them deals with a definite part of the problem.

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With this the author has analysed the factors that influence soil structure. He realises that after the discussion of the influence of the seperate factors on soil structure, the need exists to have a synthesis. Questions arise about the mutual interaction, succession and overlapping of these factors. He will try to throw some light on this matter by an example from practice.

It deals with an orchard in Overlangbroek (Utrecht) on heavy clay soil (74 % $< 2\ \mu$). The soil was blue with Fe-spots; it was smeary and sticky when wet and hard when dry. The sand grains present were very fine, the organic matter content was 5 %. Because of the large amount of mobile Fe, the content of available PO_4 was low. Further the soil was poor in Ca (pH 5.3), Mn, NO_3 and rich in Mg. The K-content was normal. On drying the soil shrinks so that cracks are formed. After rains, the water drains rapidly down along these cracks and, as a consequence, the soil does not absorb the water; moreover the absorption of water by the soil is very slow because of the very compact structure. Years ago the yield of the orchard was very small. But after adding town refuse to the soil the yield increased rapidly and nowadays it is abundant. The compost was placed at some distance around the tree trunk and left uncovered. The result is shown in fig. 42. A typical nitrophile plant association has settled on the areas supplied with town refuse and when digging in the soil many worms and other living organisms are found. The question now arises: What did the compost do to the soil?

Chemically, the soil under the compost layer had changed considerably. It was rich in Ca and NO_3, poor in mobile Fe and therefore higher in available PO_4. The soil did not shrink and the absorption of water was good because of the improved structure.

Fig. 42. The result of adding town refuse to soil around the tree trunks.

Fig 43. Left: soil with town refuse. Right: soil untreatad.

Because of the great water holding capacity of compost and because of covering the soil, suitable conditions are created for the increase of life in soil. A high moisture content and shadowing and the suitability of compost to serve as food to micro- and macroorganisms are favourable factors for living organisms. An intensive "cultivation" of the soil by worms results in thoroughly mixing the soil with compost. Because of the cation content of town refuse the soil is changed into a flocculated state that, in turn, influences the micro-structure. Moreover the mineral grains are surrounded with humus-like substances that, with the aid of the sticky action of the mucus of bacteria and fungal fibres, increase the resistance of soil structure. Because of the abundant growing of the stinging-nettles and grasses the soil is protected against atmospheric destructive forces. Moreover the organic matter inactivates the mobile Fe, that caused a considerable PO_4-fixation originally, so that the phosphate circulates again and the plants and microorganisms benefit by it. The result is a rather deep loose crumb structure (see fig. 43), that is very persistent because of the protection against raindrops and sunshine and the very active life in the soil. Here a good actual and intrinsic structure-activity exist, which result in an actual structure of crumbs.

The same reasoning is valid in the case of the good structural conditions in soils under garden-hedges. Here also shadowing, protection against destructive forces and the continuous supply of soil with organic matter (shedding of leaves) are the principal factors, that guarantee a good actual and intrinsic structure-activity.

CHAPTER VI.

INFLUENCE OF STRUCTURE ON WATER- AND AIR-CONDITIONS AND ON CULTIVATION.

§ 1. *Structure and water conditions in soil.*

Water in the soil is physiologically analogous to the blood in the animal body or to the sap in the plant body. Structure plays an important part in the movement of the water and it was Wollny (1878—1898), who has made a beginning with the study of this matter. His conclusions has been accepted generally and come to the following: Soil being in a loose structure, the surface layer dries strongly; this dry layer conserves water, that is present in deeper horizons, because evaporation is kept low. Soil with a very compact surface horizon, evaporates much more water, so that this soil, other circumstances being equal, has a smaller water content.

A crumbly surface horizon being present, the soil, after rains, absorbs much more water and the water passes more easily through the soil than in the case of a compact horizon. Cases of compact structures are known, in which only 30 % or less of heavy rainfall becomes available; the rest is lost by surface run-off. This has the additional drawback in this country, that the pumping stations have to cope with a large amount of water in a very short time.

Wollny has stated these facts in many occasions and correlated them with other phenomena and since then they have been confirmed by many workers. Wollny bases his conceptions entirely on the laws of capillarity. But he had not the means to measure the capillary forces, so that he could work only qualitatively.

Since 1910 however, considerable progress has been made in this matter by the work of Buckingham and others, who start from a new angle of view.

Suppose a soil in a very closely packed structure, in which the pores have capillary dimensions. The movement of the water is controlled primarily by the laws of capillarity. Bringing a sample of such a soil into contact with water, the water would move along the capillaries as a result of the capillary tension, independent of the place of contact of soil and water. The water moves always away from the source of supply, or in other words, the movement is caused by the difference in potential, viz., from a higher to a lower potential. The speed of the movement decreases progressively as a consequence of Poiseuille's law and is becoming infinitesimal small. No percolation is then to be expected.

In a soil, composed of well defined aggregates, that are arranged in a loose manner with respect to one another, the water movement is much easier. One has to deal then with pores in the interior of the aggregates, in which practically no water movement is taking place, because these pores are bordered by wider capillaries, and on the other hand with larger pores between the aggregates, in which the water- and air-movement take place for the greater part. After rains the water will drain through the wide capillaries carrying air downwards in its trail. In the capillaries in the interior of the aggregates water is present and no air. One obtains in this way a mosaic of water-filled and air-filled regions.

In order to describe the water movement, Buckingham (1907) introduced the term "capillary potential". The capillary potential is equivalent to the water column, that corresponds with the suction force, that is necessary to bring about a movement of water from the soil. It is a measure of the difference in free energy of soil water under the given conditions and water in the free state. It is evident that the water will move from a point with low to a point with high capillary potential. Bringing two soil samples in contact with one another, one sample having narrow capillaries (compact structure) and the other wide capillaries (loose structure), the former has, in the case of equal moisture content of both, a higher potential than the second sample and water will move from the sample with loose structure to that with compact structure.

As the capillary potential can reach considerable values in the case of a dry soil, Schofield (1935) introduced the pF-value. This is the logarithm of the capillary potential. Here also a close relationship exists between pF and the size of the pores, water content, etc. Schofield (1935) showed, that the shape of the curve, illustrating the relation of pF to water content, gives information about the distribution of the pores in the soil. However the relation is complicated by hysteresis phenomena and by swelling and shrinking of the colloidal material due to changes in moisture content.

Almost simultaneously with Schofield's work, American workers developed a method, that makes it possible to follow the fluctuations of moisture content during any desired period in soil in situ. This method measures the capillary tension, a quantity indicating the pressure existing in the water in unsaturated soil and identical with the capillary potential of Buckingham. They (Rogers, 1935; L. A. Richards, 1936; L. A. Richards and co-workers, 1936a, 1936b; S. J. Richards, 1938; S. J. Richards and Lamb, 1937; Wallihan, 1939, 1940; Childs, 1940; Russell, Davis and Blair, 1940) showed, that the value of the capillary tension is determined by the moisture content and the texture of the soil. Furthermore it was evident, as could be expected, that the water moved from points with a low capillary tension to points with a high capillary tension.

In the Netherlands recently v. Schuylenborgh and v.

Bavel (1946) have applied this method to Dutch soils. They were able to show, in agreement with the American workers, that the value of the capillary tension is dependent of the moisture content and the mechanical composition of the soil. Moreover it was realised that the structure of the soil affects the capillary tension. To show this latter fact somewhat more clearly, the author performed further experiments.

Different kinds of structure were artificially prepared. Samples were taken from a clay soil from the forelands at Wageningen, which apparently has very resistent aggregates and from a sandy soil from the Betuwe. A portion of each was crumbled by hand at a suitable moisture condition, another part was puddled in a wet state to obtain a compact structure. Moreover the cloddy clay soil was screened to obtain the fractions 4—5, 2—4, 1—2 and smaller than 1 mm. All samples were filled into Mitscherlich pots in duplicate sets. In all pots tensiometers were placed on three depths (viz. 5, 10 and 15 cm below the surface) in the way illustrated in fig. 44. Fig. 45 gives a survey of one series of pots.

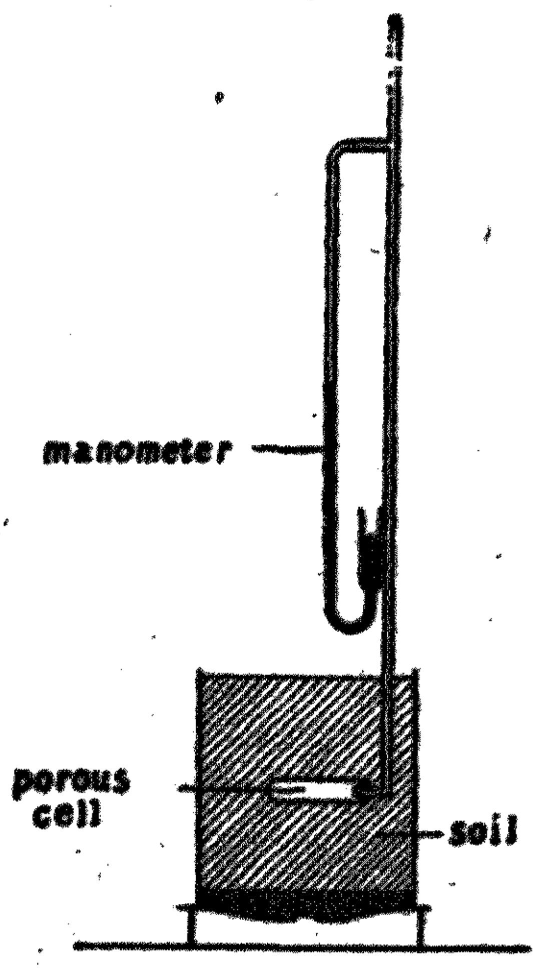

Fig. 44.

The first point of investigation was whether there could be established a relation between structure, water content and capillary tension. For that purpose water content determinations were done in the different pots and the values found plotted against the corresponding capillary tension. The data of some determinations are given in fig. 46. It is evident, that the actual structure strongly influences the value of the capillary tension, since very different capillary tensions belong to equal moisture contents. Therefore, the estimation of moisture contents of a soil from capillary tension data must be preceded by the determination of a standard curve of each soil. Moreover one must have ascertained that the structure undergoes no changes during the time the measurements are made.

When the capillary tension values are plotted against the water content, expressed as a percentage of the pore space, fig. 46a results. This figure shows that there is a distinct break in the curve of aggregates 2—4 mm in diameter and a gradual course in the curve of aggregates < 1 mm in diameter. This means that in the case of aggregates 2—4 mm in diameter there is an abrupt change from the capillary pores to the non-capillary ones, which is not the case in the structure of aggregates < 1 mm. Furthermore fig. 46a shows, that the water tension in the crumb structure is always smaller than in the other structures; because it is highly probable, that the plant growth reacts on the capillary tension and not on the water content, it may be concluded that plants growing on crumb structures absorb the water more easily than on cloddy structures, this resulting in a better plant production.

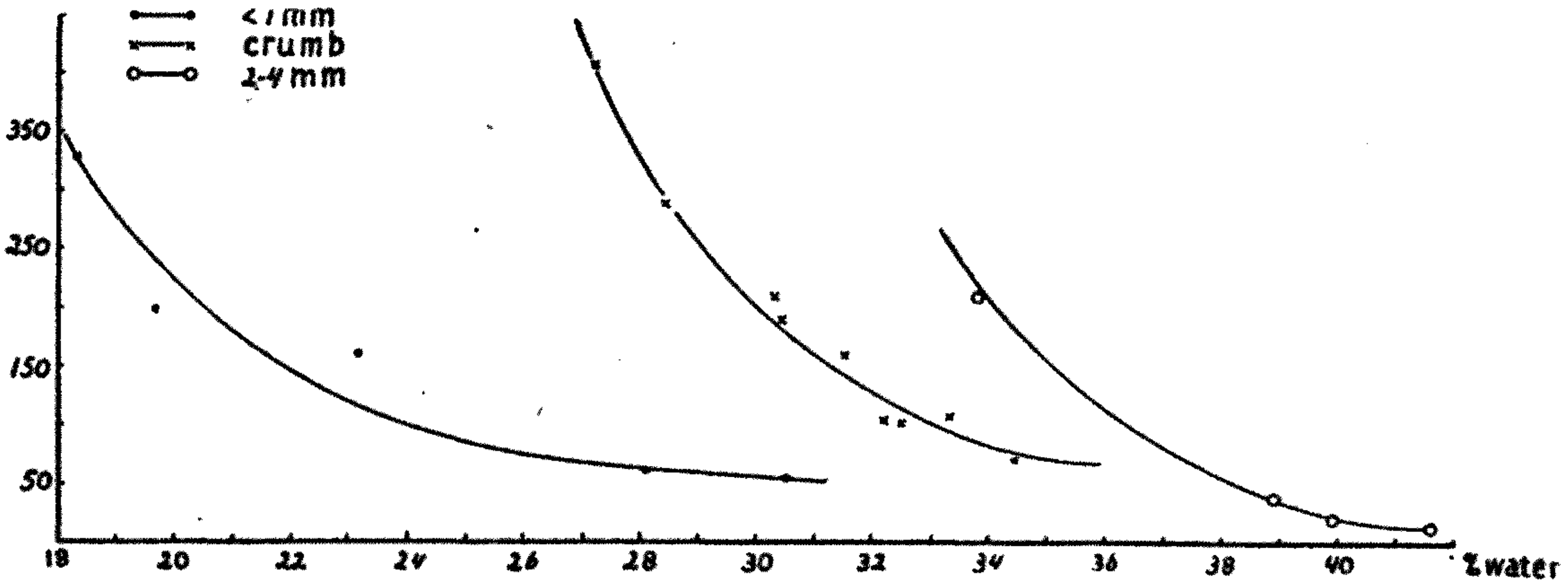

Fig. 46. Capillary tension en dependence of structure and water content.

Next the author investigated in what manner water penetrates into the soil. For this purpose water was added to all pots on one day at 9.—, 11.— and 14.— o'clock at the rate of 2 mm (= 60 ml for each pot) each time. Beginning at 9.— o'clock tensiometer readings were made twice an hour. The results are given in fig. 47. It appears, that in pots 19 and 20 (fraction 4—5 mm), pots 21 and 34 (fraction 2—4 mm) and pots 35 and 36 (fraction 1—2 mm) the capillary tension at the depth of 5 cm changes already after half an hour. This indicates that the water has reached this depth within 30 minutes. In pots 51 and 53 (fraction < 1 mm) this change sets in after one hour and in pots 5 and 6 (crumb structure) after 1½ hours. The capillary tensions at greater depths follow the mentioned order with ever increasing retardation. In the crumb structure the capillary tension at 15 cm depth does not change materially. The author declines from giving a quantitative relation that could elucidate this behaviour; it is questionable whether this is possible at all. However it can be stated, that the water intrusion

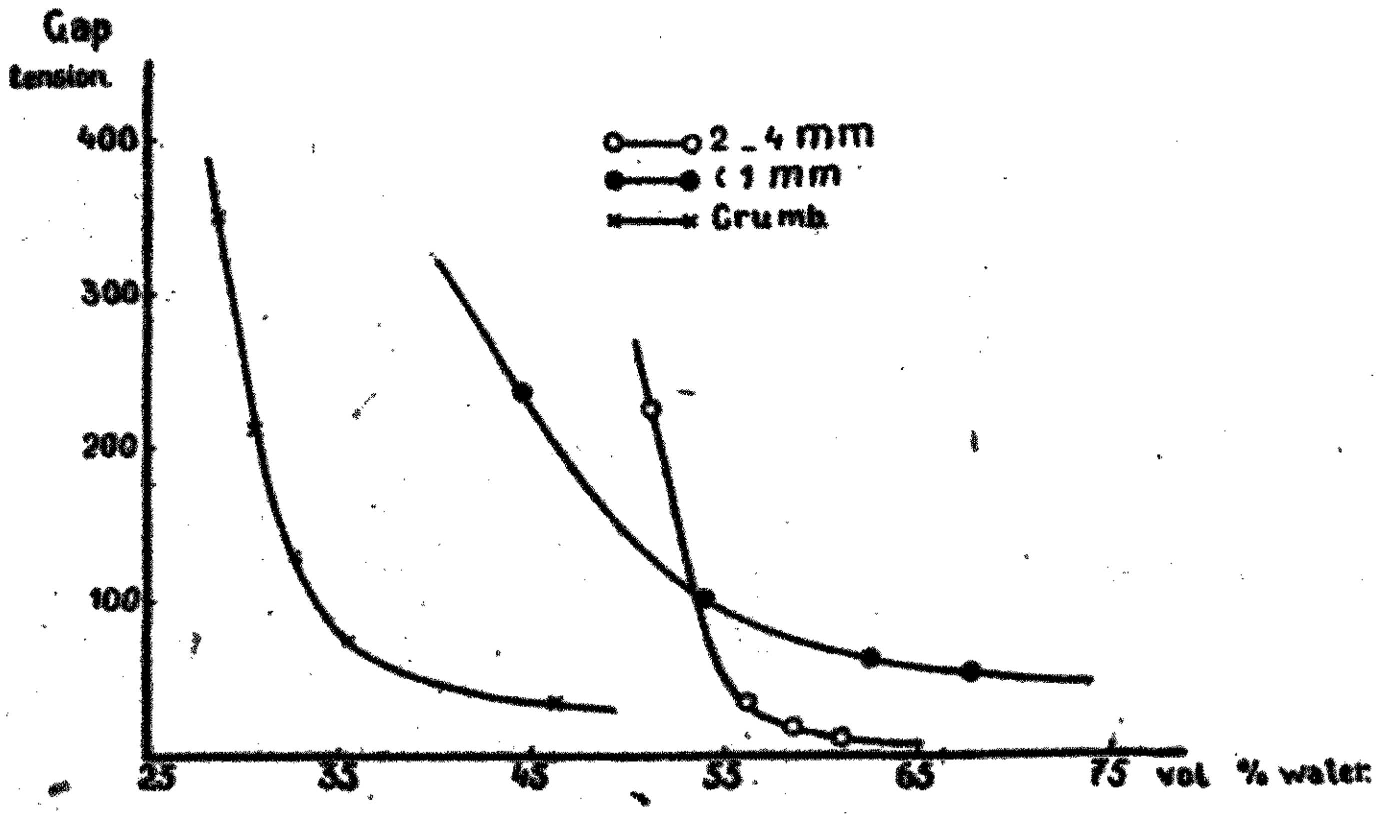

Fig. 46a.

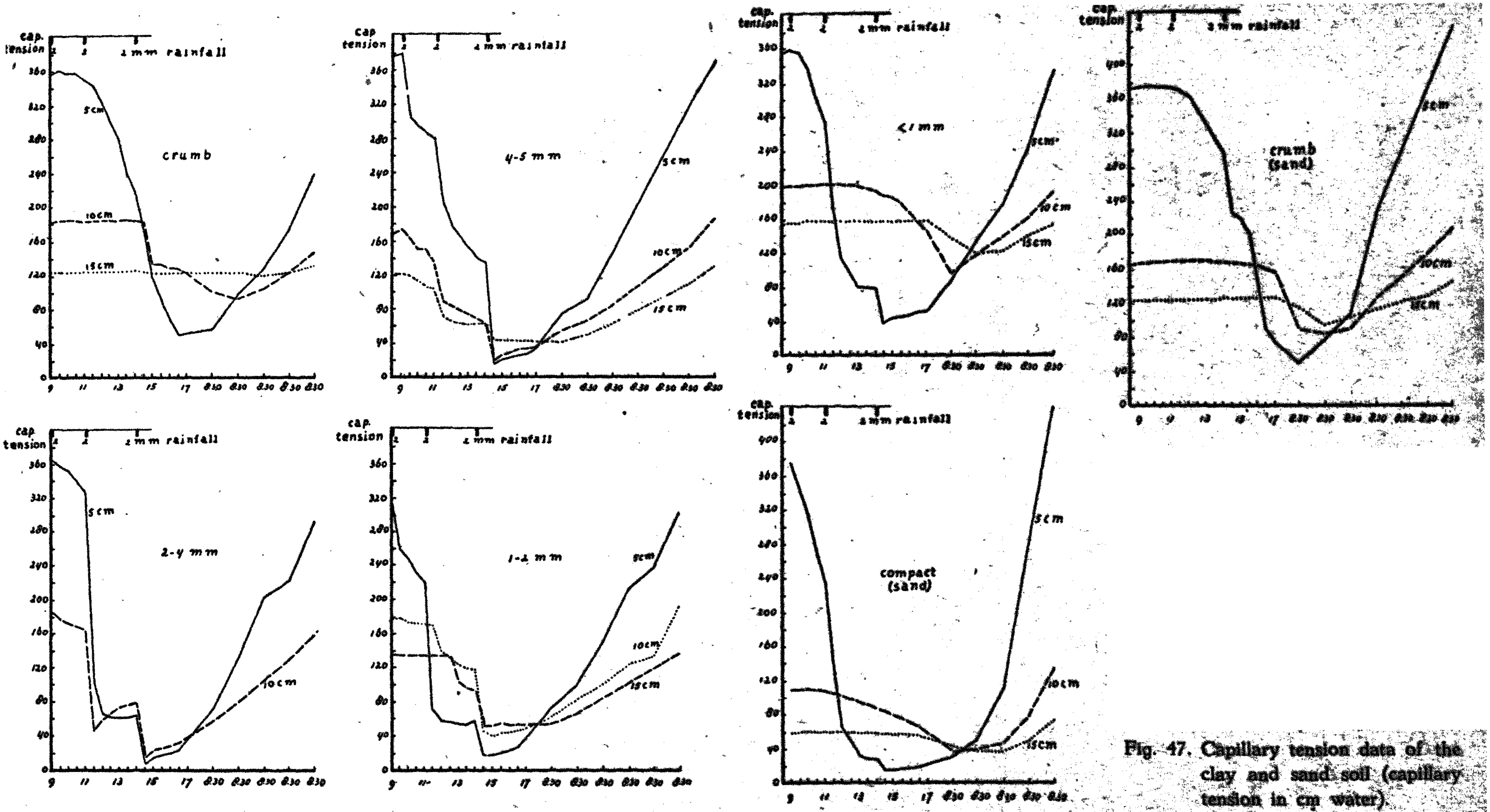

Fig. 47. Capillary tension data of the clay and sand soil (capillary tension in cm water).

depends on: 1. the resistance it meets in the soil; 2. the rate of retention. Thus, the greater the resistance, the longer it will be before the water reaches a given depth; and the more water is retained, the less far water penetrates into the soil. Now the structure determines which of these factors plays the most important part. In a soil with large clods and cracks the first feature is most important; the water runs rapidly along the large cracks between the clods and causes in this way a rapid decrease of the capillary tension at any depth. Examples are the pots with aggregates of 4—5 and 2—4 mm. The structure of aggregates of 1—2 mm offers more resistance already, so that the possibility of water absorption becomes more important. The fraction smaller than 1 mm impedes water penetration to a considerable extent, but because of the small pore space the capillary tension in the top layers will change very considerably. Hence, soils with well defined aggregates drain very rapidly.

Soils with a crumb structure behave very differently. They behave like a sponge, that absorbs all the water added. Therefore a smaller depth is reached with a given amount of water. Since the capillary tension on 15 cm depth did not change practically during the experiments, one may say that the rainfall of 6 mm had been absorbed in the upper layer of the soil. The amount of drainage water will be negligible here.

Similar observations are applicable to sandy soils and are supported by the fact, that during the period of 1 March—26 March the compact structure needs more water to keep the capillary tension within definite limits than the crumb structure; the amounts were 40 mm and 20 mm respectively. This also is a proof that soil in crumb structure utilizes water more economically that does a soil in a compact structure.

Finally in fig. 47, on drying, the capillary tension at half past eight on the days following on the above mentioned experiment is plotted out. It shows that the capillary tensions reach their initial values in the pots 19 and 20 (4—5 mm) after 5 days, in pots 21 and 34 (2—4 mm), 35 and 36 (1—2 mm) after 6 days, in pots 51 and 53 (<1 mm) after 5 days and in the crumb structure after 7 days. This is a further evidence that soils in crumb structure have a better water economy (see also: v. Schuylenborgh and v. Bavel, 1946).

§ 2. *Structure and air conditions in the soil.*

It was Dojarenko (see: Krause, 1931) who did much fundamental work to elucidate this problem. He traced for instance the influence of different tillage operations during the fallow year in the three course rotation, very commonly found in Russia, on the air and oxygen conditions in the surface layer. The tillage operations were as follows: I. An oats stubble field was ploughed in September. In spring it was harrowed and in the course of the summer ploughed three times, each time to a greater depth. II. A second field was ploughed in spring for the first time; the further tillage operations were similar to those of I. III. The field was not cultivated at all; three weeks before sowing it was ploughed once. IV. This field was grazed; in the middle of June it was ploughed, after which the very cloddy soil was harrowed many times in order to level it.

These are four tillage operations that are much used in Russia. The results of these experiments are important also for our regions, because they show very clearly the influence of the different operations on the soil in the absence of disturbing influences of crop plants. The results are given in table 12.

TABLE 12

	I			in % of the O_2-content of I	II			in % of the O_2-content of I	III			in % of the O_2-content of I	IV			in % of the O_2-content of I
	in 1 l of soil		% O_2		in 1 l of soil		% O_2		in 1 l of soil		% O_2		in 1 l of soil		% O_2	
	air cc	O_2 cc			air cc	O_2 cc			air cc	O_2 cc			air cc	O_2 cc		
April 20 th	325	65	20	100	235	46	19.6	70.7	220	43.8	19.9	67.4	150	28.7	19.1	44.1
„ 27 th	305	58	—	—	240	—	—	—	—	—	—	—	—	—	—	—
Ploughing of II and harrowing of I																
May 1 st	360	70	19.5	100	420	84	20	120	220	42.6	19.3	60.9	158	28.6	18.1	40.8
„ 12 th	290	52	17.9	—	—	—	—	—	—	—	—	—	—	—	—	—
harrowing of I																
May 15 th	340	68	20	100	360	71	19.7	104.4	200	38.2	19.1	56.2	154	22.3	14.5	32.8
June 1 st	300	55	18.3	100	320	62.5	19.5	113.6	200	37.8	18.9	68.7	156	18.2	11.7	33.1
June 12 th	290	50	17.2	100	310	60	19.3	120	200	36.5	18.2	73	150	16	10.6	32
Ploughing of III and IV „ of I and II																
June 15 th	410	81.5	20	100	400	79.5	19.9	97.5	320	64	20	78.5	280	42	15	51.5
„ 28 th	350	67	19.1	100	370	74	20	110.4	300	59.5	19.8	88.8	240	36	15	53.4
July 1 st	380	75	19.7	100	410	81.4	19.8	108.5	330	65.9	19.9	87.9	274	48	17.5	64
„ 15 th	325	60	18.5	100	340	73	21.5	121.7	315	62.8	19.9	104.7	250	46	18.4	67.7
Sowing																
August 1 st	340	70.5	20.7	100	360	71	19.8	100.7	300	58.3	19.4	82.7	240	41	17	58.1
„ 15 th	320	63	19.7	100	350	69.5	19.9	110.3	290	57.0	19.8	91.4	220	32	14.5	50.8
September 1 st	310	59	19	100	320	63	19.7	106.8	270	52	19.3	88.1	220	32	14.5	54.2

This table shows that the air content gives no indications about the O_2-content. Considering the data of IV it appears, that the O_2-content of soil air of this very compact soil decreases to half of that of atmospheric air. The determination of the air volume of a given soil volume is insufficient, because the O_2-content of soil air may be very different. Furthermore table 12 shows the considerable influence of the tillage operations on the air content. As the soil collapses progressively after each operation the air content decreases on all experimental fields and similarly the O_2-content of soil air. The biological activity, though weak, consumes more O_2 than can be supplied. Only a continuous breaking up of the surface layer guarantees a sufficient O_2 supply in an uncropped soil.

The structure of the soil is very important with respect to the movement of air through the soil. **Dojarenko** specified four mechanisms for the air transport, viz: 1. diffusion; 2. changing of the atmospheric pressure; 3. soil respiration and 4. carrying along of air by rainwater. **Romell** (1922) considers diffusion as the chief mechanism for the air transport in natural soils. On the other hand, Dojarenko thinks that the diffusion and the changing of atmospheric pressure are not important, but that the soil respiration, caused by fluctuations of the temperature is the main factor in the movement of air through the soil. Hudig and Welt (1911) stated that in our humid regions the fourth mechanism can be considered as the chief factor in soil aeration. Although there is no agreement about the fact, which of the four mechanisms the most important in the air transport through the soil, it is clear, that the mentioned mechanisms function the more easily the looser the macro-structure. This is shown in table 13. In this table one finds the permeability for air in dependence of the structure and moisture content of the soil. These data, considered in relation with those of table 14, that gives the pore space of these structures, are very illustrative. It appears, that soils consisting of aggregates with a diameter of less than 0.5 mm have a very small non-capillary pore space. Because only the very large capillaries permit adequate air movement, it will be clear, that in these cases the movement is slight and will stop completely, when the soil is wetted. Already at a moisture content of 25 % of the water capacity it is practically zero. Furthermore table 14 shows, according to Dojarenko and agreeing with other determinations, that agricultural soils should consist of aggregates of about 1—2 mm diameter, as these have a practically undisturbed permeability up to a moisture content of 80 % of the water holding capacity. This is possible only in cases of sufficient non-capillary pore space.

TABLE 13

The permeability for air of soils of different structures at different moisture contents (permeability in % of the free air-movement)

	diameter of the aggregates in mm				
	0.25	0.25-0.5	0.5-1	1-2	2
dry	43.4	85.3	97.2	96.4	100
20.0% of the minimal watercapacity	10.2	45.2	95.4	93.8	100
38.4% ,, ,, ,, ,,	—	14.1	98.2	94.8	96.4
62.3% ,, ,, ,, ,,	—	—	94.1	100	98.5
84.8% ,, ,, ,, ,,	—	—	99.0	95.6	100
100 % ,, ,, ,, ,,	—	—	60.1	55.2	74.2

TABLE 14

Pore spaces of soils, existing of aggregates of different diameter.

diameter aggregates in mm	<½	½-1	1-2	2-3	3-5	½	½-1	1-2	2-3	3-5
	in % of the volume of soil					in % of the pore space				
capillary pore space	44.8	25.5	25.1	24.4	23.9	92	51	46	41	37
non-capillary pore space	2.7	24.5	29.6	35,1	38.7	8	49	54	59	63
total pore space	47.5	50,0	54.7	59.6	62.6	100	100	100	100	100

§ 3. *Structure and agriculture.*

A. Structure and soil cultivation.

The author has already discussed this problem in Chapter V but will deal with this subject here somewhat more extensively.

With respect to soil cultivation one has to take into consideration 1. the crop to be grown ; 2. the structure of the soil profile ; 3. the nature of the implements ; 4. the chemical composition of the soil.

It seems that different crops have different soil structure requirements. Little is known about this problem. Apsits (1936, 1937) gave some information with respect to oats, barley, peas and beets. He artificially made different structures by screening the upper 20 cm layer of an experimental field through a 2 mm sieve. The sieved soil was laid down in the original place. After that he brought plot 1 in a very compact structure by treading it strongly, plot 2 in compact structure by treading it less strongly, plot 3 in a loose structure by pressing the soil slightly whereas plot 4 was not pressed at all and remained in a very loose structure. Finally the plot were drilled with the above mentioned crops. During the vegetation period Apsits measured among other things the pore space and water holding capacity.

Generally the experiments showed that the condition of the surface horizon has little influence on the germination of the seed. It appeared that in dry periods the germination was better in the cases of the more compact structures. In humid seasons the best germination was found in the looser structures.

The best growth was found on plots 3, whereas on plots 4 the crops, especially barley, oats and peas showed deficiency symptoms. On plots 1 and 2 strong disturbances in the growth occurred. In the year 1930 beets did show branched root systems on plots 1 and 2, whereas on plot 4 a strong branching could be seen. These phenomena probably originates from the water supply since beets need much water to germinate, probably also for the further growth. Therefore a very loose structure, that dries rapidly, will not be a good seedbed for beets ; the strong branched root system indicates that they tried to search for water.

During the years, in which the experiments were carried on, oats and barley showed the best crops on plot 3 and sometimes on plot 2.

Because Apsits' experiments did not include a soil in crumb structure, no conclusions can be drawn about the question which structure gives the better growth, a cloddy or a crumbly structure. The author of this work concludes that only in the case of cloddy structures, different crops have different soil structure requirements Yet a crumbly structure always gives the best cultural possibilities (see p. 86).

It is clear that the structure of the soil profile determines which tillage operations have to be performed. Cleveringa and other workers have demonstrated several times, that the subsoil may be very compact, a state, which very often can be found e.g. on eelworm-infested patches in a rye crop. It is necessary to know the depth of the under surface of this compact layer or "plough-pan". The subsoil-plough is adjusted two to three cm deeper than this level. Only then is it certain that the superfluous water will drain off and that the plant roots will develop normally in the one to two m depth present in a well aerated soil. Deep ploughing in such a case may become a failure because the compact subsoil is brought to the surface and the crumbly surface layer is buried. Therefore shallow ploughing (on sandy soil as shallow as possible) accompanied by subsoiling is most suitable.

There is much information concerning the solidity of the material, the suitability of the construction, the draft requirements, the resistance against fracture of farm implements, but one has only an approximative idea about the quality of most of the work performed. Again it is Dojarenko, who has initiated examination of this problem.

In 1911 four tillage practices were tested on the experimental fields of the Agricultural College at Moscou, viz.:

a. complete inversion of the furrow with the „Prairy Queen Breaker"-plough;
b. ploughing with the use of a screw-shaped mouldboard;
c. ploughing with a Sack-plough with coulter;
d. skimming to a depth of 6 cm, followed by ploughing with a „Sack"-plough after a week.

The results with respect to the conservation of soil water showed the superiority of the methods c and d. The water content of the surface layer is considerable higher after operations c and d than after operations a and b. The same holds for the air content of the soil, for the nitrification and for the crop yield. These results indicate that the operations c and d crumbled the soil better than operations a and b.

Other workers as Vilenski and Vassilenko (1934), Pigulewski (1934) and Nekrassbv (1934) obtained similar results. Some remarks should be made about the work of Nekrassov. This investigator compared the results of ploughing with different mouldboards and of the cultivating with a rotary-tiller. He concluded that in the latter case the soil was better crumbled (meant: the aggregates are reduced) and the crop yields were higher than in the first cases. The author of this work wishes to warn against generalisation of these results. The nature of the soil strongly influences the results obtained with the rotary-tiller. The acting part of the rotary-tiller is a revolving horizontal shaft at right angles with the line of draft. Spring-tines or blades are attached to this shaft, which is driven by a motor. The blades are forced at a high speed through the soil, by which the soil is pulverized thoroughly. The degree of desintegration of the soil depends on the speed of movement and on the number of revolutions of the axle. On light soils the danger exists, that the soil will be pulverized too much, so that the soil aggregates will be broken down into their constituent particles. In this way a grain structure results. The experiments of Cole (1939) illustrate this danger.

It is advisable to carry out similar experiments with other implements. A problem, which from the view-point of soil structure is rather urgent, is the homogenous mixing of the soil with fertilizers, so that an even distribution results. Only by a uniform distribution the soil retain an even structure (Leijenaar, 1932; Hudig, 1933; 1935). Hand spreading or mechanical distribution of fertilizers results in an uneven distribution, causing the structure of the soil to differ from place to place. The distribution of manure through the soil is a problem; one ploughs under the organic residues so that they are buried. Turning under fertilizers with a harrow or a cultivator does not lead to a homogenous distribution of them through the soil; the harrow and cultivator drag the fertilizers over the soil and do not mingle them. The disc-harrow mixes the fertilizers with the soil fairly good.

Finally the author wishes to draw attention to the fact that oftentimes not enough care is taken to spare the soil during harvesting-operations and carting. Frequent traffic along the same path with heavy implements should be avoided as far as possible, lest a severe compacting of the soil occurs, resulting in a poor crop the following year. Fig. 48 shows such a case, in which ploughing and harrowing could not correct the harm caused by injudicious carting. Fig. 48 (right) shows the succeeding crop, which is lodged along the carttracks.

B. Structure and yield of the crop.

It has been shown many times, that the structure of the soil strongly influences the yields. Some pot experiments of Dojarenko (1931) and of the author will be considered here. These experiments show once again the importance of a definite distribution of the capillary and non-capillary pore space to the plant growth.

Dojarenko filled his pots with the sieve fractions 0—0.5, 1—2 and 2—3 mm of a given soil and with mixtures of these fractions, viz. 40 % 2—3 mm and 60 % 0—0.5 mm and 70 % 2—3 mm with 30 % 0—0.5 mm. He sowed spring wheat and traced the influence of the different structures on the length of the crop, total yield and grain yield. The results are given in table 15.

This table shows that the aggregates of 1—2 mm diameter give the best results and that deviations from this size lead to a decrease in yield.

The author performed similar experiments with Synapis alba. In the pots, described previously in § 1 of this Chapter, 100 seeds were sown rather deep, viz. 2 cm below the surface on March 26th. During the growth period all pots were kept at optimum moisture content. Records were kept of the germination of the seeds. The results are given in table 16 and fig. 49.

On the first day of emergence very large differences occurred, as was to be expected in view of the known facts. The seeds in pot

TABLE 15

Yield of wheat in dependence of structure

	I	II	III	IV	V
	0-0.5	60% 0-0.5 40% 2-3	30% 0-0.5 70% 2-3	1-2	2-3
Height of wheat in cm	47	57	57	67	60
Total yield in % of IV	33.3	53.4	61.8	100	93.7
Grain yield in % of IV	23.6	51.9	62.7	100	95.2

20 (fraction 4—5 mm) were retarded in germination, probably due to the fact that the contact between soil and seed was too poor to guarantee sufficient uptake of water. In the end this pot gives the same germination as the rest. The soil with very compact structure showed very poor germination. It can be concluded, that all aggregate sizes guarantee adequate germination. In the sandy soil the seeds also germinate well with compact structure. The conclusion seems justified that the air supply in the compact sandy soil, provided that the sand particles are large as in this case, is sufficient to secure a good germination and, as will be shown furtheron, a good growth.

TABLE 16

	germination on					
	March 28 11 a.m.	March 28 4.- p.m.	March 29 $9^1/_2$ a.m.	March 29 5.- p.m.	March 30 $10^1/_2$ a.m.	April 1
crumb	35	52	80	83	88	90
very compact	8	13	26	34	57	40
4-5 mm	1	16	36	46	54	90
2-4 mm	3	21	68	85	90	93
1-2 mm	52	69	75	85	86	84
>1 mm	10	30	72	85	85	86
sandy soil						
crumb	46	58	73	75	76	78
very compact	14	28	43	62	65	71

After thinning out twice, the experiments were terminated on May 10th. The mean fresh and dry weights of the plants were determined. The results are given in table 17, together with the figures for the capillary and non-capillary pore spaces. Primarily it appears that crumb structures have given the largest yields, followed by the fractions 1—2 mm, < 1 mm, 2—4 mm, 4—5 mm respectively, whereas the compact structure closes the row. The author emphasizes the fact, that crumbly structures gives a better yield than the soils consisting of aggregates of 1—2 mm diameter, that are considered to be ideal sizes by the Russian workers. Leaving out of consideration the crumbly structure, the results agree very well with those of Dojarenko.

TABLE 17

Yields of Synapis alba on different structures and the pore spaces of these structures.

	fresh weight per plant in g	dry weight per plant in g	Volume solid phase %	Capillary pore space %	Non-capillary pore space %
Clay: crumb	0.639	0.0805	28.7	27.6	43.5
compact	0.372	0.0460	53.8	43.3	2.9
4-5 mm	0.393	0.0600	32.7	28.5	38.8
2-4 mm	0.511	0.0644	37.0	29.4	33.6
1-2 mm	0.564	0.0757	34.4	35.0	30.6
<1 mm	0.454	0.0680	46.7	44.0	9.3
Sand: crumb	0.666	0.0960	37.5	27.6	34,9
compact	0.633	0.0886	62.7	28.7	8.6

The question arises which structure is more economical, a crumb structure or a structure of aggregates with a diameter of 1—2 mm. Or, in other words, which of the two structures is easier to maintain. The opinion of the author is, that, in the soil investigated, a structure of aggregates of 1—2 mm is more water-resistant than a crumb structure (see Chapter II) and that it is easier to bring a soil to a structure of aggregates of 1—2 mm than to a crumb structure. Nevertheless it would be worth while to bring the soil to a crumb structure, as the yields would make up for the increased costs of cultivation and fertilization. Furthermore in the long run fertilizer-requirements in a crumb structure will be smaller than in a cloddy structure, because the effect of fertilizers in a crumb structure is greater than in a compact structure.

It is to be recommended to verify the results of the above mentioned laboratory experiments with field experiments.

In addition the author points to the fact that the structure of aggregates smaller than 1 mm diameter gives yields better than the structure of aggregates of 2—4 mm and 4—5 mm diameter, in spite of the fact, that the non-capillary pore space of the first is a small fraction of the latter. The author concludes, that a soil, being flocculated always has a sufficient non-capillary pore space to ensure adequate aeration and thus good plant growth. Or in other words: It is always better to have many small clods than a few large clods in a definite volume. The contact surface of the roots with the soil in the first case is larger than in the latter case, so that more food elements may be taken up.

In this connection the author emphasizes, that the compact structure of the sandy soil has a larger non-capillary pore space than the corresponding case of the clay soil. This originates from the very large sand grains of the soil. The sand grains form a closely fitting soil skeleton and the clay content is not large enough to fill up the pores between the sand grains. Because the yield on this structure is not much smaller than on the crumb structure, the author has to conclude here also ,that the air supply is quite suitable. This agrees with the findings in the clay soil (diameter of aggregates smaller than 1 mm). It may be concluded, that a non-capillary pore space of 8—10 %, provided these non-capillary pores are distributed uniformly through the soil and the water supply is good, as in these experiments, guarantees a fairly good yield at least with respect to the quantity.

The structure of the soil influences the quality of the crop also. One has to remember the occurrence of hunger-diseases on soils in compact structures. It may even be expected that before the quantity of the yield has decreased, the quality (e.g. decreased PO_4-content, starch-content, etc.) has already decreased.

Further the shape of the underground parts of plants are strongly influenced by the soil structure. The shape of potato tubers may be very irregular; it is not always due to a varietal characteristic, since it may be the result of jamming between clods during growth. Examples of malformed swedes are seen in fig. 50. The presence of a water impermeable layer may prevent the roots from penetrating into the soil, so that the plants are entirely dependent on the amount of water and plant foods in the surface layer (see fig. 51). This leads to a decrease in quality and quantity.

In this work the subsoil is left out of consideration, though this subsoil is an important factor in the growth of plants. It is of importance to investigate to what depth our cultural treatments reach down into the subsoil; questions about subsoil cultivation and other problems have to be investigated. The author believes that an approach to these problems can be found in the preceding chapters.

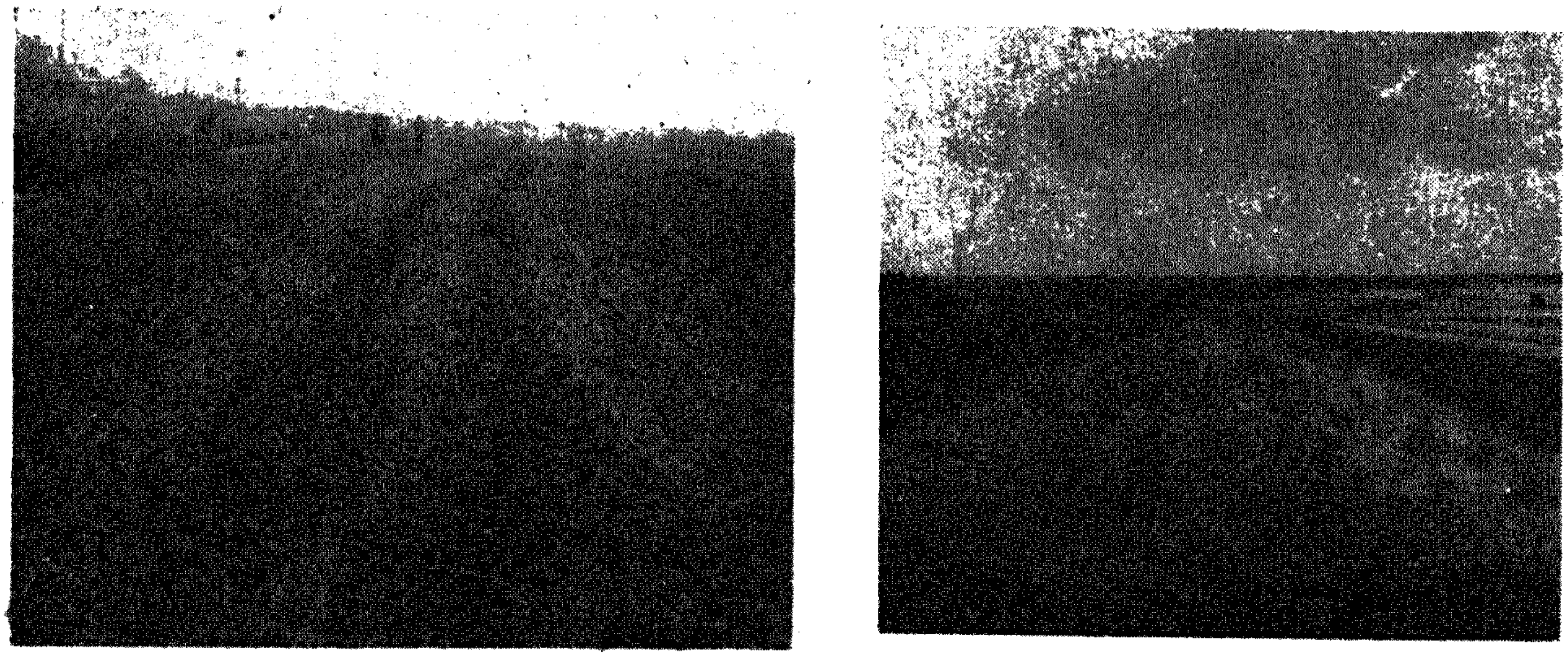

Fig. 48. Left: ploughed and harrowed field with carttracks. Right: the crop on this field. o

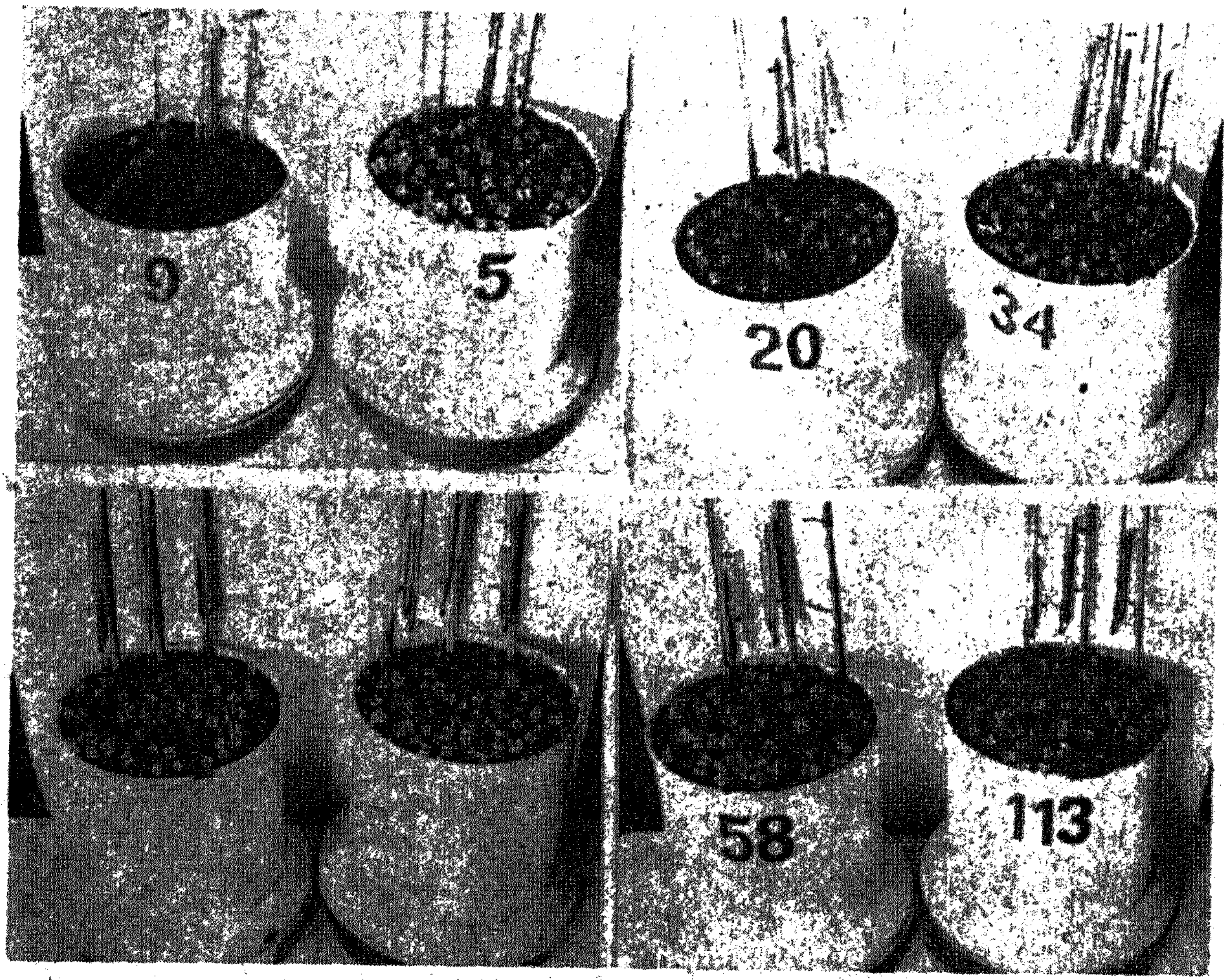

Fig. 49. State of germination on March 30th. Above: from left to right: clay soil: compact structure, crumb structure, fraction 4-5 mm and 2-4 mm. Below from left to right: clay soil: fraction 1-2 mm and < 1 mm; sandy soil: crumb structure and compact structure. x

o Photo Lab. Agric. Chem. x Photo author.

x

Fig. 45. One series of pots to investigate water condition in soils with different structures.

Fig. 50. Malformed swedes. o

Fig. 51. Horizontal roots. o

o Photo Lab. Agric. Chem. x Photo author.

SAMENVATTING.

Hoofdstuk I.

In de inleiding werd uiteengezet, dat de structuur (voorlopig gedefinieerd als de ruimtelijke verdeling van de vaste, vloeibare en gas phase) allerminst een statisch begrip is, doch veeleer een dynamisch begrip, als gevolg van het feit dat de structuur een resultaat is van de werking van een aantal factoren (electrolytgehalte, aard van het electrolyt, activiteit van de micro- en macroflora en fauna, enz.), waarvan enkele een sterk dynamisch karakter hebben, op de bodem. Het bleek verder, dat de structuur van de bodem een zodanig complex verschijnsel is, dat het noodzakelijk was het structuur-begrip in een viertal onderdelen te splitsen.

De structuur-verschijnselen, die zich zelf voordoen als physische of mechanische verschijnselen, werden kortweg aangeduid met de term structuur. Deze term moest verder gesplitst worden in de actuele en de intrinsieke structuur. De actuele structuur, een direct meetbare doch variabele grootheid, werd gedefinieerd als de physische opbouw van de bodem op een bepaald ogenblik nl. op het moment van de bepaling. Toch heeft iedere grond t.o.v. het structuur-complex een aantal vaste kenmerken. Zo zal een zand en een kleigrond onder overigens gelijk omstandigheden een verschillende actuele structuur hebben als resultaat van het verschil in kleigehalte en bodemskelet, dat eigenschappen zijn, die intrinsiek zijn aan een bepaald bodemtype. Deze verschijnselen worden dus niet gekarakteriseerd door de actuele structuur. Zij werden daarom aangeduid met de term intrinsieke structuur of structuur-capaciteit (zie noot pag. 6). Zij is niet direct meetbaar ,maar is een functie van de constante grootheden van de bodem (b.v. zand-, klei- en humusgehalte). De actuele structuur hangt af van de variabele grootheden (b.v. temperatuur, vochtgehalte, basentoestand, enz.) en tevens van de intrinsieke structuur.

De wederzijdse inwerking van de verschillende factoren bepaalt niet alleen de structuur, maar is ook een gevolg daarvan en zij kan daarom gedefinieerd worden als de structuur-activiteit. Ook hier moest weer onderscheid gemaakt worden in de actuele en intrinsieke structuur-activiteit.

Gedurende de analyse van het structuur-probleem bleek het noodzakelijk te zijn de actuele structuur uitéén te leggen in drie delen, nl. vlok-, micro-, en macro-structuur, resp. gedefinieerd als de physische opbouw van de vlok, van het aggregaat, en van het samenstel van aggregaten, als zijnde de opeenvolgende toestanden van aggregatie.

Hoofdstuk II.

Een nomenclatuur werd gegeven van de verschillende structuren, gebaseerd op het werk van Zakharov, waarbij de nadruk werd gelegd op het wezen van het verschijnsel.

Daarna werden de methoden besproken van het structuuronderzoek in het veld (Goerbing, Cleveringa) en in het laboratorium. De meting van de actuele structuur in het laboratorium gaat langs twee wegen, nl. de meting van de resistentie van een bepaalde structuur tegen een destructieve kracht en de meting van de porositeit. Uitgezet werd dat deze grootheden door verschillende factoren worden beinvloed, zodat deze methoden elkaar vaak niet behoeven te dekken. Ook de verschillende methoden ter bepaling van de porositeit en die ter bepaling van de resistentie behoeven elkaar onderling niet te dekken, waaruit de tegenstrijdigheden in de resultaten van bepaalde onderzoekingen werd verklaard.

Tenslotte werd een methode besproken, ontworpen door den schrijver, waarmee de porositeit van de bodem langs indirecte weg gemeten kan worden uit de snelheid van opstijging van het water in de grond. De differentiaalvergelijking, die deze opstijging formuleert, kan echter wiskundig nog niet opgelost worden. De methode heeft bepaalde voordelen, daar zij laat zien op welke wijze het water in de grond wordt opgenomen en lucht afgestaan, processen, die in de praktijk niet van belang ontbloot zijn.

Hoofdstuk III.

De vorming van de vlok-structuur werd diepgaand besproken aan de hand van literatuur gegevens en van experimenten met kleimineralen en gronddeeltjes $< 2\ \mu$. De factoren, die de vlokstructuur bepalen zijn de kationen en de humus. Het bleek, dat de toevoeging van H- en meerwaardige kationen aan kleisuspensie's resulteerde in een poreuze vlok met geringe resistentie tegen mechanische invloeden, terwijl de éénwaardige kationen een dichte vlok met grote resistentie tot gevolg hadden. Het liet zich dus aanzien, dat de landbouwkundig gewenste poreuze vlok met behoorlijke resistentie niet bereikbaar was. Echter humus toevoeging bleek dit mogelijk te maken. Na toevoeging van een humaatoplossing aan de minerale suspensie's bleek dat nu de vlok, ontstaan door toevoeging van H- en meerwaardige kationen poreuzer en resistenter was dan de vlok verkregen door toevoeging van éénwaardige kationen. Met deze gegevens werden schijnbare tegenstrijdigheden in de literatuur met elkaar in overeenstemming gebracht.

Het K-ion bleek een uitzonderingspositie in te nemen bij de vorming van de vlok. Waarschijnlijk is dit terug te voeren tot het feit, dat de vlokkende werking van K tussen die van het Na- en Ca-ion instaat.

Verder bleek een geringe hoeveelheid Na-ionen een Ca-vlok poreuzer te maken, hetgeen verondersteld werd overeen te komen met de werking van het K-ion.

De practische betekenis van bovenstaande gegevens werd uiteengezet aan de hand van de verbetering van de zoutgronden in het algemeen en die van de geïnundeerde gronden van Nederland in het bijzonder.

Hoofdstuk IV.

De factoren, die de micro-structuur direct bepalen, werden besproken. Het bleek uit de critische discussie van de in de literatuur bekende feiten, dat het zwellen en krimpen van de bodemkolloiden tengevolge van een wisselend vochtgehalte, de samendrukking van lucht in de bodemaggregaten gedurende regens en de fauna de porositeit van de aggregaten verhoogden, terwijl de vorst de porositeit verlaagde; de resistentie van de micro-structuur tegen mechanische invloeden werd vergroot door de vorst-werking, fauna en flora en verkleind door het zwellen en krimpen en de samendrukking van lucht.

Aan de hand van experimenten, verricht met mengsels van zand en kleimineralen, kon duidelijk de invloed van de structuurcapaciteit op de actuele micro-structuur aangetoond worden. Hierbij bleek dat, hoe groter het kleigehalte en hoe fijner het gebruikte zand, hoe groter de resistentie van de gevormde aggregaten. M.a.w. een verschil in intrinsieke structuur resulteerde in een verschil in actuele structuur, terwijl de omstandigheden, waaronder de experimenten verricht werden, constant waren en daardoor een gelijke actuele structuur zouden impliceren.

Hoofdstuk V.

De bewerking van de grond, de beworteling, de bescherming van de bodem door het plantendek en de fauna zijn de factoren, die direct de macrostructuur beïnvloeden.

Voor de bewerking van de bodem is het vochtgehalte op het moment van de bewerking van doorslaggevende betekenis, zoals werd uiteengezet aan de hand van een hypothetisch geval en van enkele literatuurgegevens. Uit de discussie van de invloed van deze factor op de structuur bleek, dat zij moest resulteren in de vorming van kleine onregelmatig gevormde aggregaten.

Tenslotte werd de verbetering van de structuur van de bodem door bemesting met compost aan de hand van een praktijkgeval beschreven.

Hoofdstuk VI.

Aan de hand van potproeven en met behulp van tensimeters werd de waterhuishouding in verschillende structuren nagegaan. Aangetoond werd dat de verplaatsing van water in de grond afhankelijk is van de weerstand die het water ondervindt in de grond en van de mate, waarin het water wordt geabsorbeerd. Tevens werd duidelijk gemaakt, dat de capillaire spanning, waaronder het water in de bodem staat, o.a. sterk afhankelijk is van de structuur van de bodem en dat, indien men met behulp van tensimeters het vochtgehalte van de bodem wil bepalen, de structuur gedurende de tijd van de metingen niet mag veranderen.

De in de literatuur als voor een goede opbrengst beschreven gewenste doorsnede van de bodemaggregaten van ongeveer 2 mm werd eveneens gevonden door den schrijver. Echter kon hij aantonen dat een kruimelstructuur aanzienlijk hogere opbrengsten gaf.

Uit deze en andere overwegingen volgt, dat, wil men een grond, die zich in een compacte en dus landbouwkundig slechte structuur bevindt, beter voor de productie van plantenmateriaal geschikt maken, dat men dan genoodzaakt is, door doelmatige bemesting en bewerking, de bodem in een zodanige toestand te brengen dat een structuur ontstaat van kluiten, die de doorsnede van 2 mm zoveel mogelijk benadert en dat daarna de voorwaarden geschapen moeten worden voor een goede ontwikkeling van de activiteit van de biologische buffer; wanneer dan de goede cultuurmaatregelen genomen worden, ontstaat automatisch de voor de landbouw zo gewenste kruimelstructuur.

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APPENDIX I.

Some remarks, both of qualitative and of quantitative nature, should be made with respect to the suction method (Chapter II, p. 17) in determining soil structure.

In all physical processes in soil, where water plays a part, like in our problem of soil structure, in swelling and shrinking, in capillary ascension of water, etc., the degree of wetting of the soil particles by water plays a very important rôle. This was found by the author when he tried to determine the structure of a sample of dried peaty soils (sample XX, table 3) with the suction method. This appeared to be impossible because the soil did not absorb water as a consequence of the nonwetting properties of this soil. Again, the author prepared, by sieving, aggregates of a diameter of 1—2 mm of the Nude-clay and the clay soil of the forelands. These aggregates were filled in glass tubes of 1 cm diameter and brought into contact with a free water surface and the ascension of water was measured in dependence of time. Moreover the specific weights were determined, using both water and CCl_4 (see Chapter II, p. 17), and the pore space. The results are given in table 18. The table shows that, althougth the forelands clay has a larger pore space than the Nude-clay, the rise of water is slower. The reason is, that the Nude-clay is more wettable than the forelands clay. This incomplete wetting appears clearly after determining the specific weight with water and with CCl_4. The foreland soil gives a greater difference between these values than the Nude clay as a result of the better spreading of water in the latter case. In determining

TABLE 18

	Nude clay	foreland clay
specific weight in water	2.5	2.0
specific weight in CCl_4	2.6	2.4
pore space computed with specific weight in CCl_4	62.1 %	73.5 %
ascention in cm after 1 min.	0.7	0
2 „	1.4	0
3 „	2.0	0.2
6 „	4.0	0.6
9 „	4.6	0.9
12 „	5.2	1.1
15 „	5.6	1.2
organic matter content	1.8 %	4.8 %

the specific weight with water, smaller amounts of air are removed from the pores than by immersing the soil in CCl_4. In the first case one determines the volume of the solid phase increased with a part of the volume of air in the interior of the aggregates and a too small value for the specific weight is found. In both examples, the incomplete wetting seems to be determined by the nature and the amount of the organic matter in the clays.

The conclusion is that, determining the structure with the suction method, inaccurate results are possible in some cases. There are two ways to remove this complication: 1. by using a spreading liquid; 2. by determining the angle of contact α. 1. The author mentioned already that the method described could not be applied to irreversibly dried peats, because of the non-wetting properties of the soil. The spreading of liquids upon solid surfaces depends on the surface tension of the liquid, the surface tension of the solid material and the interfacial tension between the solid phase and the liquid (see fig. 52). The work of adhesion W_{SL} of the interface SL can be given by the expression:

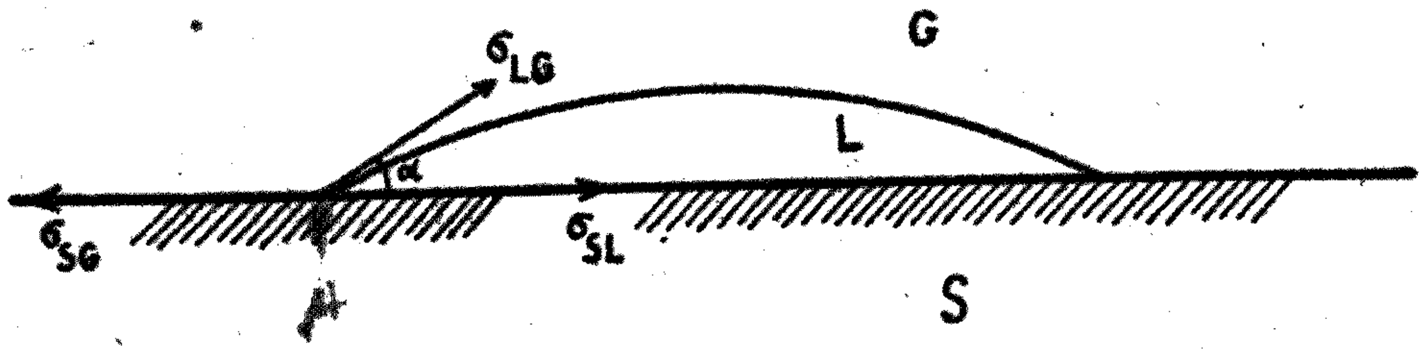

Fig. 52.

$$(9)\quad W_{SL} = \sigma_{SG} + \sigma_{LG} - \sigma_{SL} \quad \text{erg/cm}^{-2}$$

Point A being in an equilibrium position, the relation holds:

$$(10)\quad \sigma_{SG} = \sigma_{SL} + \sigma_{LG}\cos\alpha \quad \text{erg/cm}^{-2}$$

A combination of the equations (9) and (10) gives

$$(11)\quad W_{SL} = \sigma_{LG}(1 + \cos\alpha) \quad \text{erg/cm}^{-2}$$

In the case of the extremely dehydrated peaty clays α approaches 180°, so $\cos \alpha = -1$. Hence, W_{SL} is 0 practically, in other words, water does not spread over the surface. Using CCl_4, then it appears that $\alpha = 0$, or $W_{SL} = 2\,\sigma_{LG}$ and the liquid spreads over the surface.

Therefore the author tried to use CCl_4 for this purpose, but a new complication arises. The ascent of CCl_4 in the soil sample was very slow, or, in many cases, even 0, because the capillary pressure (small surface tension of CCl_4) could not cause a shifting of the drop of mercury in the apparatus.

2. It is principally possible to determine the work of adhesion of solid

substances in an indirect way. Bartell and Osterhof (1928) have shown this. This method will be studied and, if possible, adapted to soils.

Finally the derivation of equation (1) on page 18 of Chapter II will be given here somewhat more extensively. The experimental arrangement may be represented by a bundle of capillary tubes (the soil), that absorbs water from a wide capillary tube. Using the law of mechanics, K = m.a, the pressure p_t at the moment t, responsible for the rise of water in the capillaries can be computed in the following way:

In the narrow capillaries the relation holds:

$$K_1 = n \pi r_1^2 Dh_1 \frac{d^2h_1}{dt^2} \quad \text{or} \quad p_1 = Dh_1 \frac{d^2h_1}{dt^2} \qquad (12)$$

In the wide capillary tube:

$$K_2 = \pi r_2^2 Dh_1 \frac{d^2h_2}{dt^2} \quad \text{or} \quad p_2 = Dh_2 \frac{d^2h_2}{dt^2} \qquad (13)$$

Because $h_2 = \frac{nr_1^2}{r_2^2} h_1$, $\frac{d^2h_2}{dt^2}$ can be substituted by $\frac{nr_1^2}{r_2^2}\frac{d^2h_1}{dt^2}$. Hence the pressure p_t equals to

$$p_t = p_1 + p_2 = \frac{d^2h_1}{dt^2}\left(Dh_1 + \frac{nr_1^2}{r_2^2} Dh_2 \right) \qquad (14)$$

where $\frac{d^2h_1}{dt^2}$ = the acceleration of the water in the soil
D = density of water
h_1 = rise of the water after time t
r_1 = radius of the capillary tubes in the soil
n = number of capillaries in the soil
h_2 = length of the water column in the wide capillary tube after time t
r_2 = radius of the wide capillary tube.

The pressure p_t is composed of the capillary pressure in the narrow capillaries, $\frac{2\sigma}{r_1}\cos\alpha$, minus the pressure in the wide capillary tube, $\frac{2\sigma}{r_2}$, minus the pressure, caused by the weight of the water in the narrow tubes, h_1Dg, minus the pressure, caused by the internal friction of the liquid in both capillary tubes and minus the resistance, caused by the convection currents occurring during the entry of water into the capillaries.

The pressure drop, caused by the internal friction of the liquid is given by the Poiseuille formula, viz.:

$$p_i = \frac{8\eta h}{r^2}\frac{dh}{dt}$$

where η = the viscosity of the liquid and p_1 = the fall of pressure, caused by the friction, when the movement is stationary ; and the convection resistance by

$$(15) \qquad p_2 = \frac{1}{4} \pi r^2 n D \left(\frac{dh_1}{dt} \right)^2$$

according to Hughes and Safford (1911).

Hence, by substituting p_t by these quantities, the equation is obtained :

$$\frac{2\sigma}{r_1} \cos \alpha - \frac{2\sigma}{r_2} - h_1 D g - \frac{8\eta h_1}{r_1^2} \frac{dh_1}{dt} - \frac{8\eta h_2}{r_2^2} \frac{dh_2}{dt^2} - \frac{1}{4} \pi n r^2 D \left(\frac{dh_1}{dt} \right)^2 =$$

$$(16) \qquad \frac{d^2 h_1}{dt^2} \left(D h_1 + \frac{n r_1^2}{r_2^2} D h_2 \right)$$

Substituting $\frac{dh_2}{dt}$ by $\frac{n r_1^2}{r_2^2} \frac{dh_1}{dt}$ and h_2 by $h_0 - \frac{n r_1^2}{r^2} h_1$, when h_0 is the lenght of the water column in the wide capillary tube at the beginning of the measurement, the relation results :

$$\frac{d^2 h_1}{dt_2} \left\{ h_1 \left(D - \frac{n^2 r_1^4}{r_2^2} D \right) + \frac{n r_1^2}{r_2^2} D h_0 \right\} + \frac{1}{4} \pi n r^2 D \left(\frac{dh_1}{dt} \right)^2 + \frac{dh_1}{dt} \qquad (17)$$

$$\left\{ h_1 \left(\frac{8\eta}{r_1^2} - \frac{8\eta}{r_2^2} \cdot \frac{n^2 r_1^4}{r_2^2} \right) + \frac{8\eta h_0}{r_2^2} \cdot \frac{n r_1^2}{r_2^2} \right\} - h_1 D g - \frac{2\sigma}{r_1} \cos \alpha + \frac{2\sigma}{r_2} = 0$$

or :

$$(18) \qquad (a_0 h + b_0) \frac{d^2 h}{dt^2} + a \left(\frac{dh}{dt} \right)^2 + (a_1 h + b_1) \left(\frac{dh}{dt} \right) + a_2 h - b_2 = 0.$$

when :

$a_0 = h_1 \left(D - \frac{n^2 r_1^4}{r_2^2} D \right)$

$b_1 = \frac{8\eta h_0}{r_2^2} \cdot \frac{n r_1^2}{r_2^2}$

$h_1 = h$

$b_0 = \frac{n r_1^4}{r_2^2} D h_0$

$a_2 = D . g$

$a = \frac{1}{4} \pi n r^2 D$

$a_1 = \frac{8\eta}{r_1^2} - \frac{8\eta}{r_2^2} \cdot \frac{n^2 r_1^4}{r_2^2}$

$b_2 = \frac{2\sigma}{r_1} \cos \alpha - \frac{2\sigma}{r_2}$

APPENDIX II.

The flocculation experiments were done with purified minerals. Because no electrodialysator was available the dialysis bags were put into jars filled with 0.05 n HCl, which were shaken in an end-over-end shaker. The dialysis liquid was renewed daily. The kaolinite was Ca- and Fe-free after 4 weeks, the bentonite after 6 weeks, the illite after 2 weeks and the fraction $< 2\ \mu$ of the clay soil from Neerlangbroek after two weeks. At the end of this period the Cl-ion was washed out by shaking the bags in distilled water. The kaolinite, illite and soil fraction $< 2\ \mu$ was Cl'-free after 1 week, the bentonite after 2 weeks. As a precaution dialysis with distilled water was continued for one week after the Cl'-free state. A dialysis with double distilled water during 4 days followed. The purified H-preparates were dried at 105° C.

To prepare the Na, K and Ca-preparates the base exchange capacities (at pH 7) of the minerals had to be determined. These were measured by potentiometric and conductometric titrations of the minerals, dispersed in water, with the hydroxides of Na, K and Ba.

The conductivity measurements were carried out with the Philips "Philoscop", type GM 4140, combined with the Philips oscillator GM 4260. After the determination of the cell constant of the conductivity cell with the aid of KCl solutions, the specific conductivities could be computed. The conductivity cell used is shown in fig. 53. It consists of a Jena vessel, in which the tubes A and B are fused. These tubes are closed with two Pt-discs (a) and filled with mercury. The lid of the cell holds a tube C, used for the introduction of N_2-gas, a microburette D and the stirrer E. In this way the conductivity of the system could be determined up to high pH-values. The cell was put in an electrically heated thermostat filled with paraffin-oil. The temperature was kept at 21.98° ± 0.025° C; the fluctuation was 0.05° C.

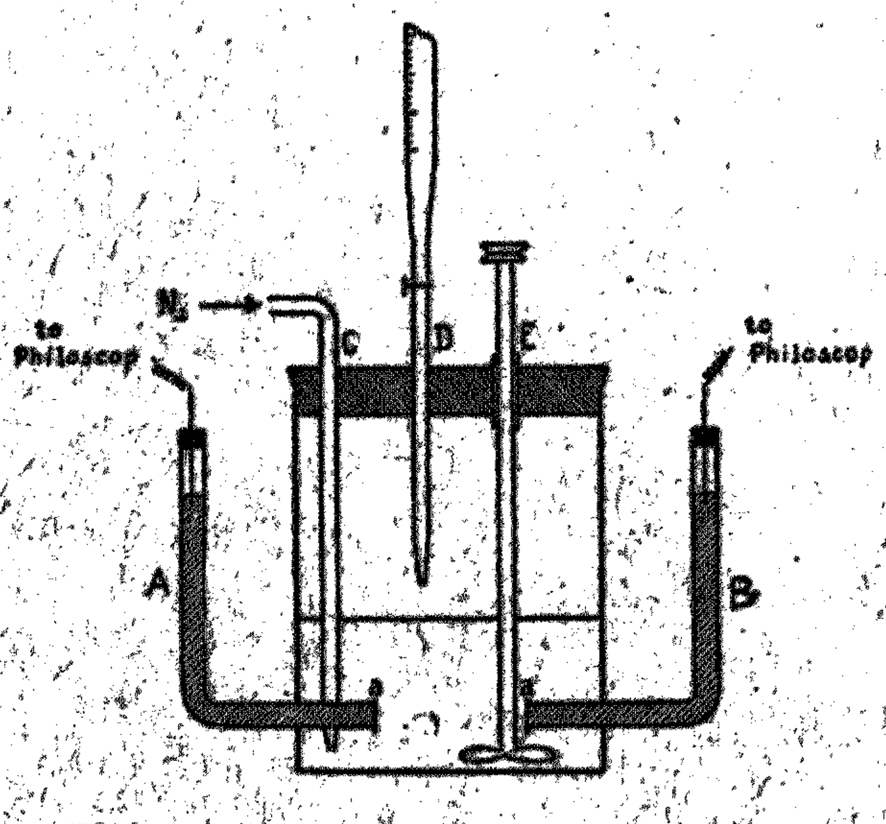

Fig. 53. The conductivity cell used.

The potentiometric titrations were carried out with a similar type of cell. It is shown in fig. 54. In this case, thoroughly purified H_2-gas was introduced, because a hydrogen-electrode was used for the pH-measurement. The potential of the H_2-electrode against a saturated calomel-electrode was measured with a Cambridge-electrometer.

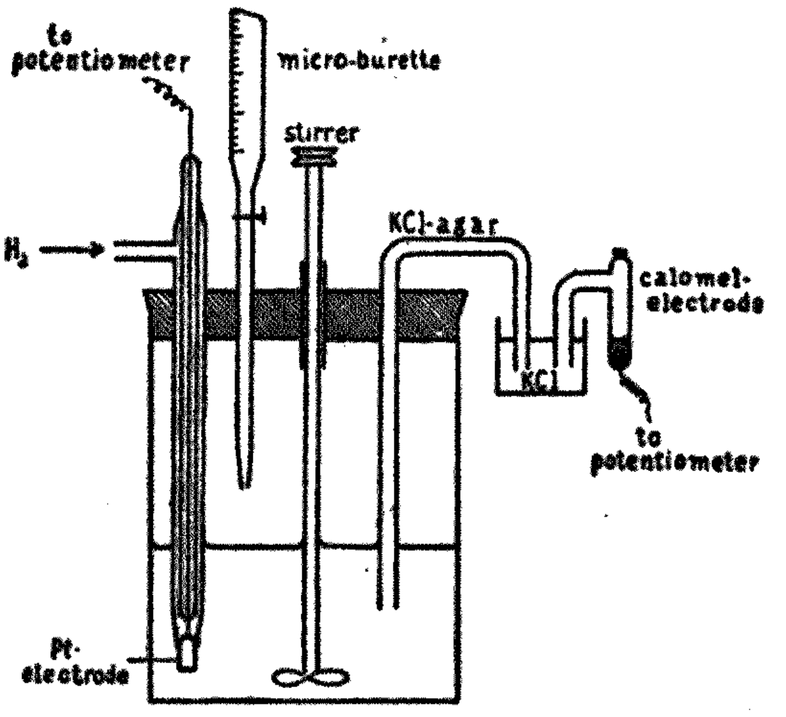

Fig. 54. Cell used for the potentiometric titrations.

The kaolinite suspensions had a concentration of 1 g in 25 cc double distilled water, the bentonite suspensions of 100 mg/25 cc double distilled water and the illite and soil fraction $< 2\,\mu$ suspensions of 150 mg/25 cc double distilled water. The result of some titrations of kaolinite and bentonite are given in figs. 55, 56 and 57; a detailed discussion of the results will begiven in a later paper.

The base exchange capacities were found by reading the number of milli-equivalents of base, required to raise the pH value to 7. From the conductometric titration curves they can be found as the point of intersection, obtained by elongating the base line and the initial, more or less straight part of the curves. The values are in the case of kaolinite: Na, 0.054 m.e.; K, 0.056 m.e. and Ba, 0,057 m.e./g; of bentonite: Na, 0.623 m.e.; K, 0.632 m.e.; Ba, 0.710 m.e./g; illite: Na, 0.293 m.e.; Ba, 0.393 m.e./g: of soil fraction $> 2\,\mu$: Na, 0.380; Ba, 0.393 m.e./g.

Because a quantitative formulation of the particular titration curves given in fig. 54 and 55 is not possible up to now, some titrations were done with suspensions of the clay minerals in HCl solution. The results are given in fig. 56 (kaolinite suspension + 2 ml. N/10 HCl titrated with NaOH). The shape of this curve can be explained with the aid of the theories of Mattson (1929 a and b, 1940), of Tendeloo, Verveide and Zwart Voorspuy (1944 a and b) and of Verveide (1946). These workers consider the titration of H-colloids with bases as the neutralisation of acids; the adsorption of ions, during the neutralisation is considered to be the establishment of a membrane equilibrium according to Donnan. Mattson did not formulate these phenomena quantitatively, but by introducing a quantity A, representing the concentration of the acidoid (in this case kaolinite), Tendeloo c.s. and Verveide obtained definite results.

To compute the above mentioned titration curve theoretically the author had to choose some quantities arbitrarily. Consider the kaolinite suspension to be an acid HZ with one dissociation constant K, volume V ml. and base exchange capacity of a m.e./g. These values are now chosen, viz. $K = 10^{-3}$ (and 10^{-5}, $V = 2$ ml. and $a = 0.05$ m.e./g. The volume of the suspension is 100 ml. and 4 g kaolinite is used. The concentration of the acidoid HZ is therefore $\frac{4 \times 0.05}{2} = 0.1$ n. Furthermore 0.1 m.e. HCl is present. The system is titrated with t m.e. NaOH.

Because the cations are attracted by the acid, they are hindered in their movement, so that the conditions of the establishment of a membrane equilibrium

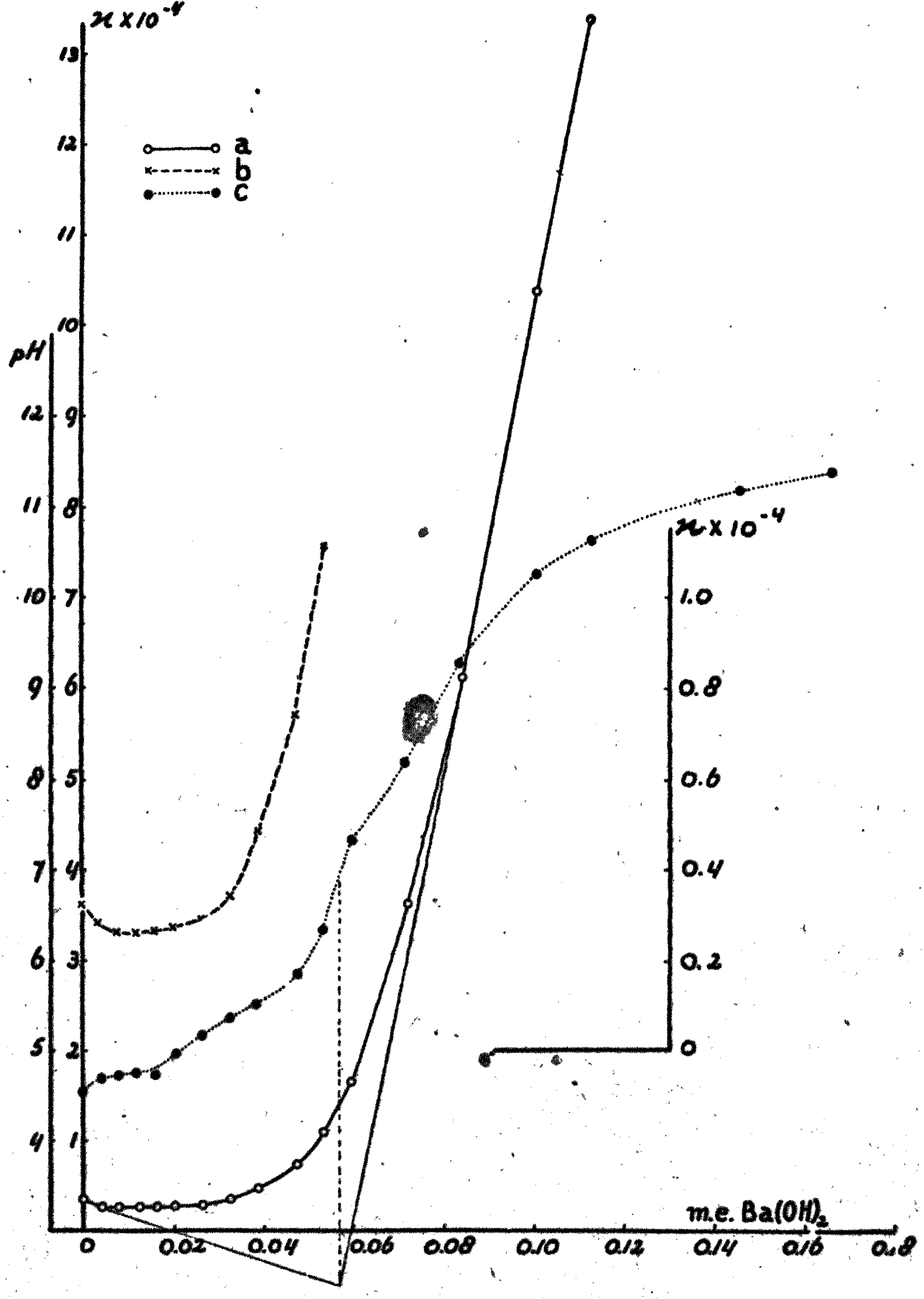

Fig. 55. Titration curves of kaolinite with $Ba(OH)_2$
a. Conductometric titration curve.
b. Conductometric titration curve on a larger scale.
c. Potentiometric titration curve.

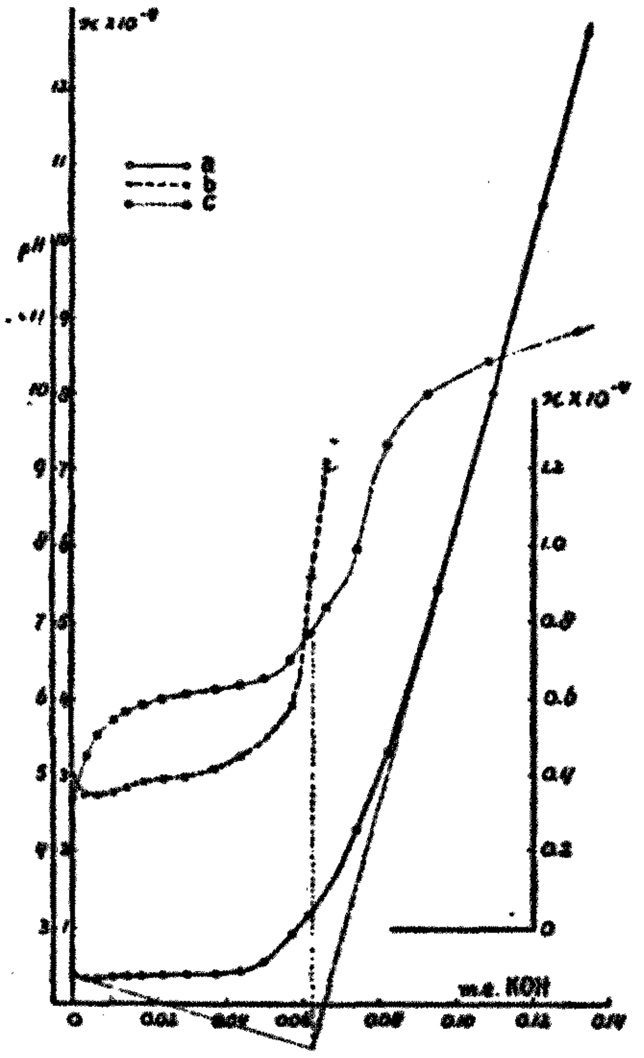

Fig. 56.
Titration curves of bentonite with KOH
a. Conductometric titration curve
b. " " " on a larger scale
c. Potentiometric titration curve.

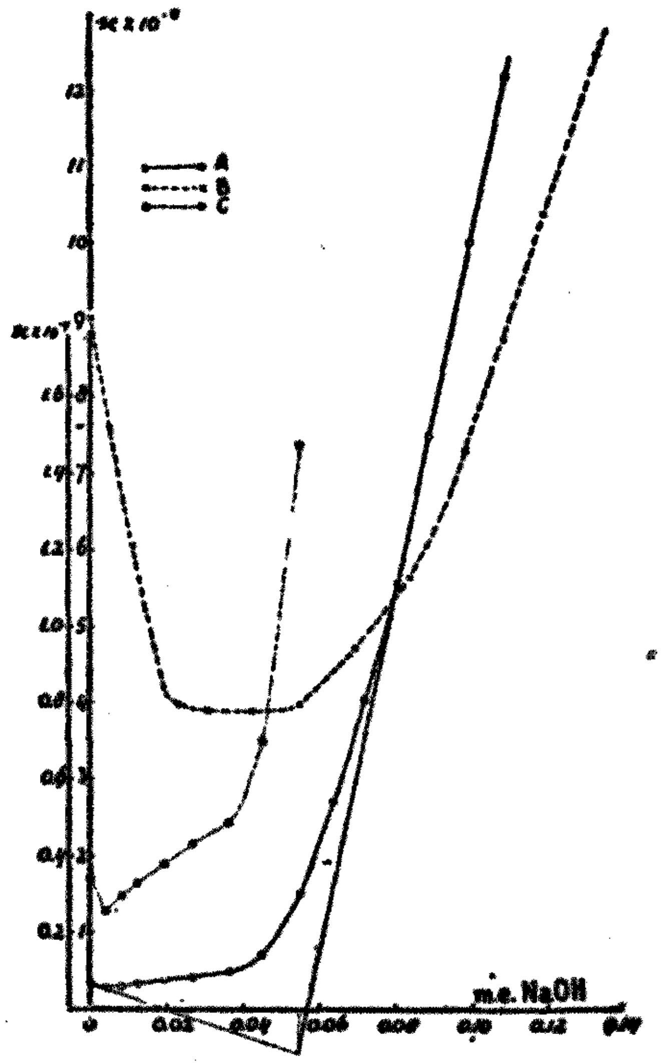

Fig. 57.
Conductometric titration curves.
a. kaolinite with NaOH
b. kaolinite + HCl (0.02m.e.) with NaOH.
c. Equals to A but plotted out on a larger scale.

(DONNAN) is realised. Theoretically the system may be presented by the following scheme:

micelle						intermicellar liquid			
HZ $\uparrow\downarrow$									
H· +	Z′	Cl′	Na·	OH		H·	Na·	Cl′	OH′
x_1	z_1	z_2	y_1	z_3	conc.	c_1	c_2	c_3	c_4

To simplify the calculation of the titration curve, some assumptions must be made, viz.:

1. $z_2 = 0$; 2. $z_3 = 0$; 3. $\varkappa = \frac{c_1 \times 350 + c_2 \times 50 + c_3 \times 75 + c_4 \times 190}{1000}$ reciprocal ohms per cm or, in other words, only the ions in the intermicellar liquid contribute to the conductivity of the system.

The author computes therefore the conductivity of the equilibrium liquid, but the shape of the titration curve of the equilibrium liquid is analogous to that of the suspension (see equation 4 below). Assumption 2 is not quite exact, since $x_1 . z_3$ equals to 10^{-14}. Because this influence on the conductivity is very slight up to pH 7, the author neglects it. Assumption 1 holds in cases, where c_3 is not too high. Assumption 3 is not correct, but no data are known about the contribution of adsorbed cations to the conductivity of suspensions, so that the author is forced to compute only the conducivity of the intermicellar liquid.

To be able to compute the concentrations, six equations must be given because of the six unknowns. These equations are:

1. The dissociation equilibrium $HZ \rightleftarrows H^{\cdot} + Z'$ gives:

$$K = \frac{(c_{H^{\cdot}})_i \, (c_{Z'})_i}{c_{HZ}}, \quad \text{or} \quad 10^{-3} (\text{or } 10^{-5}) = \frac{x_1 z_1}{0.1 - z_1}$$

2. Electroneutrality requires: $(c_{H^\cdot})_i + (c_{Na^\cdot})_i = (c_{Z'}) + (c_{Cl'})_i + (c_{OH'})_i$

$$\text{or: } x_1 + y_1 = z_1$$

$$(c_{H^\cdot})_o + (c_{Na^\cdot})_o = (c_{Cl'})_o + (c_{OH'})_o$$

$$\text{or: } c_1 + c_2 = \frac{0.1}{98} + c_4$$

4. The membrane equilibrium requires: $\dfrac{(c_{H^\cdot})_i}{(c_{Na^\cdot})_i} = \dfrac{(c_{H^\cdot})_o}{(c_{Na^\cdot})_o}$, or $\dfrac{x_1}{y_1} = \dfrac{c_1}{c_2}$

5. The amount of NaOH in m.e. can be expressed by:

$$98(c_{Na^\cdot})_o + 2\,(c_{Na^\cdot})_i = t \quad \text{or: } 98c_2 + 2y_1 = t.$$

6. The dissociation of H_2O gives the relation:

$$(c_{H^\cdot})_o (c_{OH'})_o = 10^{-14}, \quad \text{or: } c_1 c_4 = 10^{-14}$$

The equations (3) and (6) give the values of c_2 and c_4 when c_1 is chosen. The corresponding t-values can be computed by combining equations 1, 2, 4 and 5. In the case of $K=10^{-3}$, one finds:

$$t = 98\,c_2 + \frac{2\,c_2}{c_1}\left\{\frac{-10^{-3}\frac{c_2}{c_1} - 10^{-3} \pm \sqrt{(10^{-3}\frac{c_2}{c_1} + 10^{-3})^2 + 4.10^{-4}(1+\frac{c_2}{c_1})}}{2\,(1+\frac{c_2}{c_1})}\right\}$$

and if $K=10^{-5}$:

$$t = 98\,c_2 + \frac{2\,c_2}{c_1}\left\{\frac{-10^{-5}\frac{c_2}{c_1} - 10^{-5} \pm \sqrt{(10^{-5}\frac{c_2}{c_1} + 10^{-5})^2 + 4.10^{-6}(1+\frac{c_2}{c_1})}}{2\,(1+\frac{c_2}{c_1})}\right\}.$$

In this way curves are computed as represented in fig. 58 (drawn lines). Especially the initial part of the curve in the case of $K=10^{-5}$ is quite analogous to the experimental curve. However, the gradual transition to the base line in the experimental curve cannot be found in the theoretical one. This divergence may be caused by: a. the incorrectness of assumption 2; b. the presence of more dissociation constants; or, in other words, by the acidoid being a di- or polybasic, formula 1 cannot be applied in that case (see: Schuffelen and Dal, 1947).

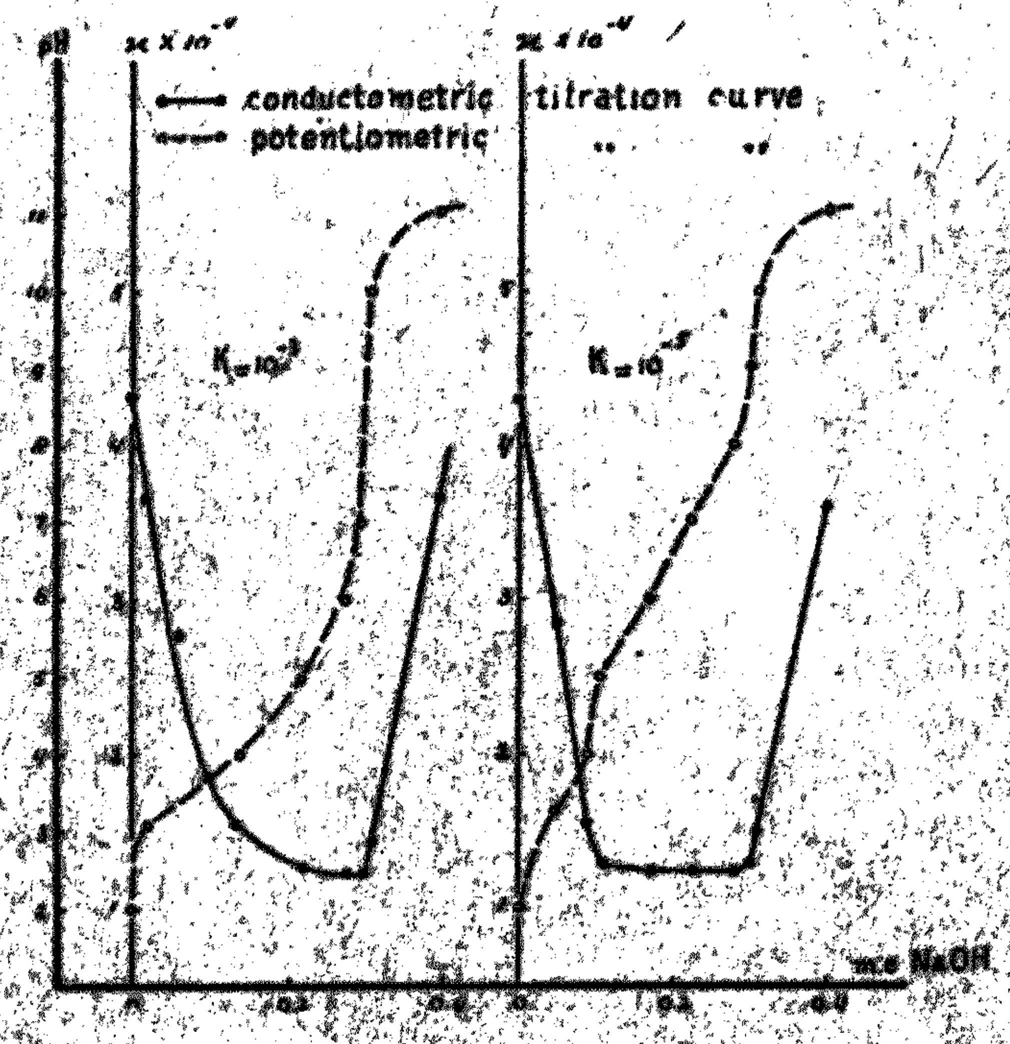

Fig. 58. Theoretically computed titration curves.

The suspensions, used in the flocculation experiments, were prepared in the following way: 500 mg H-kaolinite, 300 mg H-bentonite, H-illite, and soil fracton < 2 μ were each brought into flasks of 100 ml. Base was added up to pH 7; the quantity required can be computed from the base exchange capacities. In some cases 1 ml. of a Na-humate solution (prepared by extracting a sandy soil with 3 % NH_4OH, dialysing the extract and adding NaOH up to pH

7), containing 0.3 mg organic matter or 0.1 % of the amount of the minerale, was added.

After that, 1 ml of each of the suspensions was brought into solutions of the corresponding chlorides, or in some cases into mixtures of NaCl and $BaCl_2$. The total volume always was 2 ml. The concentrations of the chlorides were : 0.005, 0.015, 0.03, 0.04 and 0.05 n. The resulting flocs settle in the calibrated parts of the haematocrits, so that the volume of the sediment can be read. The readings were made 4 hours after the introduction of the suspensions into the salt solutions. Next, all hematocrytes were centrifuged in a uniform way. The results of these experiments were given and discussed in Chapter III.

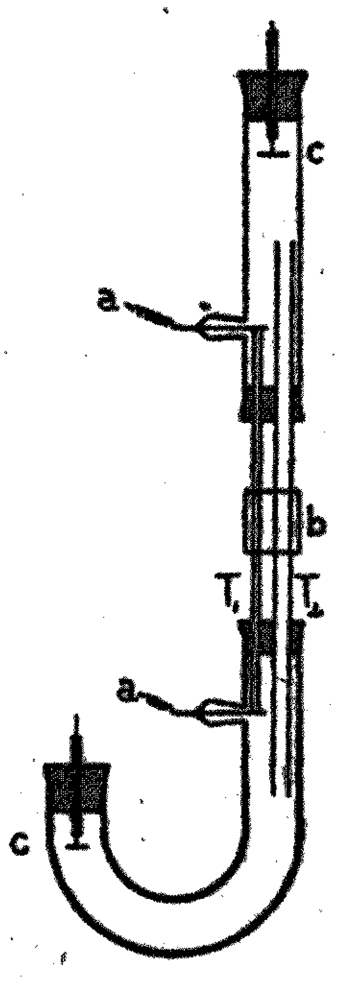

Fig. 59.
Electrophoresis apparatus.
a. auxiliary electrodes (Pt.)
b. cover slips
c. working electrodes (Pt.)

The electrophoretic velocity of the particles was measured by means of the instrument represented in fig. 59. It is a combination of the vertical cell of Enslin, Lindau and Rhodius (1935) and the vertical one of Smith and Lisse (1936). The vertical position was chosen because the particles (the measurements were done in kaolinite suspensions) were rather coarse. Using the horizontal cell in this case, there is a great chance that a particle under observation, disappears during the time of observation. This danger does not exist in the vertical cell, though it is necessary to determine the velocity twice, viz. before and after reversing the electrical field. The actual electrophoretic velocity is found by halving the sum of these velocities. The use of an instrument with two parallel tubes of unequal diameter and length gives several advantages in comparison with a single tube cell, especially in the case of rather coarse suspensions. By giving the two tubes definite diameters and lengths, to be computed from the equation :

$$L_2 = \frac{L_1 (R_2^4 - 2R_1^2 R_2^2)}{R_1^4} \tag{19}$$

(Smith and Lisse, 1936)

where L_1 = length of the narrow tube with radius R_1 (tube T_1), and L_2 = length of the wide tube with radius R_2 (tube T_2), both the electro-osmotic velocity of the liquid along the axis of tube T_1 and the velocity gradient (change in velocity with depth) at that point become zero. The velocity of the particles along the axis of tube T_1 is their actual velocity. According to Smith and Lisse the advantages of this type of cell are : a. the level, at which the velocity of the particles is greatest can be readily found by doing a few readings above and below this depth ; b. a slight error in focussing does not result in appreciable errors in velocities since the velocity gradient is small at points near the correct level ; c. rotational effects on particles are very small, since the veocity gradient near the correct level is small.

The capillary tubes used had radii of 0.32 mm (T_1) and 0.52 mm (T_2). Since the length of tube T_1 was 10.24 cm, the length of tube T_2 must be 14.68 according to equation (19).

Since the particles in tube T_1 were not well visible, two cover slips were stuck with Canada balsam at opposite sides of the tube. In this way the particles along the axis of tube T_1 became very well visible. The particles were observed with a Zeiss-microscope put in a horizontal position. The length of time required for the particles to cover a definite number of scale parts of the ocular micrometer was measured with a stopwatch.

The working potential was produced by a rectifier, that was connected to the 220 V lighting-circuit. The voltage of the direct current could be regulated from 0 to 220 V. The working electrodes were Pt-discs and the voltage between the electrodes was 150 V during all measurements. The potential of the auxiliary electrodes was measured with the Poggendorff-method of determining E.M.F.

The electrophoretic velocity of the particles of Na- and Ba-kaolinite in the chlorides of the corresponding bases was measured. The concentrations of the chlorides were 0, 0.005, 0.015 and 0.05 n. The electrophoretic velocity of the H-kaolinite particles was determined in HCl-solutions of 0.005, 0.01, 0.015 and 0.03 n. The results were given in fig. 34 of Chapter III and discussed on page 48. Each dot in this figure represents the mean of the velocities of thirty particles; the electrophoretic velocity is plotted out in dependence of the salt concentration at a potential gradient (potential drop/cm) of 10 V.

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See also pag. 98—104.

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