J. Bouma

Microstructure and stability of two sandy loam soils with different soil management

J. Bouma

Microstructure and stability of two sandy loam soils with different soil management

PROEFSCHRIFT
ter verkrijging van de graad van
doctor in de landbouwwetenschappen
op gezag van de Rector Magnificus, dr. ir. F. Hellinga,
hoogleraar in de cultuurtechniek,
te verdedigen tegen de bedenkingen van een commissie uit
de Senaat van de Landbouwhogeschool te Wageningen
op dinsdag 24 juni 1969 te 16 uur

1969 Centrum voor landbouwpublikaties en landbouwdocumentatie
Wageningen

ERRATA.

Page 16 sent. 4 In winter a crust forms at the surface ......

Page 16 sent. 21 Puddling moves them by the swelling process ...

Page 26, section 4.1.3, sent. 7: In the aggregates very fine pores were found .....

Page 39 sent. 4 .... using voids between 30 and 100 µm.

Page 60 sent. 12 ...... capillary conductivity.

sent. 18 ...... cores of 100 cc.

Page 62 sent. 24 Differences in organic matter .....

Stellingen

I

Uitgaande van een moderne landbouw kan een bodemgeschiktheidsanalyse van een bepaald bodemtype alleen door een team van deskundigen worden opgesteld. De taak van de bodemkundige hierin is primair bodemkundig en bestaat niet slechts uit het omschrijven van de eigenschappen van het natuurlijk bodemprofiel op een bepaald moment, maar bovendien uit het aangeven van de te verwachten eigenschappen, en de grenswaarden hiervan, als functie van de bodembehandeling.

II

De macrostructuur in bouwvoren kan niet bevredigend worden beschreven met behulp van de bestaande schema's.

Soil Survey Manual (1952) p. 225 e.v.
JONGERIUS (1957) Morphologische onderzoekingen over de bodemstructuur.
BREWER (1964) Fabric and mineral analysis of soils.

III

Voor het karakteriseren van de structuur van bouwvoren in lichte zavelgronden verdient de toepassing van fysische methoden, die gebaseerd kan zijn op een morfologische analyse, de voorkeur.

IV

Bij de waterbeweging onder natuurlijke omstandigheden in de bouwvoor van lichte zavelgronden spelen de zeer fijne pakkingsporiën tussen de zandkorrels een zeer belangrijke rol.

V

Het onderploegen van versmeerde grond of het versmeren van de grond in de open voor is zeer ongunstig, aangezien de mogelijkheid tot latere regeneratie door droging, met de diepte afneemt.

VI

Het verdichtend effect van druk op monsters, bestaande uit aggregaatjes, is niet alleen een functie van het vochtgehalte maar ook van de microstructuur.

SÖHNE (1955) Zeitschr. für Pflanzenern. Düng. Bodenk. Band 69: 116.
HUTTER (1966) Annales Agronomiques Vol. 17 no. 1: 37.

VII

Naast het bewortelingspatroon, bepaalt vooral het capillair geleidingsvermogen van de grond de opneembaarheid van de bodemoplossing voor de plant.

VIII

De mechanische weerstand van bodemfragmenten in de bouwvoor van lichte zavelgronden kan, bij veldcapaciteit, het binnendringen van de wortels verhinderen. Wanneer echter deze oppervlakteweerstand wordt uitgeschakeld, vormt de mechanische weerstand geen beletsel voor de wortelgroei door de fragmenten.

IX

Door een extra bemesting van versmeerde grond kunnen de nadelige gevolgen van het lage capillaire geleidingsvermogen voor de plantengroei gedeeltelijk worden gecompenseerd.

X

In loessprofielen, waarin de albische horizon tongvormig in de argillische doordringt (Groepen: Glossudalf en Glossaqualf) bevindt de albische horizon zich alleen in de argillische, en niet daarboven. De bovenliggende horizon is gevormd in een nieuw moedermateriaal.

BOUMA, J., L. J. PONS and J. VAN SCHUYLENBORGH. Neth. J. of Agric. Sci 16 (1968) 58-70.

XI

Bij de bodemvormingsprocessen in het hooggebergte speelt de chemische verwering een belangrijker rol dan tot nu toe is verondersteld.

KUBIËNA (1953) Böden Europas.
MÜCKENHAUSEN (1962) Entstehung, Eigenschaften und Systematik der Böden der Bundesrepublik Deutschland.
BOUMA et al. (1969) Journal of Soil Science in press.

XII

De in de praktijk veel gehoorde opmerking dat in de bouwvoor van zavelgronden 'het zand naar beneden zakt' berust op het plaatselijk voorkomen van concentraties van zandkorrels die zijn ontstaan door het onderploegen van oppervlaktekorsten met duidelijke zandlaagjes.

XIII

De wetenschappelijke onderzoeker mag verlangen dat bij de redactionele bewerking van te publiceren manuscripten niet slechts de vaktechnische inhoud maar ook de eigen stijl niet ingrijpend wordt veranderd.

XIV

De term 'wittebroodsweken' heeft zijn oorspronkelijke betekenis ten onrechte verloren.

PROEFSCHRIFT VAN J. BOUMA
WAGENINGEN, 24 JUNI 1969

Microstructure and stability of two sandy loam soils
with different soil management

Dit proefschrift met stellingen van Johannes Bouma, landbouwkundig ingenieur, geboren te Vrouwenparochie op 29 oktober 1940, is goedgekeurd door de promotoren, dr. ir. L. J. Pons, hoogleraar in de regionale bodemkunde, en ir. H. Kuipers, hoogleraar in de grondbewerking en de gronddynamica.

De Rector Magnificus van de Landbouwhogeschool,
F. HELLINGA

Wageningen, 21 mei 1969

Dit proefschrift verschijnt tevens als Verslagen van Landbouwkundige Onderzoekingen 724.

VOORWOORD.

Het afsluiten van een onderzoek met een publikatie betekent meestal dat op vrij abrupte wijze een groeiproces wordt onderbroken. Het bepalen van het juiste moment hiervoor vereist niet alleen inzicht en doortastendheid maar ook een flinke dosis optimisme, omdat de moeizaam aan de complexe problemen ontworstelde oplossingen, of liever: datgene wat men als oplossingen meent te kunnen beschouwen, in het niet dreigen te vallen tegenover de vele nieuwe vragen die werden opgeroepen. Het te snel onderbreken van genoemd groeiproces leidt tot een onrijp, slecht verteerbaar product, terwijl na een te lange groeiperiode het overrijpe resultaat evenmin tot vertering noodt.

Aangezien de onderzoeker het eigen werk moeilijk meer objectief kan beschouwen, dient hij de presentatie ervan met gepaste terughoudendheid te omringen.

Nu dit moment door de toestemming van mijn promotoren Prof. Dr. L.J. Pons en Prof. Ir. H. Kuipers is aangebroken, en het verrichtte werk aan een bredere kring ter kennisname en ter discussie wordt voorgelegd, gaat mijn dank uit naar allen die tot de totstandkoming in deze vorm hebben meegewerkt:

Prof. Dr. L.J. Pons heeft dit onderzoek zeer gestimuleerd, niet alleen door de vele discussies over de stof, maar ook door het scheppen van een prettige, open werksfeer. Prof. Ir. H. Kuipers maakte mij vertrouwd met problemen en mogelijkheden van de grondbewerking en stelde mij uitgebreide faciliteiten ter beschikking op het Laboratorium voor Grondbewerking. Hier was de Heer B. Kroesbergen steeds bereid tot het geven van hulp en advies.

Dat het onderzoek concreet mogelijk werd dank ik aan de Heren D.A. Bijlsma en J. van Gaalen, landbouwers uit de Haarlemmermeer, die toestemming gaven tot het periodiek bemonsteren van de hun toebehorende pedons B en G.

Contacten met verschillende onderzoekers, waarvan ik noem Dr. Ir. F.F.R. Koenigs en Dr. R. Brouwer, waren zeer waardevol. Prof. Dr. G.J. Vervelde, directeur van het I.B.S., gaf toestemming tot het verrichten van enkele potproeven op genoemd Instituut, in samenwerking met Dr. R. Brouwer.

In het kader van een Ir. practicum zijn enkele onderdelen van het onderzoek verricht door de Heren D. Barël en A.P.J.M. Oomen.

De Heer Th. Pape was behulpzaam bij de micromorphologische studies, terwijl de Heren G.H. Broekhuizen en G.J. de Waal de slijpplaten vervaardigden.

Dat ik mij het afgelopen jaar meer op dit werk kon concentreren dank ik voor een groot deel aan Dr. S. Slager. Dr. L. van der Plas gaf het inspirerende en verlichtende voorbeeld dat kritisch onderzoek niet noodzakelijkerwijs gepaard hoeft te gaan met loodzware ernst.

De Heren Dr. E. Meyer Drees en C.G.L. Dirks, verbonden aan het Pudoc, gaven redactionele adviezen. De figuren werden getekend door de Heer G. Buurman; de Heer Z. van Druuten maakte de foto's en Mej. W.J.Oudhof typte het manuscript.

Aan het College van Rector en Assessoren wil ik tenslotte mijn grote erkentelijkheid betuigen voor de mij geboden mogelijkheid dit proefschrift in een andere dan de gebruikelijke vorm te laten verschijnen.

Aan mijn ouders dank ik mijn bestaan; aan hen draag ik dit werk op.

CONTENTS.

1. General Introduction

A practical problem initiated this study. In the Haarlemmermeer, a former lake reclaimed about 1850, several farmers had difficulties with soil structure. Land, plowed in autumn, was very wet in spring. Free water was sometimes present on the soil surface. Planting and seeding were long delayed in spring and yields were unsatisfactory because of irregular crop development.

Some farmers ascribed it to pressure from the back wheel of the tractor in the open furrow during plowing, compacting the subsoil and severely reducing permeability. Plowing practices were therefore changed. Equipment was used that could be moved by driving the tractor with all four wheels over the normal soil surface. This sometimes needed very old horse ploughs, adapted to tractors. Other farmers tried to improve drainage by laying more tile drains alongside existing systems, but usually the drains did not conduct water.

The problems occurred on several soil types, but especially on the somewhat lighter textured sandy loams of the Hoofddorp Complex (Pgb) (Haans, 1954).

The Agricultural extension service helped in the selection of two farms, where a pedon was selected. In one, henceforth called G, no problems occurred. In the other, called B, soil structure had deteriorated. Morphological and physical properties of each pedon were frequently investigated for about 18 months. Soil management was left to each farmer. Profile descriptions, particle size distributions and routine analytical data of each pedon are in Appendix I. Differences in these values between the two profiles are mainly a result of soil management.

Originally the carbonate content of Pedon G was very low throughout. The content of 1%, as found now in the surface soil only, results from the application of lime for 30 years. The subsoil still contains no free carbonates. On Pedon B, decalcification during the formation of the profile, caused by a vegetation (Haans, 1954) was less pronounced. At about 50 cm the profile has much lime deposited as shells and small fragments. The surface soil, however, has been decalcified. It has not been limed as much as Pedon G as is shown by the difference in pH value (Appendix I). Pedon G has been green-manured and dunged for at least 25 years. During the last 10 years every field of the farm has been used for the growth of grass during three years, to be followed by use as arable land for the next three years. When wheat is grown, the soil is always green-manured. The field where Pedon G is found was notoriously bad about 1930. The surface soil had a weak unstable structure. Continued investment in lime and careful management has converted it into a productive soil.

Pedon B, however, is on a field whose ownership has changed several times over the last thirty years. It was never green-manured until 1966. The surface soil therefore contains less organic matter and lime than that of Pedon G.

The particle size distribution of the two pedons is identical. Average yields, as roughly estimated by the farmers from varying data of several years, were different for both farms. For sugar beet a yield of 50 tons, for wheat of 5.0 tons per ha was considered normal for farm G. For farm B this was40 and 4.5 tons respectively. Such uncontrollable yield values, however, are not satisfying for describing soil quality and suitability. More important therefore was the opinion of the farmers that in general, soil B seemed more susceptible to structure deterioration and offered more problems than soil G. The suitability for agriculture of soil B was therefore considered inferior to that of soil G.

The aim of this study is to investigate this general statement and to describe it in quantitative terms. Before discussing the results of the fieldwork and a series of model experiments, the term suitability, as used when comparing both soils, must be explained.

The soil is used by the farmer to produce agricultural crops. His profit is determined by a difference between crop value and costs. A low yield may not necessarily be unfavourable, at least not when relatively high prices are being paid, as may be expected when generally low yields are found on other soils. On the contrary, in a year when average yields are high, prices tend to be lower. Then, in spite of higher yield, the amount of cash received for the crop may be lower as well, whereas costs of management will be simular. Prices, however, not only vary as a function of the amount of supply but also because of differences in quality.

Cost figures are governed by the system of management of the farmer. Certain costs are inevitable, like those for seeding or planting and those for fertilization. The procedure followed in practice and its efficiency will determine its magnitude. Others, seem less inevitable. Some tillage practices for example are subject to discussion in this regard.

Each farmer will judge the quality of his land considering these factors. He will call a soil suitable when a regular and high production, both in volume and quality, is possible, especially in years when the general productivity level is low.

Besides, each crop to be grown is one from a cycle of different crops grown in a specific pattern of rotation. His final opinion on suitability will therefore be based on a judgment, considering the degree of financial succes by which certain crops can be grown during the years as a part of a rotation, that seems most lucrative.

A farmer will thus be able to give a description of the quality of each of his fields, based on experience of many years and on his own system of management that he considers to be the best.

The question of suitability of certain soil types as shown on a soil map will be posed to the soil surveyer, whether he likes it or not. Access to the experience of farmers is then indispensable. A soil scientist however, will have to realize that his pattern of thinking may differ from that of the farmer. He primarly thinks in terms of well described and classified soil types, as expressed on soil maps, that have been formed in a certain parent material under influence of the soil forming factors. He digs a pit and considers one of its vertical walls. The picture obtained then is considered representative for the type of soil. A farmer thinks more in terms of management and economy, and above that in fields of landuse. A certain field will normally be covered by several soil units of the map. This is certainly true when relatively large fields are present, to enable efficient use of machinery. To get a suitability concept for a certain soil type, occurring on different farms, the soil scientist has to normalize as good as possible all factors not directly related to his object of study, the soil profile itself (Vink & van Zuilen, 1967). These factors are: the capability of the farmer, expressed by his management; landshape and accessibility of the land and the type and size of farm, as well as the usual system of crop rotation.

Except for these factors it should be realized that each judgement is a clear function of the general economic situation, changing with time. Yields obtain on a certain type of soil usually vary considerably among years on the same field and also in the same year on different farms. Differences in weather during the growing season contribute to the first phenomenon, differences in soil management to the second.

Modern agriculture shows many points of agreement with industry, emphasizing an increase in production for each worker. Therefore mechanization developed. In a relatively short period of time concepts of soil productivity and management have changed. Practical problems, often concerning soil structure and soil stability, are submitted ever more frequently to specialists.Their judgment, based on an analysis of farmers experience, can only be given in a rather static agricultural system. When this system changes, as is the case with the present general drive to mechanization, the answers of the past no longer satisfy. Therefore an independant analysis should be made of the soil profile and its soil material only, describing its range of variable properties as a function of soil management. This will be attempted in the next chapters for the two pedons of discussion.

2. FIELD STUDIES AND PROPERTIES OF UNDISTURBED SAMPLES.

2.1 Introduction.

This chapter covers field observations between August 1966 and December 1967. Pedon descriptions, particle size distributions and routine analytical data are in Appendix I and micromorphological characteristics in Appendix II. This chapter also includes physical data from undisturbed field samples; data on permeability are given in Appendix III. Rather than discuss each item of data separately, all the properties are discribed together as they were at each date of sampling in an attempt to give a coherent description of changes.

2.2 Methods.

2.2.1 Morphological methods.

Horizon Ap is difficult to describe in terms of peds as in the Soil Survey Manual (SSM, 1951, p.225).
Peds are formed by natural genesis and are bounded by natural voids, that may have cutans (Brewer, 1964, p. 134). The fragments in an Ap horizon are formed by applying shear forces to the soil during tillage. Their size and shape depend on the implements used, and how and when they are used. After formation, fragments will change in shape with mechanical pressure and with weather. Thus a certain morphological picture of an Ap horizon is bound to change. However, a description of a pedal material in a natural undisturbed profile is supposed to yield a much more permanent picture.

Even if these pedons were undisturbed, they would only have weak grades of structure since in the soils of this study, the clay content amounts to only 13% and peds are essentially formed by processes of swelling and shrinkage. These phenomena only occur when sufficient clay is present. More recent schemes (Jongerius, 1957; Brewer, 1964), however, go beyond the SSM system of describing the arrangement of peds and grade of structure. They also describe the size, shape and arrangement of the primary particles that may form secondary units like peds.

This type of scheme will be used here since microstructure as observed in thin sections is well defined (Brewer, 1964).

Jongerius (1957) points also to the importance of voids, that are treated as discrete units. Observations on porosity offer difficulties.

In pedal or apedal soil materials larger pores (more than 100 μm) can be readily observed in the field with the naked eye or with a hand lens. Tubular pores, known as biopores by Slager (1964) which are channels left by roots or soil animals, can readily be counted and measured in homogeneous materials. This is possible because the channels can easily be recognized as discrete entities. More irregular voids, like vughs are more common in surface horizons and can only be measured morphologically by point counting in thin sections (Kubiena, 1967). Pores between peds or aggregates, mostly planar or compound packing voids, are described indirectly by noting sizes of peds or fragments and grades of structure. Here a rather homogeneous soil materials is needed. Point- counting on large thin sections can yield total pore volumes of larger pores, arranged in classes by size and type (Kubiena, 1967) but there are some limitations on the method. The Ap is markedly heterogeneous so that many sections of a horizon must be counted. Besides, it is often difficult to determine the type and size of a pore in a thin section. Use of polished sections (Kubiena, 1967), examined by incident light, is therefore preferrable to the use of thin sections. Thus a somewhat three-dimensional picture is obtained, and less time is needed to prepare the sample. This method has been applied here. However, for this study of structural aspects polished sections gave insufficient information to justify the considerable effort.

Physical data, obtained from cylinders of 100 cm^3 provided much information about pore volume and air contents directly and so did permeability values indirectly. All these measurements are relatively easy with results from a few replicates. Physical data has therefore been used to define soil structure and morphological data has been used as illustration material, both in static description of the soils and in studying environmental effects.

2.2.2 Physical methods

Undisturbed samples were collected in steel cylinders 5 cm high and holding 100 cm^3. Pore volume was estimated by drying the soil at 105°C and weighing. Volume of the solid phase was calculated from density (Soil B 2.67, Soil G 2.62). Volumes of solid, liquid and gas phases were estimated gravimetrically in samples after equilibrating them in sand beds at pF values of 1.0, 1.5 and 2.0 and in a pressure membrane apparatus at pF 4.2.

Permeability (K) was estimated in quadruplicate with saturated undisturbed samples in cylinders of 100 cm^3. Outflow was measured over 1 hour with a constant head of 2.5 cm water K (defined in cm per day) could be calculated from the following formula:

$$\underline{K} = 1440\ \underline{Q}.\ \underline{\Delta}\ \underline{L}\ /\ \underline{A}.\underline{t}.\ \underline{\Delta}\ \underline{H}$$

in which $\underline{Q}$ = volume of water in ml percolating the sample in $\underline{t}$ min., $\underline{\Delta}\ \underline{H}$ = head of water (2.5 cm), $\underline{\Delta}\ \underline{L}$ = length of core (5 cm) and $\underline{A}$ = cross-section of the cylinder (20 cm^2). Results, which were variable for each layer, are tabulated in Appendix 3. A precise value for each layer could not be given because of the high variability between these relatively small samples.

2.3 Field sampling and interpretation of analytical data.

In this chapter soil management will be described briefly for both soils over the period of observation (August 1966 to December 1967).

Structure is described in general morphological terms. Photographs among Fig. 1-13 demonstrate the most striking features. Fig. 3 gives pore volumes and air content at pF 2.0 for each layer. Kuipers (19616) suggested the arrangement of moisture contents at pF 2.0 (percentages of dry weight) and pore volumes in Figs. 4 and 5.

Permeability values in cm per day for saturated soil have been assembled in Appendix III.

In the text reference will frequently be made to these graphs and to this Appendix. Two interesting pedological features were investigated more closely in the Laboratory:

The morphology and genesis of soil crusts (Section 2.3.3 and figs. 6 and 7) and the morphology and genesis of mineral cutans (Section 2.3.6, Figs. 10 and 11).

2.3.1 The situation before tillage (August 1966)

Two weeks after harvesting the winter wheat, grown on both soils, but before tillage, both profiles were described in detail (Appendix 1). During the three years previous to the wheat crop soil G had been covered by grasses and had not been tilled. Pedon G showed clear evidence of biological activity: wormholes with excrements were found in the Ap horizon.

(Fig. 1) resulting in a relatively high permeability. Dense fragments without channels also occurred. Structure therefore is very heterogeneous (Fig. 1).

Before 1950 the soil had been ploughed to about 35 cm; since then tillage had not exceeded a depth of 25 cm. The layer between 25 and 35 cm, henceforth called Ap_2 (Fig. 2), in German called a 'verlassene Krume', resembled in field colour the adjacent Ap_1 and had favourable properties: about five root channels per cm^2, and a perforation by worm holes. Pore volume was 43% and the air content at pF 2.0 was 12% (Fig. 3). Consistence was firm.

The top of the Ap (1-6 cm) had been partially puddled while harvesting, resulting in an air volume of 3% at pF 2.0. Fig. 4 shows how some samples contained more moisture (28%) and higher pore volumes (47%) than the rest.

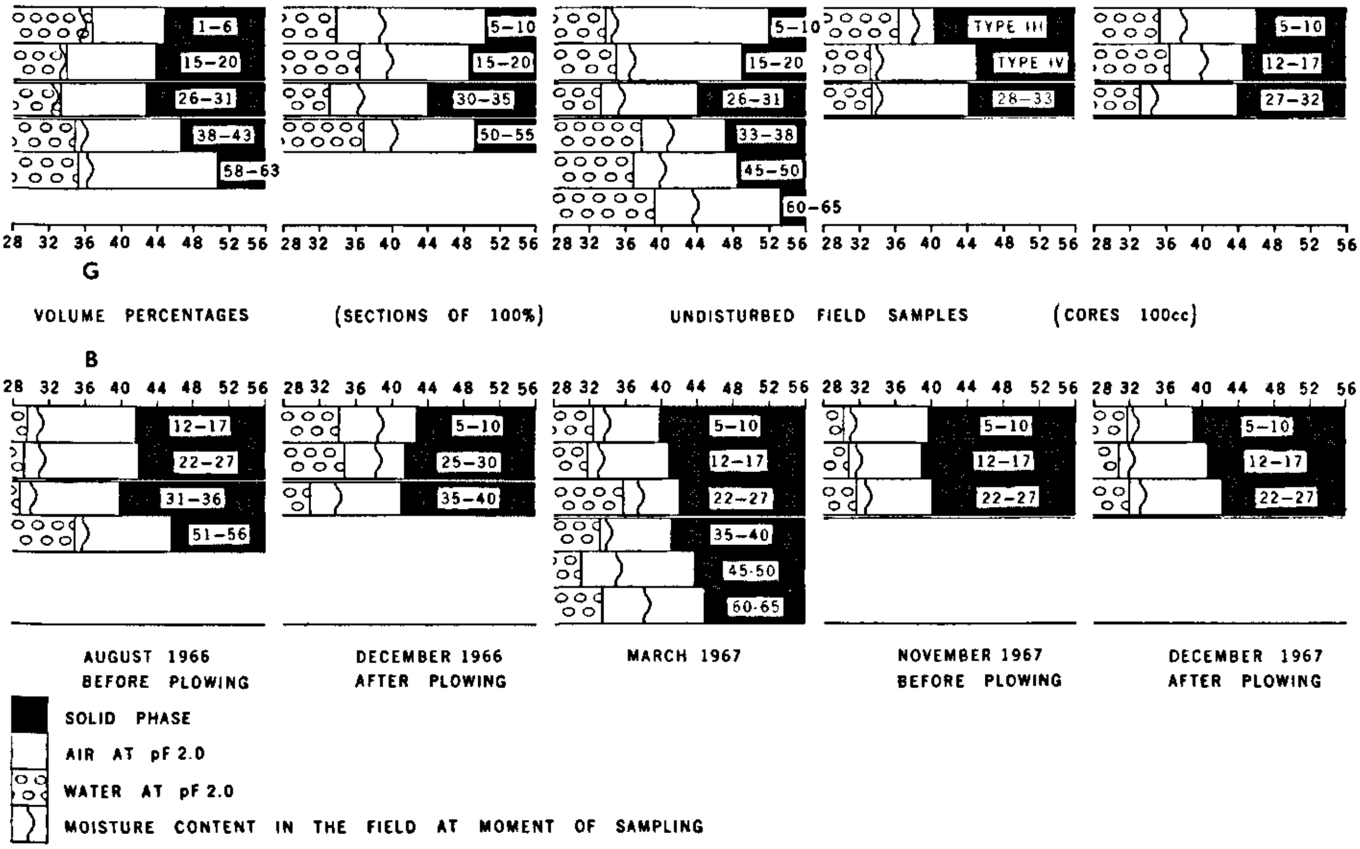


Fig. 3. Truncated diagrams of phase composition of Pedons G (above) and B (below) at pF 2.0 on the five dates of sampling. The numbers marked in the solid phase are depths in cm and the scales are in percentage units with solid and water phases truncated. Values are averages of at least four field samples of 100 cm³.

Fig. 1. The Ap_1 of pedon G in August 1966. Earthworm excrements are visible between very dense fragments.

Fig. 2. The Ap_2 ('verlassene Krume') of Pedon G. Of the channels formed in the apedal soil material the finer ones have been formed by roots and the larger one on the right by an earthworm (×8).

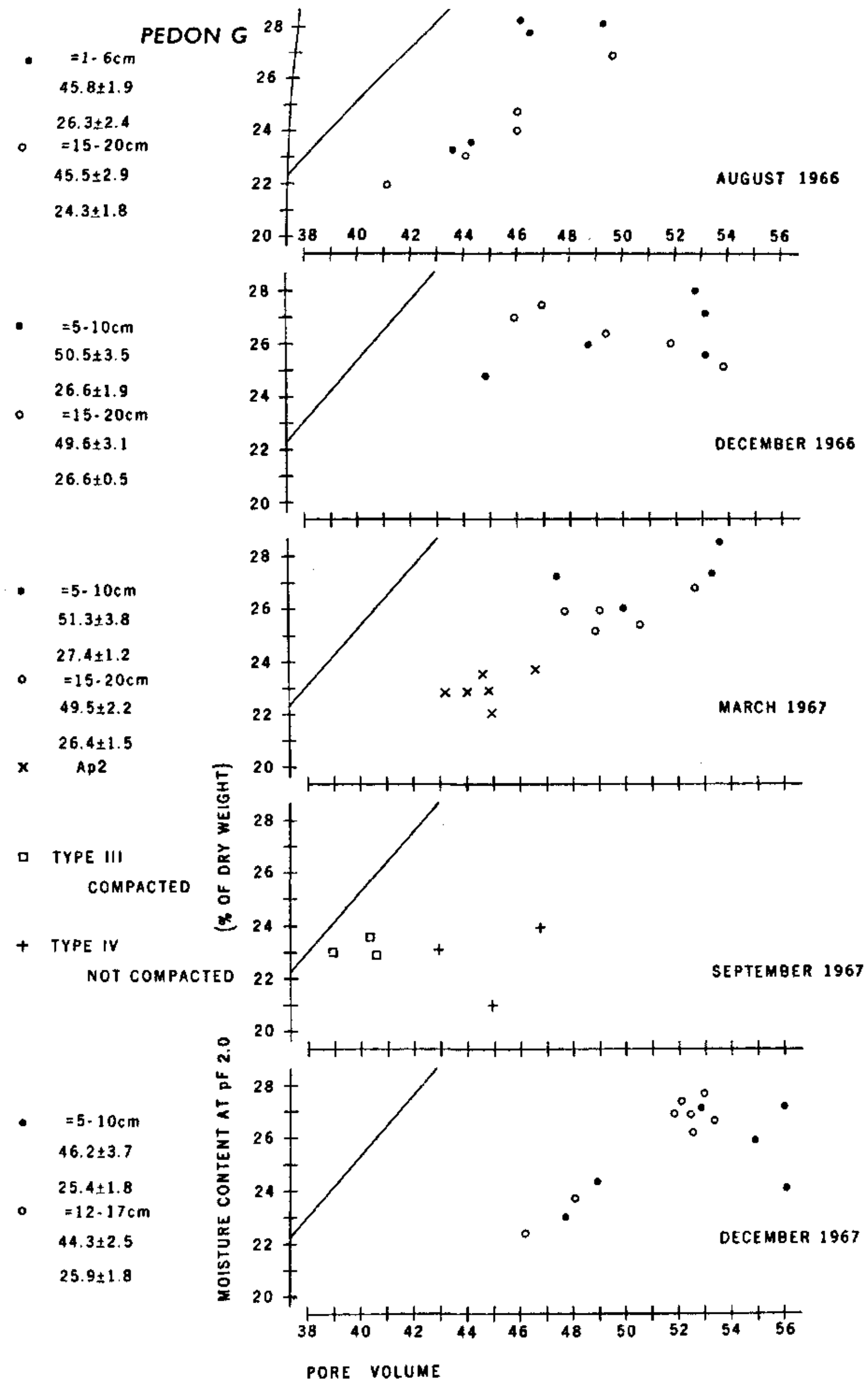


Fig. 4. Relation between pore volume and moisture content in Pedon G at pF 2.0. For each layer, average values and two times their standard deviation are indicated below the figures. The straight line in each figure indicates an air content of 0 %.

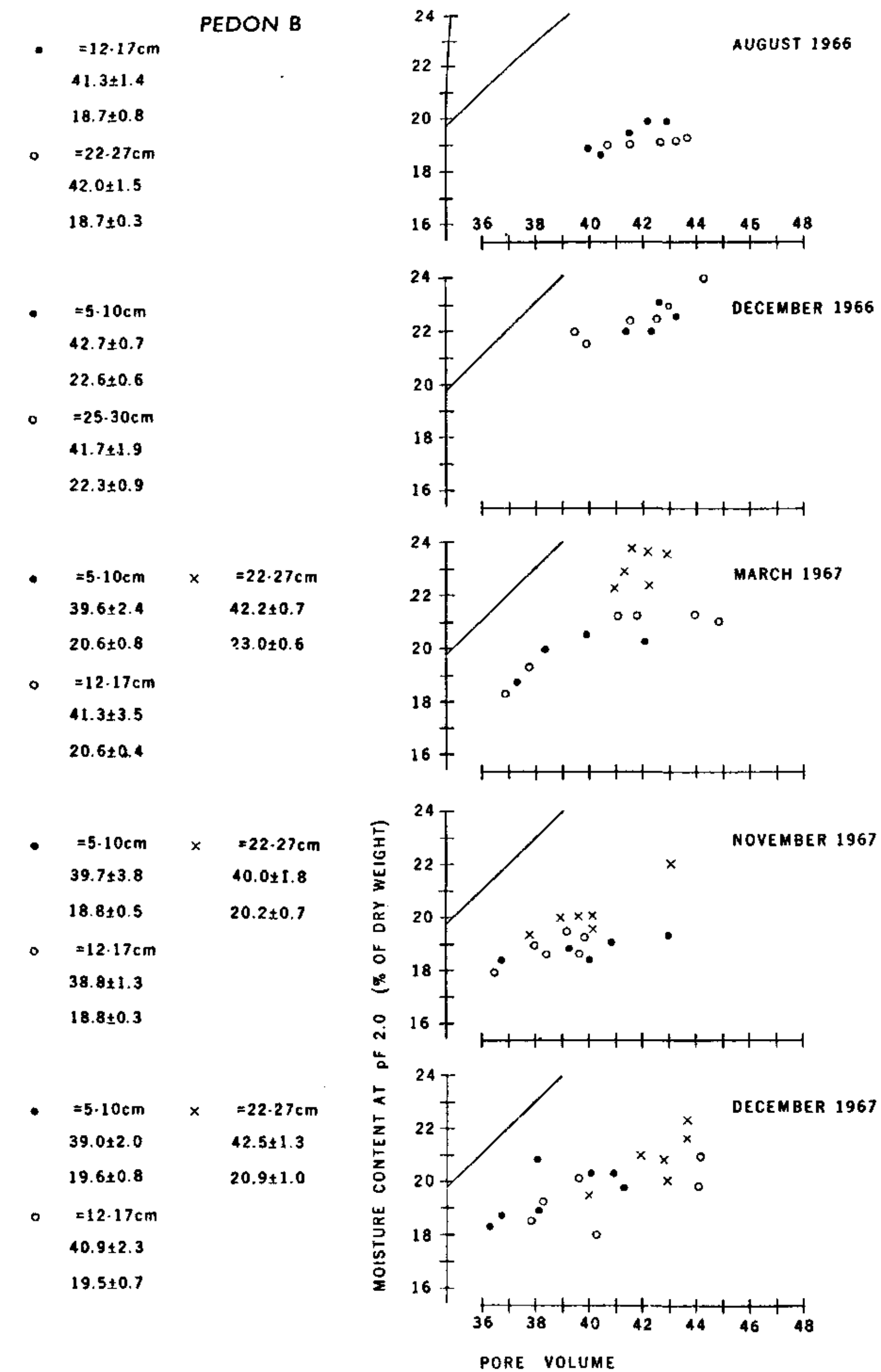


Fig. 5. For explanation see fig. 4.

This combination indicates puddling. At the same suction the clay in a puddled soil will retain more water than the same amount of clay in a porous previously dried field sample (Chapter 3). This layer was also less permeable (Appendix III).In Pedon B pore volume was less than in Pedon G; the air content at pF 2.0, however, was about 13%. Consistence was firm. Except for the Ap_2 of Pedon G, in both cases the Ap horizons clearly contrasted with the subsoil (C horizons).

In both cases the upper part of the subsoil (immediately below the Ap), had fewer root channels and a lower pore volume than the deeper subsoil. In Pedon G a platy structure was found. This was relict and dated from the time when the soil was ploughed to 35 cm with the tractor wheels in the furrow.

Pedon B was still ploughed in this way so that immediately below the Ap pore volume was only 40% and air content only about 11% at pF 2.0. The deeper subsoil contained many very fine root channels. No wormholes were observed in Pedon B, which was therefore considerably less permeable than the subsoil in Pedon G.

2.3.2 Autumn and winter tillage (1966)

On 14 October the field with green manure from which Pedon G was collected, was ploughed to 25 cm with a three-furrow plough. Clover had a height of about 15 cm. The tractor was driven with its four wheels over the uncut soil, alongside the furrow. At that moment the Ap contained about 22% moisture.

As desired, ploughing fragmented the soil, distributed the clover throughout the Ap, and distinctly raised the then irregular soil surface. A representative pore volume could not be measured in the relatively small cylinders, because of the irregular locally loose arrangement of clods. Other methods (Andersen et al., 1966; Kuipers & van Ouwerkerk, 1965) were not attempted. After the soil had settled and a surface crust had formed, samples were taken (15 December).

The field from which Pedon B was collected was ploughed on 8 December. Previously it was also covered with green manure grass, but in this case this grass was sown for the first time; it had grown longer and was more luxuriant (about 25 cm high). The three-furrow plough was set at 32 cm with two tractor wheels in the furrow. The results were poor: the wheels and plow caused severe puddling, because of excessive spin of the wheels.

Just before ploughing the Ap had a moisture content of about 25%.

2.3.3 Formation of surface crusts.

On December 15 a crust had been formed on Pedon G (Fig. 6). As a result the irregular surface after tillage had been flattened considerably. Only the tops of the fragments were still exposed. The spaces between surface fragments were filled with alternating layers of sand and finer particles (Fig. 7). Each layer of crust seemed to have formed during rain. The fragments were insufficiently permeable to allow all the water to percolate through them, so that some water ran over the fragments. Splashing of rain broke down the fragments at the point of impact; the separated particles were then washed into the hollows between the fragments. In general finer particles will be washed down more easily than coarser. As a function of the intensity of rainfall, the crust is therefore stratified, each layer being of a specific narrow grain size (Fig. 6 and 7), corresponding with a certain velocity of the water flowing down the fragment. The resulting crust was up to 2 cm thick between the fragments; most layers were of skeleton grains but others were of plasma only.

The permeability of the crust (Pedon G) was measured in the usual steel cylinders. The core consisted of 2.5 cm soil including crust and some Ap material. The cylinder was gently pressed to half its depth into the soil surface. To avoid the influence of larger voids along the sides of the core, its surface near the walls of the cylinder was thinly waxed.

The values found for the permeability were 90, 102, 90 and 226 cm/day, which means that the crust was highly permeable.

In December 1966, a week after tillage, Pedon B seemed only weakly crusted. When sampled in March 1967 the crust was similar in fabric to that of Pedon G but had fewer layers of plasma. It was, therefore, somewhat more permeable, with values of 100, 250 and 270 cm/day.

2.3.4 Soil structure after tillage (December 1966)

In the Ap of Pedon G pore volume and air volume at pF 2.0 clearly had increased after tillage (Fig. 3 and 8). The moisture content at pF 2.0 (Fig. 4) increased in the 15-20 cm layer. Although the Ap was mainly rather firm, some fragments were plastic. Only a few fragments of clover were still visible; the remainder was already well decomposed. There

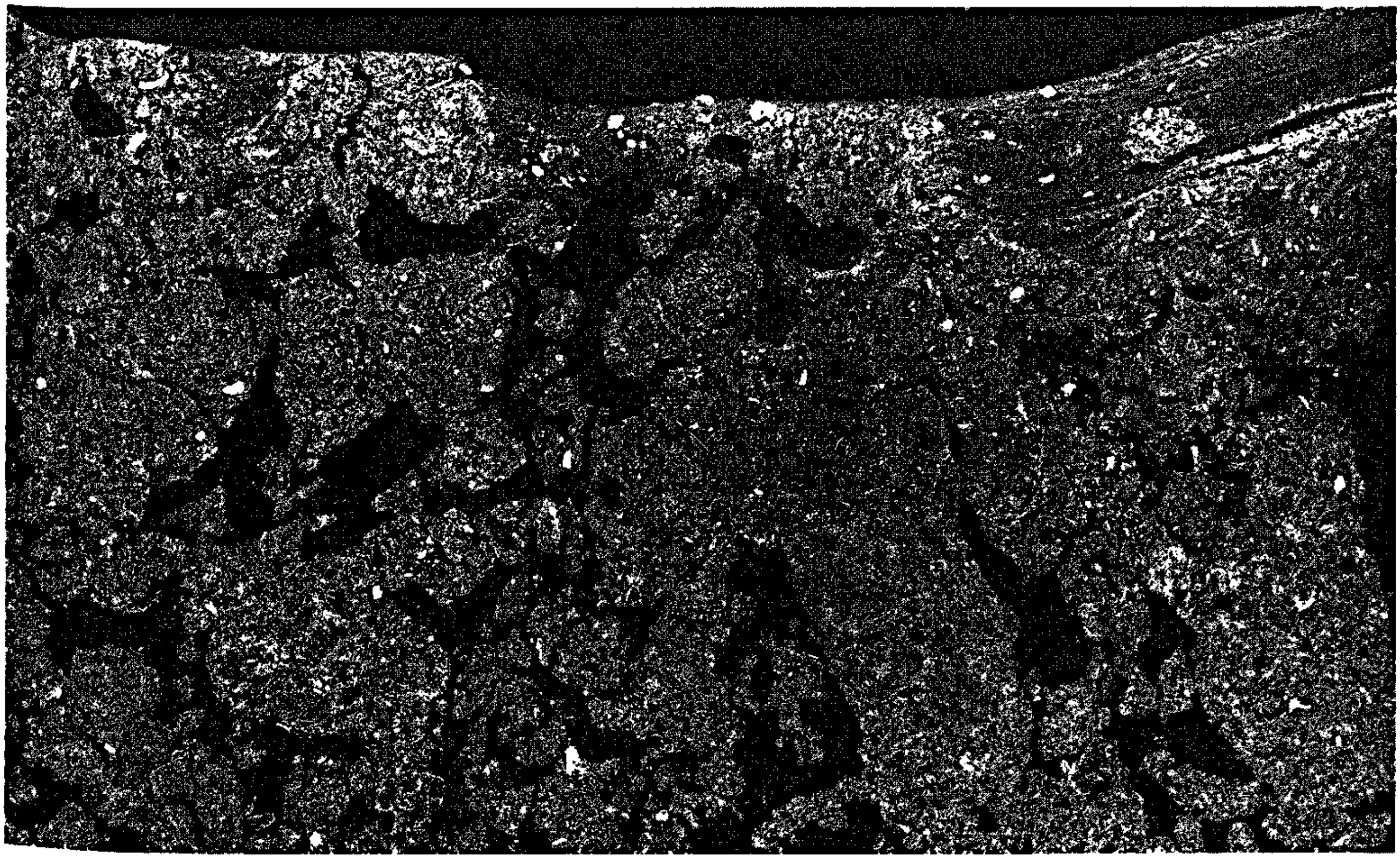


Fig. 8. Surface soil of Pedon G in December 1966. Between fragments are large pores. Part of the crust can be seen on the soil surface (x 2.5).

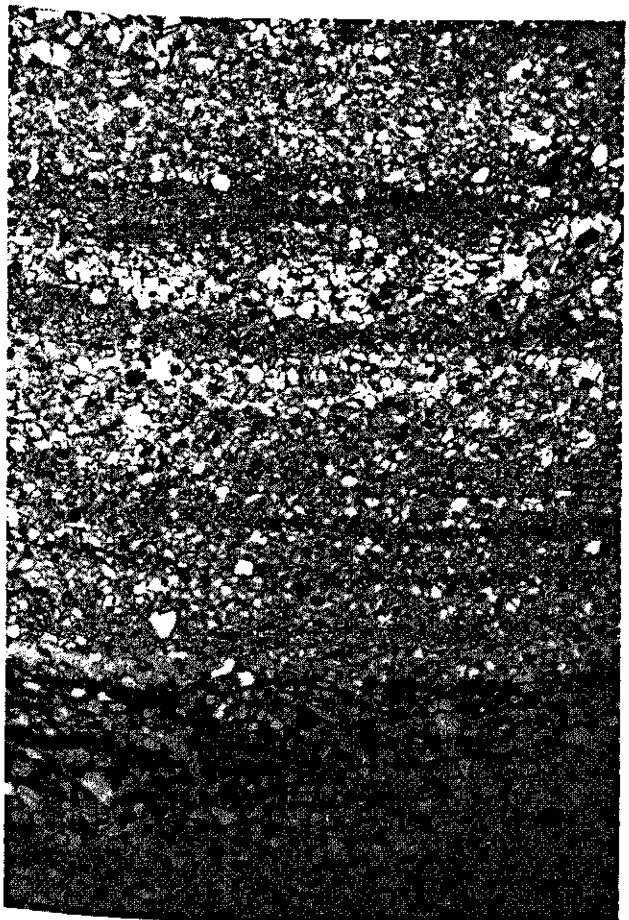


Fig. 6. Crust on Pedon G, with stratified sandy layers of different grain size alternating with dark layers of plasma (x 15).

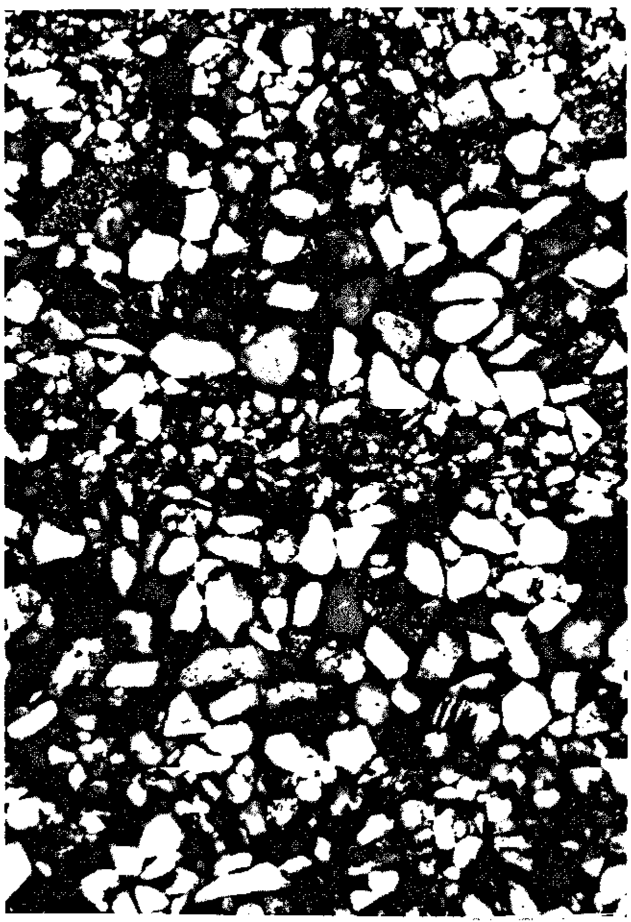


Fig. 7. Detail of crust on Pedon G (see Fig. 6) with stratified sand layers (x 85).

was no free water at the soil surface.

The Ap of Pedon B looked quite different (Fig. 9). Tillage had not increased pore volume but had reduced air content of the Ap at pF 2 from 13 to 8%. Moisture content at pF 2 increased strongly (Figs. 3 and 5), indicating puddling. Water stagnated on the surface (Frontispiece). The soil material in the Ap was plastic and had local pockets of mud. The grass, mixed with the soil during ploughing, looked rotten and yellow. Water and mud flowed from the surface soil into the profile pit. The subsoil below the Ap had, in contrast, a firm consistence.

2.3.5 Soil structure before seedbed preparation (March 1967).

Physical data did not differ significantly from those obtained in December 1966, except for the lower moisture content at pF 2.0 and the lower pore volume of the upper part of the Ap in Pedon B (Fig. 5). This was caused by drying. The winter had been mild but occasionally frosty.

Differences in permeability between samples of March 1967 and August 1966 are evident. Surface soil from Pedon G was more permeable after tillage. The surface soil from Pedon B was less and even impermeable! Tillage in this soil had failed to create large pores between fragments.

2.3.6 Illuviation cutans.

Of special interest were cutans (argillans) in the Ap of Pedon B in March 1967. In thin sections these argillans were strongly oriented (Fig. 10). Clay was mobilized during ploughing by severe puddling which formed a suspension of clay particles. When the suspension is sucked into the s-matrix the clay plates will settle on the walls of the pores. The same process seems to occur in textural B horizons of Alfisols, where argillans have a similar fabric; there the clay is chemically mobilized whereas here the process is mechanical.

Pedon G did not have such argillans except moderately oriented ones locally in the Ap_2, perhaps formed after severe puddling in previous years.

Other cutans (organo-argillans) occurring in both pedons are entirely different in morphology (Fig. 11). They are composed chiefly of fine-grained plasma with a flecked, locally striated orientation pattern. They contain some very fine sand grains and many fine organic

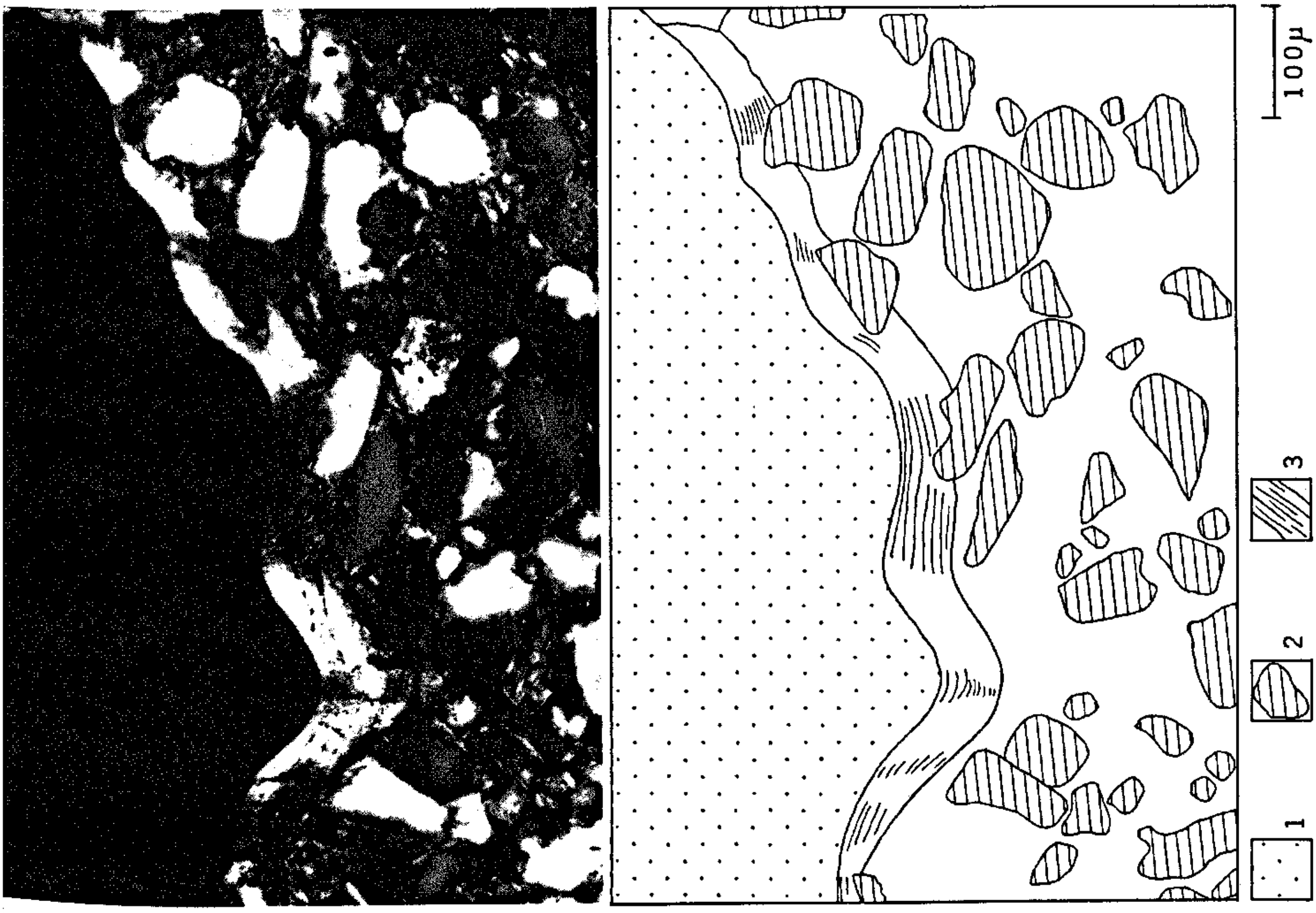


Fig. 10. Argillan with a strong orientation in the Ap of Pedon B, observed in March 1967 after puddling during ploughing in autumn.
1 = void; 2 = skeleton grains; 3 = argillan.

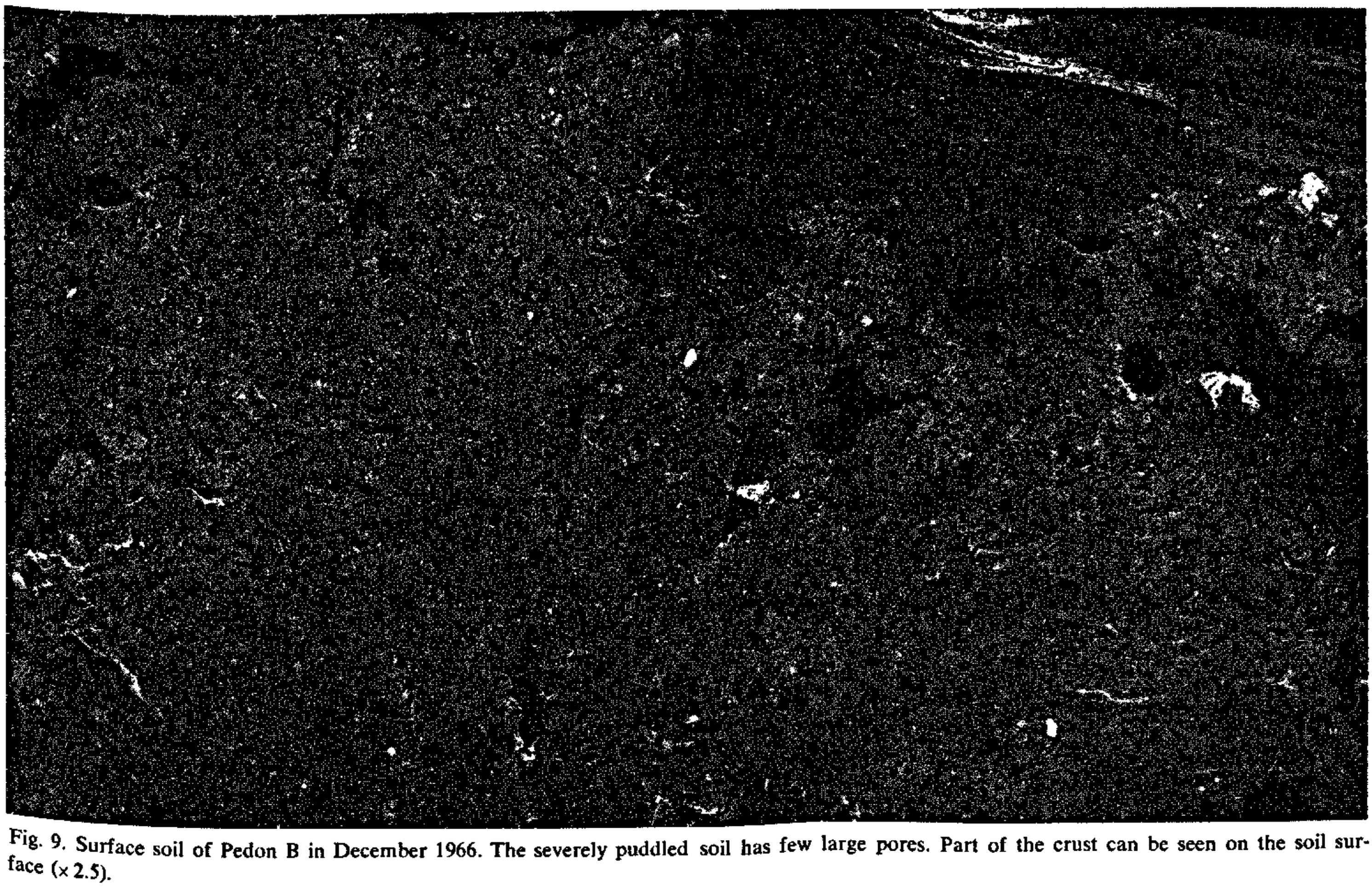


Fig. 9. Surface soil of Pedon B in December 1966. The severely puddled soil has few large pores. Part of the crust can be seen on the soil surface (× 2.5).

Fig. 12. Surface soil of Pedon B in March 1967 (soil peel). The apedal soil material is dense and lacks channels.

Fig. 13. Subsoil of pedon B at 40 cm. Channels visible in the apedal soil material. A cutan has formed on the walls of a larger void (x 8).

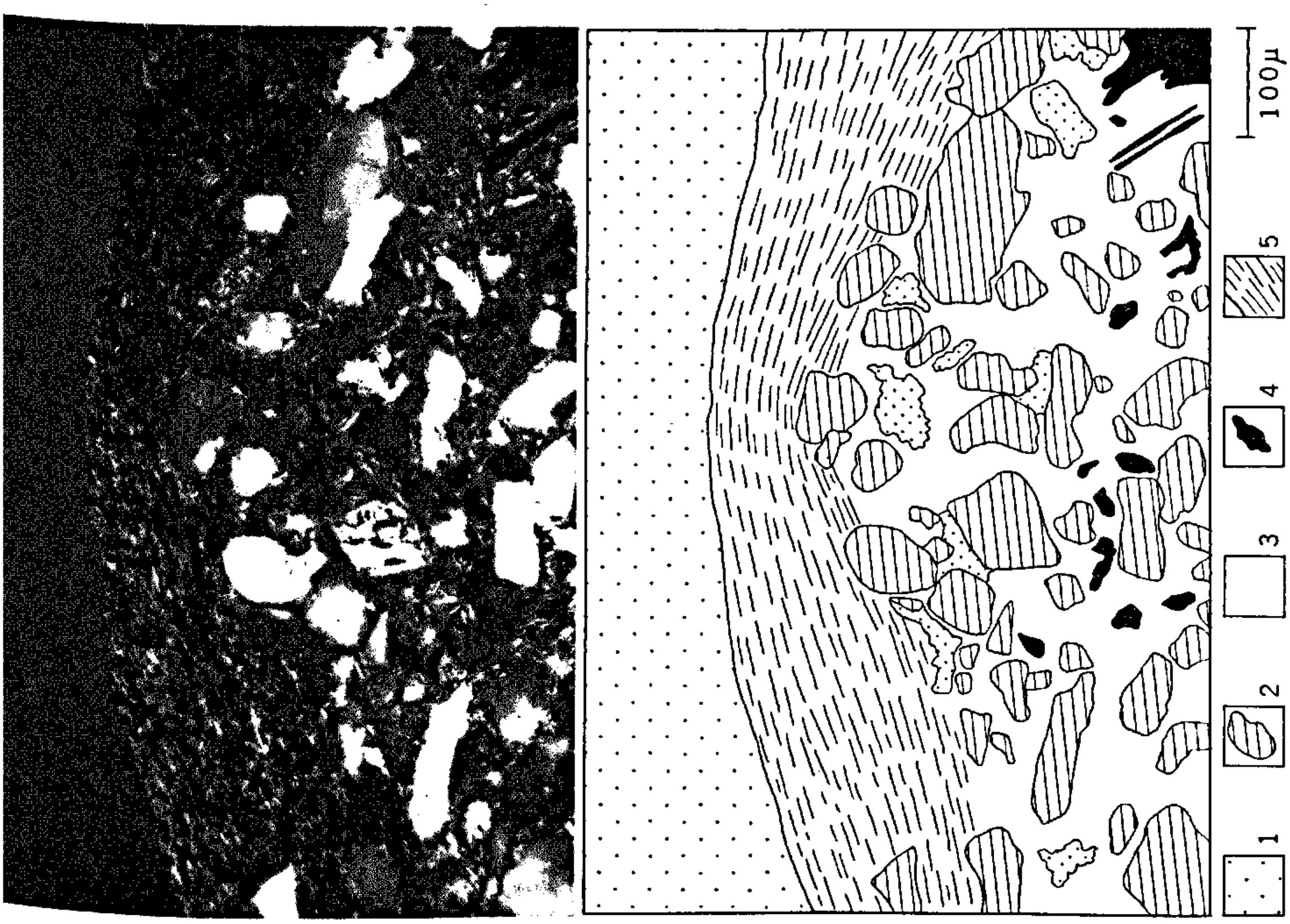


Fig. 11 Organo-argillan with a flecked orientation observed on a face of a fragment in the Ap of Pedon G. They also occur in Pedon B.
1 = voids; 2 = skeleton grains; 3 = plasma; 4 = opaque organic fragments, also found in the cutan; 5 = cutan.

particles. These cutans have the same structure as the plasma between the skeleton grains in the s-matrix. These cutans seem therefore to originate by transport of relatively little disturbed plasma. Little water will percolate very slowly through the plasma between the skeleton grains in the natural soil. Since no peptization occurs, it seems hardly possible that plasma is transported in this way. The most probabale mechanism of transport is started when a soil with crusts is ploughed. Afterwards concentrations of clean sand grains, often with a layered structure as in the crust, alternating with plasma layers are found throughout the Ap. This introduces a pronounced microheterogenity in the Ap after several years (Figs. 14 and 30). Micromorphological observations strongly suggest that layers of plasma from crusts, now scattered through the Ap, are easily re-organized and retransported.

The process of transport of plasma from these buried crust layers occurs in winter, when rainfall exceeds evaporation and when the soil is bare. Water will then flow through larger pores. Cutans are formed on faces of fragments or in pores, when water is sucked from the larger pores into the s-matrix, leaving the mineral particles on the wall.

2.3.7 Soil structure, before tillage (1967).

In 1967 potatoes were grown on Soil G and sugar beet on Soil B. After harvesting the potato crop Pedon G showed clear structural deterioration in September 1967. The Ap horizon could not be sampled in normal horizontal layers. Different types of structure could be distinguished (Fig. 15). The ridges consisted of loose Type V over Type IV, the latter rather porous and firm with also dense fragments. Pore volume, moisture content at pF 2.0 and permeability were about similar to those previously obtained in the Ap of pedon G after summer.

Type III, between the ridges had been compacted during mechanical harvesting of the potatoes. Pore volume was only 40%. The material had a dense fabric. Of interest is the low moisture content (23%) at pF 2.0 (Fig. 4). Machinery had compacted the soil when it was moist enough to be plastic but insufficiently moist for the clay plates to take up any more water (chapter 3). Pressure and shear forces from tractor wheels, sprayers and harvesters had compacted the structure to an air volume of about 4% at pF 2.0.

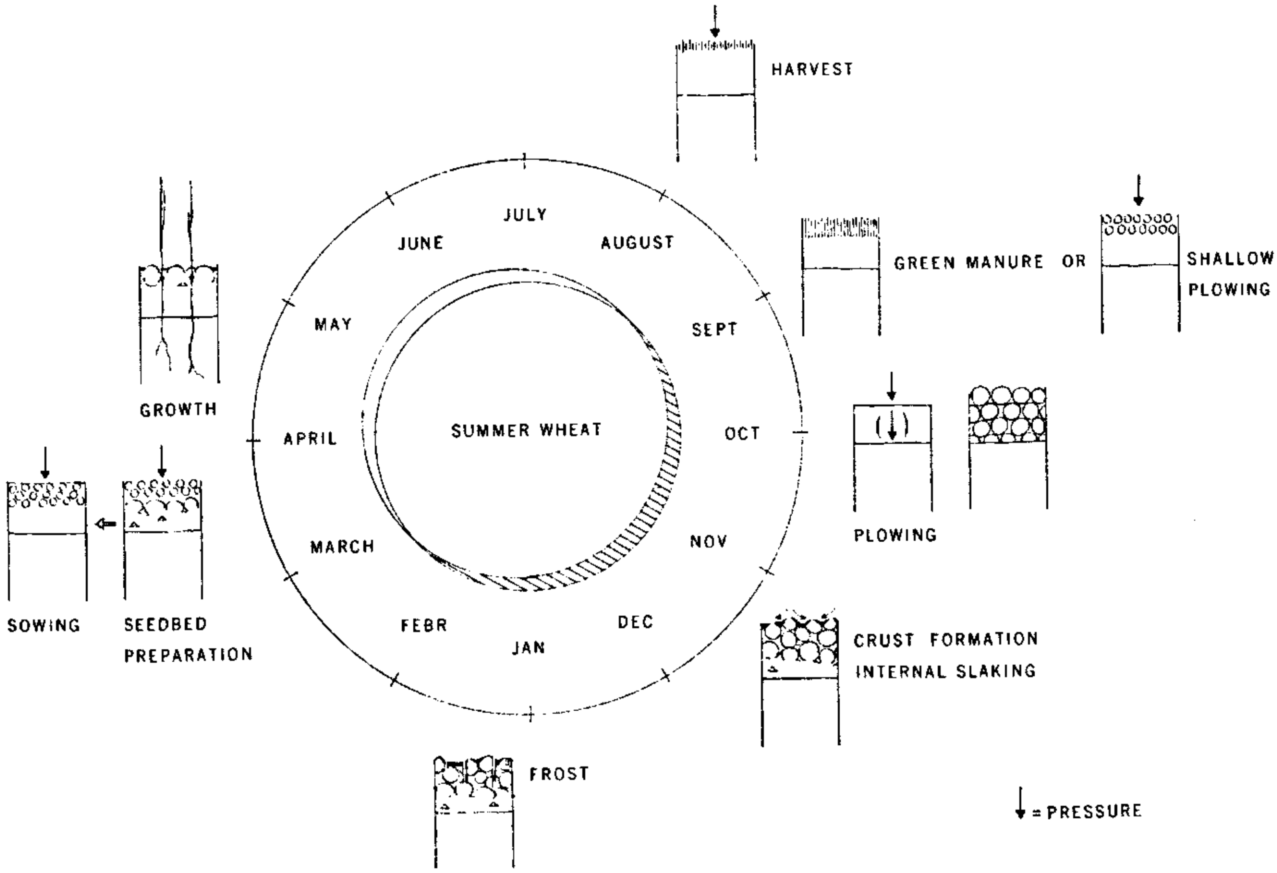


Fig. 16. The yearly management cycle for a crop. The period in which precipitation exceeds evaporation is indicated by the shaded crescent of the intersecting circles.

Fig. 14. Remnant of former crust at 20 cm depth in the Ap of Pedon G. Also frequent in the Ap of Pedon B (× 70).

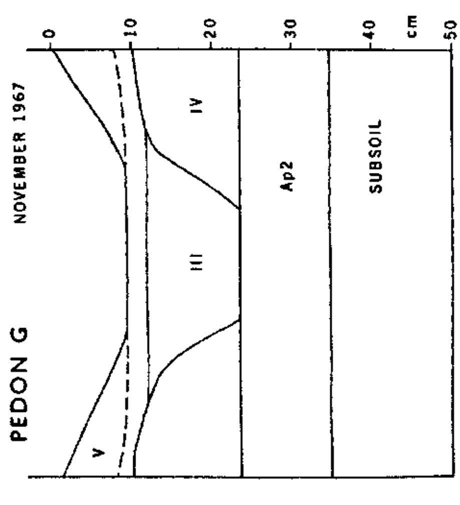


Fig. 15. Profile of Pedon G in November 1967 (schematic): III = compacted soil, IV and V position of potatoe ridges.

Permeability was very low; two samples were impermeable. The Ap_2, that had a sharp boundary with type III had the same characteristics as before (Fig. 2, Ap_2, March 1967); thus its structure must have been very stable to resist the forces causing compaction in the Ap_1, which certainly would have reached deeper than the Ap_1 (Söhne, 1955).

Pedon B was examined on 24 November 1967, when the beet crop was still standing. Pore volumes were a bit less than in March (Fig. 5). There seemed to be slightly more air at pF 2.0 and permeability tended to be higher. Moisture contents at pF 2.0 were clearly less (Fig. 5): In March usually about 22%, in November about 19%.

Pore volume and moisture content at pF 2.0 had decreased by drying in summer, altering consistence. In March consistence was slightly plastic and in November firm or even rather brittle. Moisture contents were similar at the moments of observation corresponding to a pF of about 1.5 (25% moisture).

Samples from the deeper layers of the Ap_1 (22-27 cm, Fig. 5), still had most moisture at pF 2.0, obviously because drying was less pronounced at greater depths.

2.3.8 Tillage and resulting soil structure (December 1967).

Field G was ploughed in October and Field B in December immediately after harvesting the sugar beet. Before ploughing both fields, the weather was rather dry and there was no surface water, except on the compacted soil of Pedon G (Type III, Fig. 15). Moisture content in the surface soil at the moment of ploughing was at about pF 2.0. The tilled soils were sampled on 15 December.

Tillage of Soil G, in the same manner as the previous year, had increased pore volume (Figs. 3 and 4). Moisture at pF 2 had increased in some samples (Fig. 4). Permeability varied widely because of mixing of the compacted and the more porous soil (Types III and IV). Differences between Ap_1 and Ap_2 persisted. The former had locally a rather weak and plastic consistence, whereas the latter was firm and slightly brittle.

Pedon B was little affected by tillage. Tillage hardly affected pore volumes but slightly increased moisture content at pF 2.0 (Fig. 5). Permeability tended to increase, but not significantly.

2.3.9 Preliminary conclusions from the field data.

One of the purposes of tillage is to improve the physical root environment in order to obtain a better crop (Kuipers, 1963). Boekel (1963) gives optimum values for pore volume and air content at pF 2.0 in silt soils: yields should be highest with a pore volume of 48 to 50% and an air content of 14 to 17%.

Slager (1966) states that air content at pF 2.0 should be at least 10% for roots to develop well.

These facts and the field data lead to the following conclusions:

1. After tillage of Soil B in 1966 air volume at pF 2.0 was clearly less than 10%, and even less than before tillage. In 1967 tillage increased air volume only very slightly. In soil G air volume at pF 2.0 increased after tillage in 1966. In 1967 this occurred for only part of the Ap.
2. In winter 1966, water accumulated after tillage on the surface of Soil B but not on Soil G. In 1967, water stood on a compacted surface layer on Soil G before tillage, but not on either soil after tillage.
3. Pore volumes in the Ap of Soil B were never more than 45%. In Soil G they varied up to 56%. This suggests that soil material G was more stable in structure (Figs. 4 and 5).
4. After tillage moisture content at pF 2.0 usually increased; sometimes very slightly. If so, the soil material in the Ap was weak and had a slightly plastic consistence.
   Before tillage it had been slightly firm at the same moisture content.
5. Soil G was strongly compacted in part of the layer that had previously been ploughed with favourable results.
   This compacted layer was sharply marked off from an underlying uncompacted porous layer that had not been ploughed.

To reach a better understanding of these phenomena, attention has to be paid to the factors that govern structure and stability of both soil materials.

3. Microstructure and stability of the soil material in the ploughed layer.

3.1 Introduction.

During the year the growing of each crop is accompanied by certain, more or less fixed management practices. For summer wheat for example (Fig. 16) the cycle starts with ploughing to create large pores between newly formed fragments. In winter a crust or at the surface and internal slaking may occur. Frost may form ice wedges and the soil may dry out. In spring the seedbed is prepared, the crop is sown and starts growing. After the harvest a green manure crop may be grown or the soil may be shallow ploughed.

Such a very general cycle can be given for each crop. The application of pressure and shear forces by machinery may result in puddling of the soil material when its moisture content is sufficiently high. Most soil traffic and -tillage occurs in a period when rainfall exceeds evaporation (Shaded area of the intersecting circles of Fig. 16). In the soils considered here the water table is at about 1 m. The moisture content in the surface soil, with rainfall exceeding evaporation, will therefore, as a very general average, be in equilibrium with a suction of pF 2.0 or will be higher during desorption to this suction.

At these relative high moisture contents processes of puddling are probable to occur.

Some processes illustrated in Fig. 16 and described above, imply that soil particles will more relative to one another. Puddling moves them by swelling the process. Internal slaking implies a change in the arrangement of particles in fragments. Crust formation involves a separation of plasma and skeleton grains by mechanical action of raindrops. The result of these processes depends on the external forces applied to the soil material and the cohesive forces keeping the soil particles together. In this section cohesion will be discussed, as related to moisture content and the microstructure of the soil material.

3.2 A short analysis of soil cohesion and plasticity.

For two spheres with water at the points of contact (Fig. 17) the total tensile force is given by the formula:

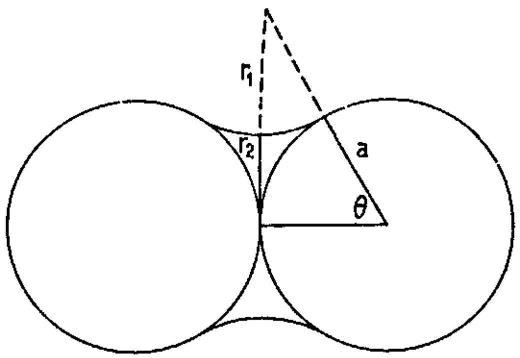


Fig. 17. Two spheres with water at the point of contact.

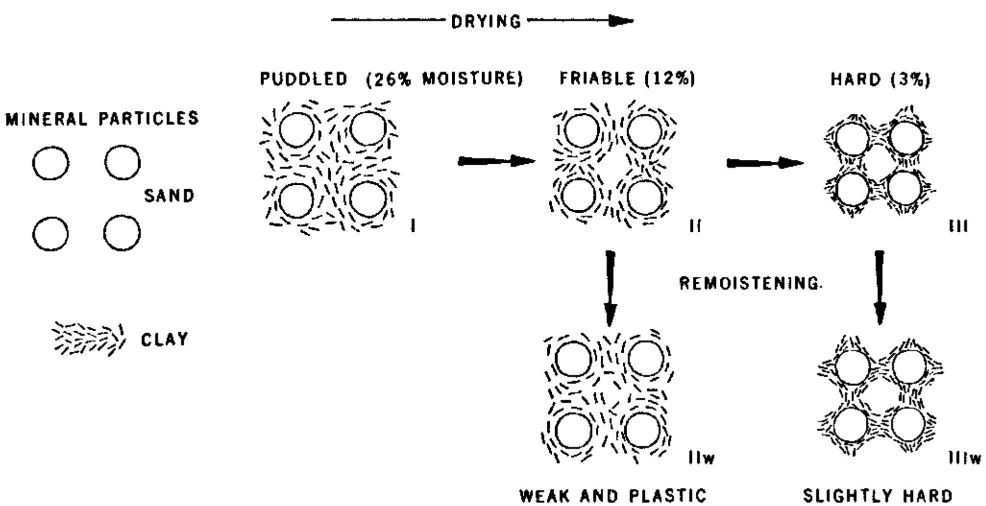
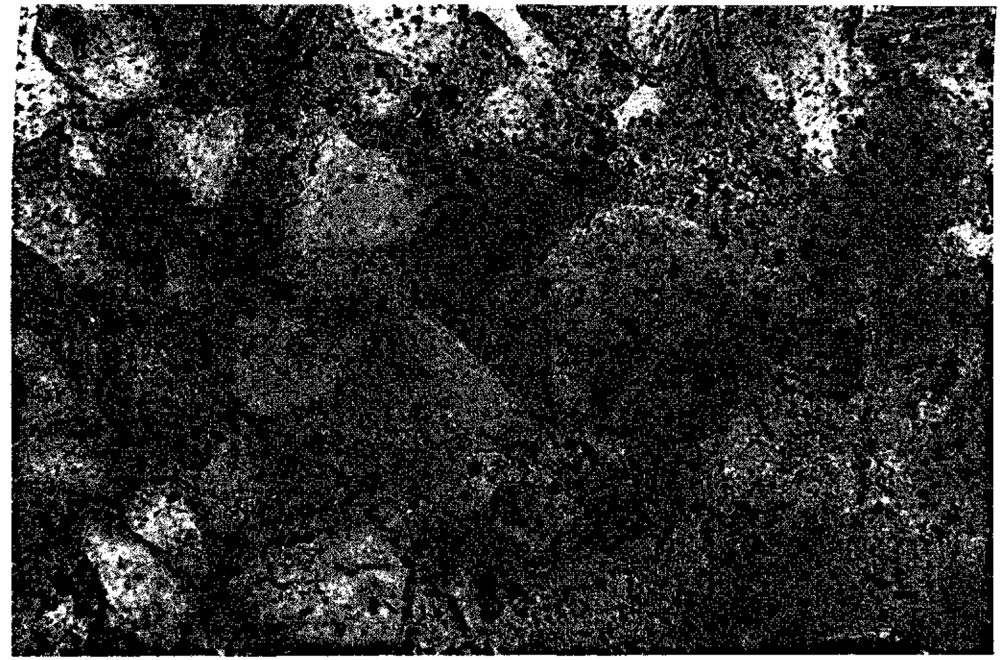


Fig. 18. Microstructures in this soil material as a function of treatment. When puddled soil (I) is dried, the fine particles concentrate around larger grains (III) leaving fine pores between. These pores remain after remoistening (IIIw). This material is slightly hard. After slightly drying to a friable consistence (II) remoistening forms a weak and plastic soil (IIw). The following figures illustrate some of the stages.



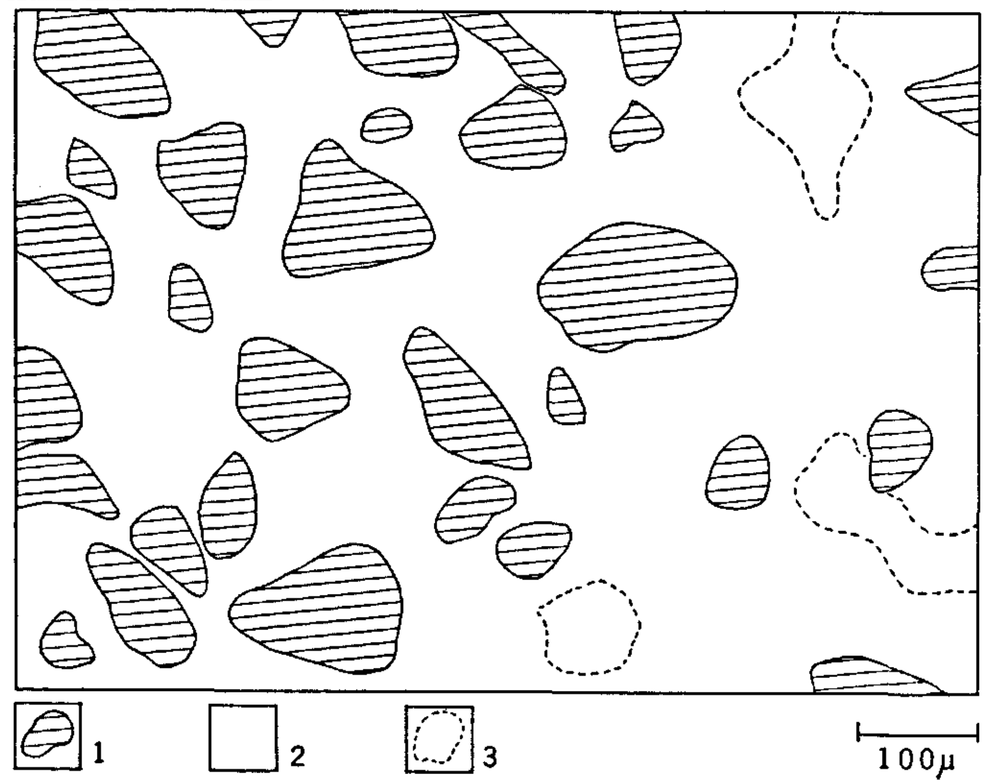


Fig. 19. Puddled soil material B (stage I, Fig. 18), impregnated with Carbowax 6000 (normal light).
1 = skeleton grains; 2 = plasma; 3 = voids formed during preparation of the thin section.

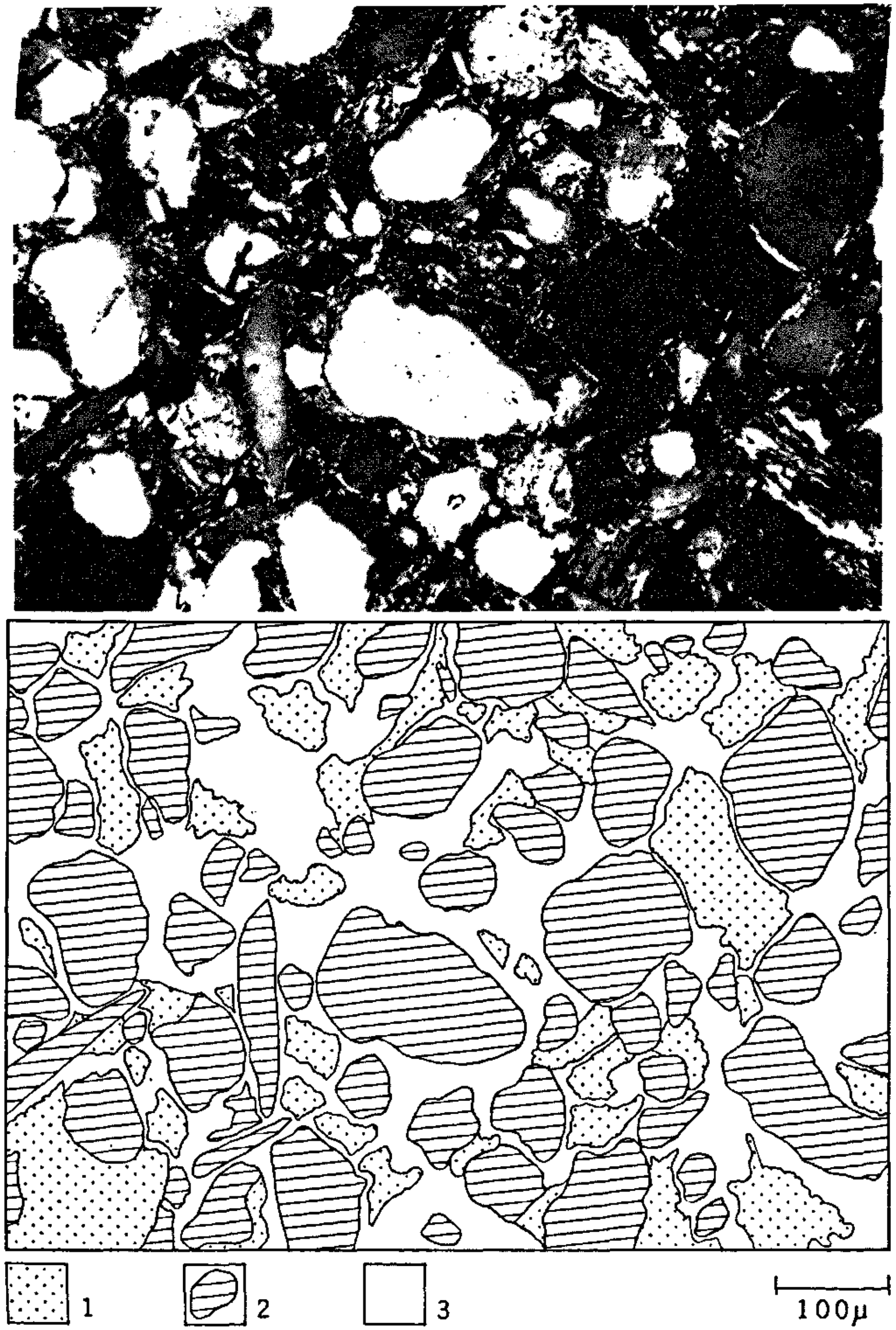


Fig. 20. Puddled and dried soil material B (stage III, Fig. 18) impregnated with Vestopal-H (crossed polarizers).
1 = voids; 2 = skeleton grains; 3 = plasma, locally strongly oriented around skeleton grains.

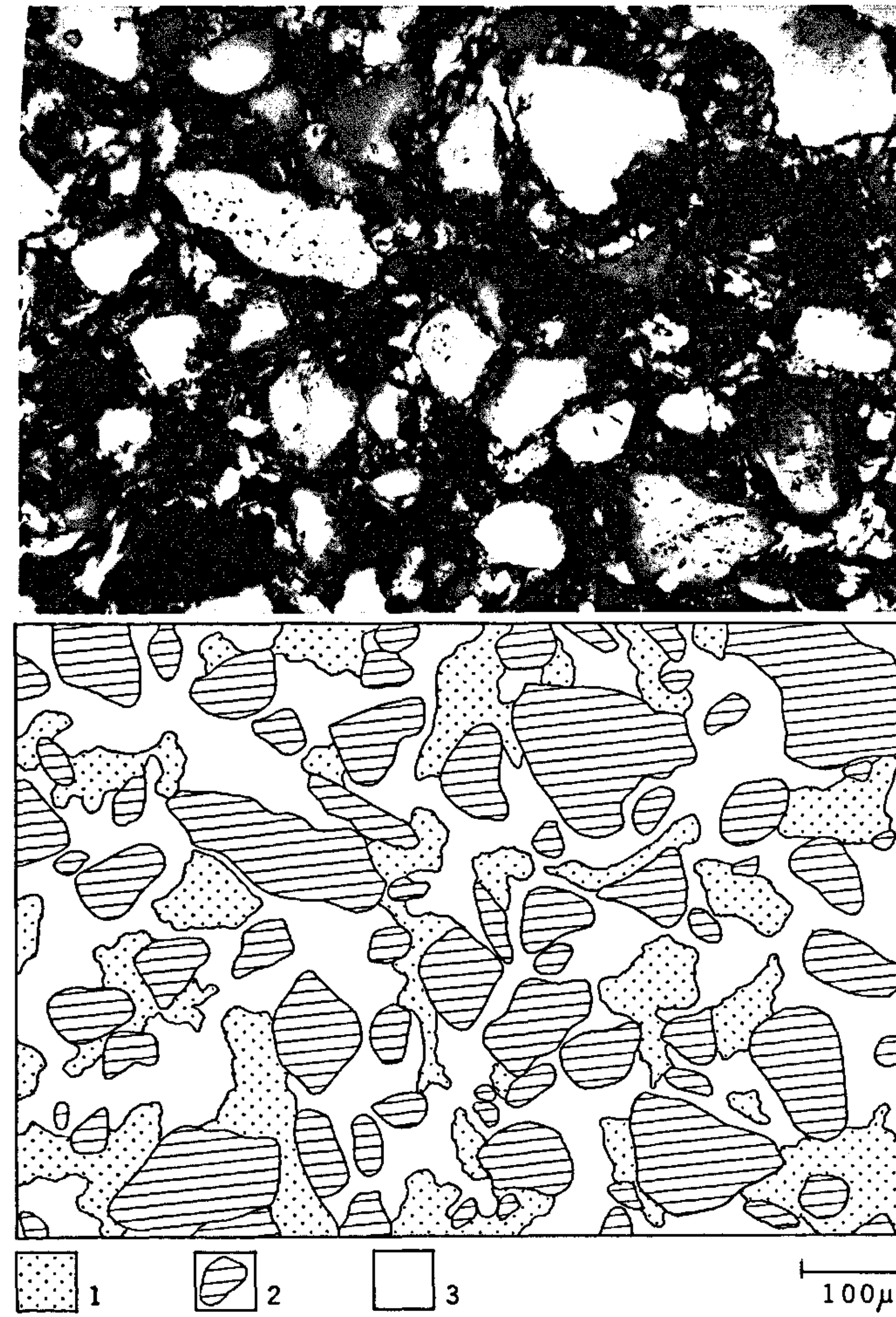


Fig. 21. Puddled, dried and remoistened soil material B (Stage IIIw, Fig. 18) impregnated with Carbowax-6000 (crossed polarizers).
1 = voids; 2 = skeleton grains; 3 = plasma.

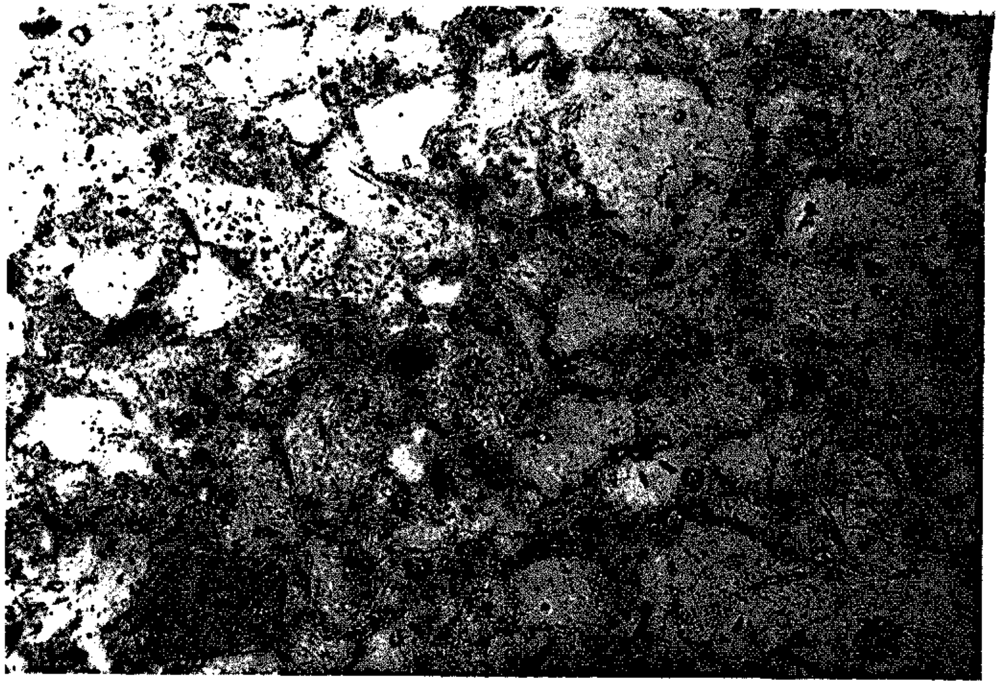


Fig. 22. As Fig. 21, but with normal light.

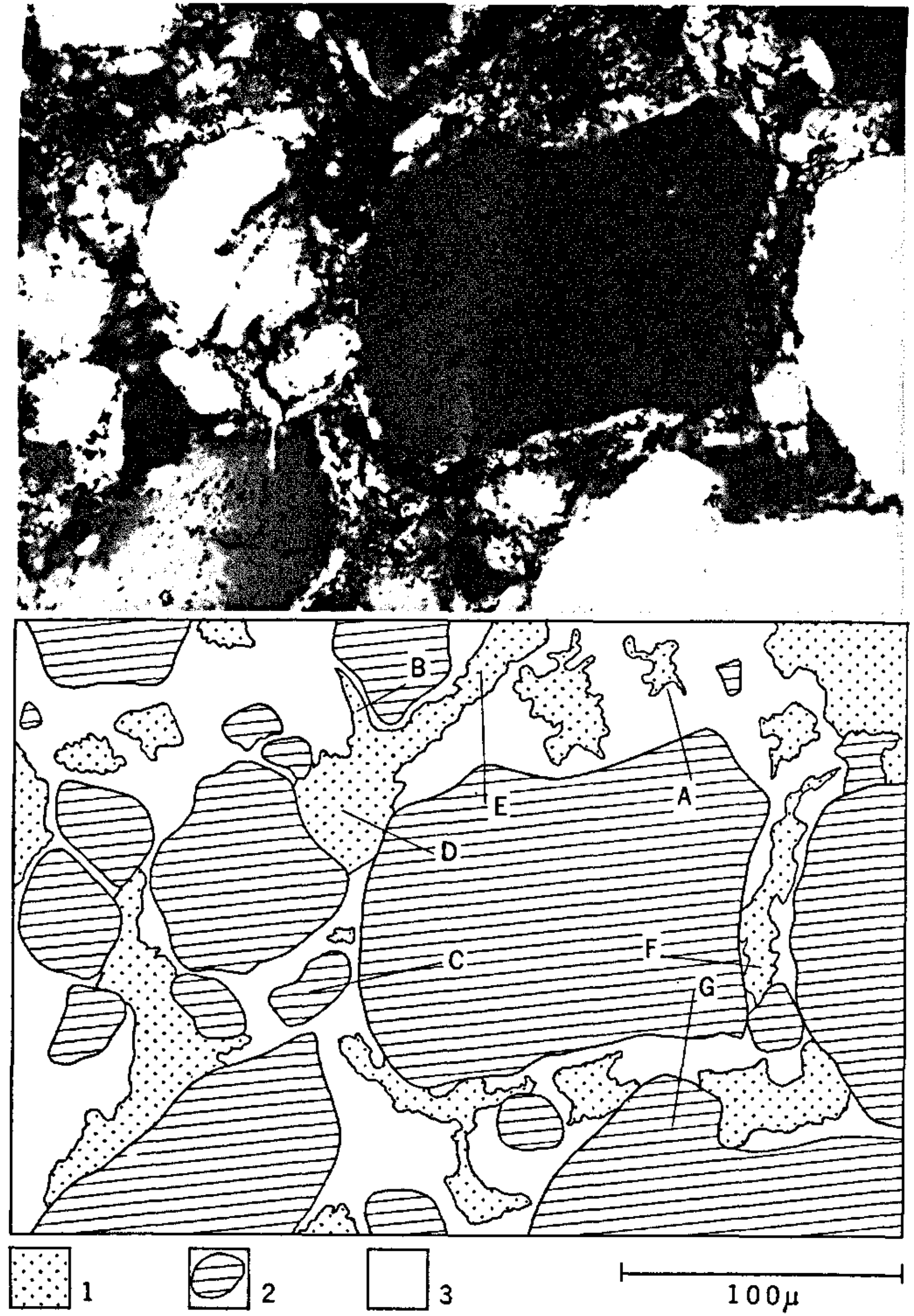


Fig. 23. Puddled and dried soil material G. Explanation of letters (A-G) is given in the text. *During the determination the microscope table is turned at each point. This picture gives only* one image (crossed polarizers) (stage IIIw, Fig. 18). 1 = void; 2 = skeleton grain; 3 = plasma.

$$F = \frac{2 \pi a T}{1 + \tan \frac{1}{2} \theta}$$ (Baver, 1956 p. 101, Haines 1925 a, 1925 b)

in which F = tensile force a = radius of particle T = surface tension of the liquid; r_1 and r_2 (Fig. 17) are the radii of curvature of the moisture film in each of its two principal directions, that determine θ (at lower moisture content θ decreases and so F increases). Cohesion is the sum of these individual film forces over unit cross-sectional area.

However, the soils under study contained clay, so a discussion of cohesion based on a model of spheres bound together only by moisture films is not realistic. Other, more important, binding mechanics must be considered too.

Normally clay minerals are closely packed as birefringent stacks that are present in several patterns between the sand grains (Fig. 20). Koenigs (1963) calls them domains of polyplates and gives a clear picture of the nature of the bonds between the clay plates in a cluster when the soil is dry. Madelung forces acting over short distances, edge-to-plate attraction and the binding action of organic bonds are most important. When the clay is moistened, it swells. At zero suction osmotic swelling tends to expand the aggregates indefinitely, but this is counteracted by frictional forces such as the edge-to-plate attraction and the organic bonds. Norrish (cited by Koenigs, 1963) called it and 'internal load'. It includes all attractive forces which prevent indefinite swelling.

If sufficiently large shear forces are applied to sufficiently moist soil material (e.g. by kneading), polyplates slip over each other. Forces that cause the internal load and limit swelling are inactivated, and either the suction will increase or (if the suction remains constant) more water will be taken up. This occurs when sufficient water is present in the soil, or when it is added during kneading (Koenigs, 1963). In the final (theoretical) state the distances between the polyplates are almost equal, and the suction corresponds with the theoretical swelling equilibrium. In the laboratory studies soil was puddled by kneading at a moisture content corresponding to about pF 1.5 (G = 27%; B = 24% moisture).

A very weak plastic soil mass was formed then with a relatively high pore volume (G: 44%, B: 41%) most of which was filled with water, and a relatively high moisture content at pF 2.0 (G: 24%, B: 21%). This type of structure was frequent in our soils after tillage.

Generally speaking below a certain moisture content, corresponding with the 'lower plastic limit' (Baver, 1956, p. 109), the puddled soil material becomes friable and ceases to be plastic when rolled into a wire. Plasticity is the result of movement and subsequent parallel orientation of the clay particles each of which surrounded by a thin film of water. When the moisture content is below the lower plastic limit, soil cohesion is higher: the soil is friable, it breaks into fragments when rolled into a wire.

When the moisture content of a puddled soil sample exceeds the "upper plastic limit": cohesion is so low that the puddled soil mass flows when a relative low amount of energy is applied. The plastic limits, known as the Atterberg-consistency values, are determined on puddled soil material.

Natural unpuddled soil usually has a higher internal load therefore a higher resistance. In addition the pressure and shear forces to which the soil is subject under natural circumstances may be quite different from those exercised by Human hands during rolling, so that natural soils may be more stable than indicated by these limits. Nevertheless the consistency values of Atterberg are usefull in discussing soil stability. Values for lower and upper plastic limits of the two soil materials are marked in Fig. 58.

3.3 Microstructure of the soils.

The two soil materials are sandy loams with sufficient very fine particles to make them plastic in a certain moisture range. They have chiefly an intertextic basic fabric (Brewer, 1964, p. 170), which observation from thin sections supplements the information on particle size distribution that is based on weight percentages of the components (Appendix 1).

There is insufficient plasma to fill all intergranular simple packing voids (Figs. 20 and 30) so that it can be assumed that the arrangement of the fine particles between the skeleton grains will determine mechanical stability at any moisture content (see also Willet, 1962).

As wet puddled soil dries, soil moisture will concentrate around the skeleton grains and thus will draw the plasma onto the grains. After drying the plasma will bind the grains together. If rewetted, the plasma does not swell back to its original volume and incoherent structure(cf. Croney & Coleman, 1954). Only working of the soil with sufficient water will reverse this process. The drawings shown in Fig. 18 may illustrate these phenomena.

Fig. 19 shows a puddled sample of Soil B (24% moisture) prepared in Carbowax 6000 (Mitchell, 1956). The plasma is scattered between the skeleton grains and the clay plates are separated by swelling. Fig. 20 shows a sample which has been puddled and dried to 3% moisture (air dry). This was impregnated with Vestopal-H (Jongerius and Heintzberger, 1963). Here the plasma is concentrated around skeleton grains and at points of contact. With crossed polarizers the plasma exhibits specific patterns of orientation that will be discussed in the following section. Figs. 21 and 22 show a puddled and dried sample which has been remoistened and impregnated with Carbowax 6000. The soil plasma is still present around and between the skeleton grains, leaving small pores in between.

Impregnation with Carbowax is a cumbersome procedure, the sample remains soft afterwards and thin sections are fragile. But it is the only way of preparing thin sections of wet materials.

3.4 Measuring microstructure of dried soil samples.

In thin sections dried puddled samples (Fig. 20 for soil B) have a dominantly skelsepic plasmic fabric, locally with neostrains around skeleton grains and asepic or weakly insepic plasma. An attempt was made to express this microstructure quantitatively.

First puddled and dried samples with a homogeneous s-matrix will be discussed. For this purpose skeleton grains of about 100 μm were selected at random under a polarization microscope. The grains were moved to the centre of the field of vision and with the aid of two perpendicular axes in the ocular eight points on the border of each grain were fixed at random.

At each point the kind and thickness of material bordering the grain was determined. The table of the microscope was turned to determine the degree of orientation of the plasma at each point. The following types have been distinguished (see Figs. 23 and 24)

skeleton grain - neostrian - plasma	(A)
skeleton grain - neostrian - void	(B)
skeleton grain - neostrian - skeleton grain	(C)
skeleton grain - void	(D)
skeleton grain - plasma thicker than 10 μm	(E)
skeleton grain - plasma thineer than 10 μm - void	(F)
skeleton grain - plasma thinner than 10 μm - skeleton grain	(G)

The term plasma includes both asepic and insepic plasma. Sets of 40 observations were collected to estimate the number of observations necessary for sufficiently reliable results. It appeared that the number of observations could be limited to 200 for both soils. According to the table of van der Plas and Toby (1965) the percentages are to be read as $\pm$ 4% (95% probability).

The data on orientation of the plasma bordering the skeleton grains are summarized in Table 2. Finally the degree of orientation of the neostrians has been noted (Table 3).

Both Bp and Gp can also be described in general terms: Sample Bp has an intertextic, Sample Gp an intertextic to agglomeroplasmic basic fabric (Brewer, 1964, p. 170). These denominations are supported by quantitative analyses (Table 1). The greatest difference between the two samples is found in E: in Sample Gp the skeleton grains are more frequently covered with a relatively thick layer of plasma.

Since neostrians generally have a limited thickness, the difference between the two measurements concerning point B has the same implications. The degree of orientation of the plasma around and between the skeleton grains is lower in Sample Gp than in Sample Bp (table 2 and 3).

This may have been caused by the presence of more organic matter, as during drying, when the moisture films contract, domains in the plasma do not orientate themselves to each other as well as in the sample with less organic matter. This results in an asepic or weakly insepic plasmic fabric with organic matter between the clay plates.

The quantitative analysis of dried field samples offers considerable difficulties because of the heterogenity of the microstructure. Parts without any plasma at all are found next to parts where the simple packing voids are filled with plasma (see Fig. 30 and the micromorphological description in Appendix 2).

Counting a large number of grains does not give a representative set of data, as the heterogenity results in rather varying figures. For the present purpose a thin section with a rather 'average' appearance has been selected and granular and porphyroskelic basic fabrics have been left out of consideration. Again based on 25 skeleton grains (200 values) the figures in Tables 4 and 5 have been obtained. As with the puddled samples the strongest orientation was found in sample B. For both soils the figures for the degree of orientation in the field samples were comparable to those for the artificially puddled and dried samples. Therefore it is concluded that drying resulted in a certain pattern of orientation, irrespective of previous treatment.

The pore space in soil aggregates determined with an apolar liquid (see chapter 4.1) was lower in dried field samples than in puddled and afterwards dried samples. A lower pore volume is characterized by a shorter average distance between the skeleton grains. This explains why the values of point C are highest in the field samples.

Table 1. Distribution of plasma between skeleton grains in puddled and dried soil (expressed as percentages of all observations).

	A	B	C	D	E	F	G
From the Ap of profile B (Bp)	37	26	24	6	2	1	4
From the Ap of profile G (Gp)	32	17	19	6	15	2	9

Table 2. Degree of orientation of plasma in puddled and dried soil (expressed as percentages of all observations).

	Skeleton grain-oriented plasma (A + B + C)	Skeleton grain-non-oriented plasma (E + F + G)	Skeleton grain voids (D)
From the Ap of profile B (Bp)	87	7	6
From the Ap of profile G (Gp)	68	26	6

Table 3. Degree of orientation of neostrians in puddled and dried soil (expressed as percentages of all observations).

	Strongly oriented	Moderately oriented	Weakly oriented
From the Ap of profile B (Bp)	25	72	3
From the Ap of profile G (Gp)	12	72	16

Table 4. Distribution of plasma between skeleton grains in dried field samples (expressed as percentages of all observations).

	A	B	C	D	E	F	G
From the Ap of profile B (Bf)	33	20	35	5	4	1	2
From the Ap of profile G (Gf)	28	17	27	12	9	3	4

Table 5. Degree of orientation of plasma in dried field samples (expressed as percentages of all observations).

	Skeleton grain-oriented plasma (A + B + C)	Skeleton grain-non-oriented plasma (E + F + G)	Skeleton grain voids (D)
From the Ap of profile B (Bf)	88	7	5
From the Ap of profile G (Gf)	72	16	12

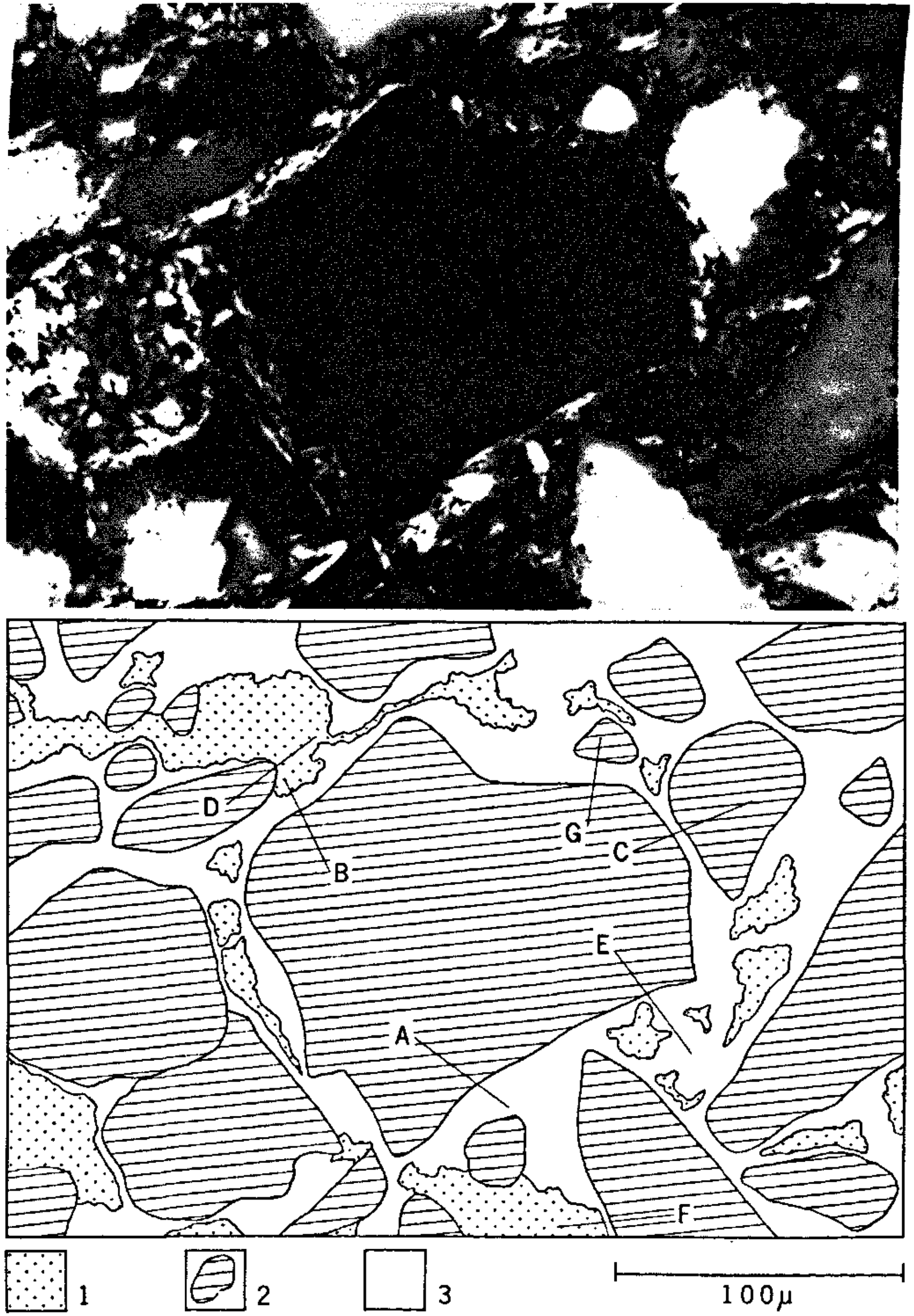


Fig. 24. Puddled and dried soil material B. As Fig. 23.

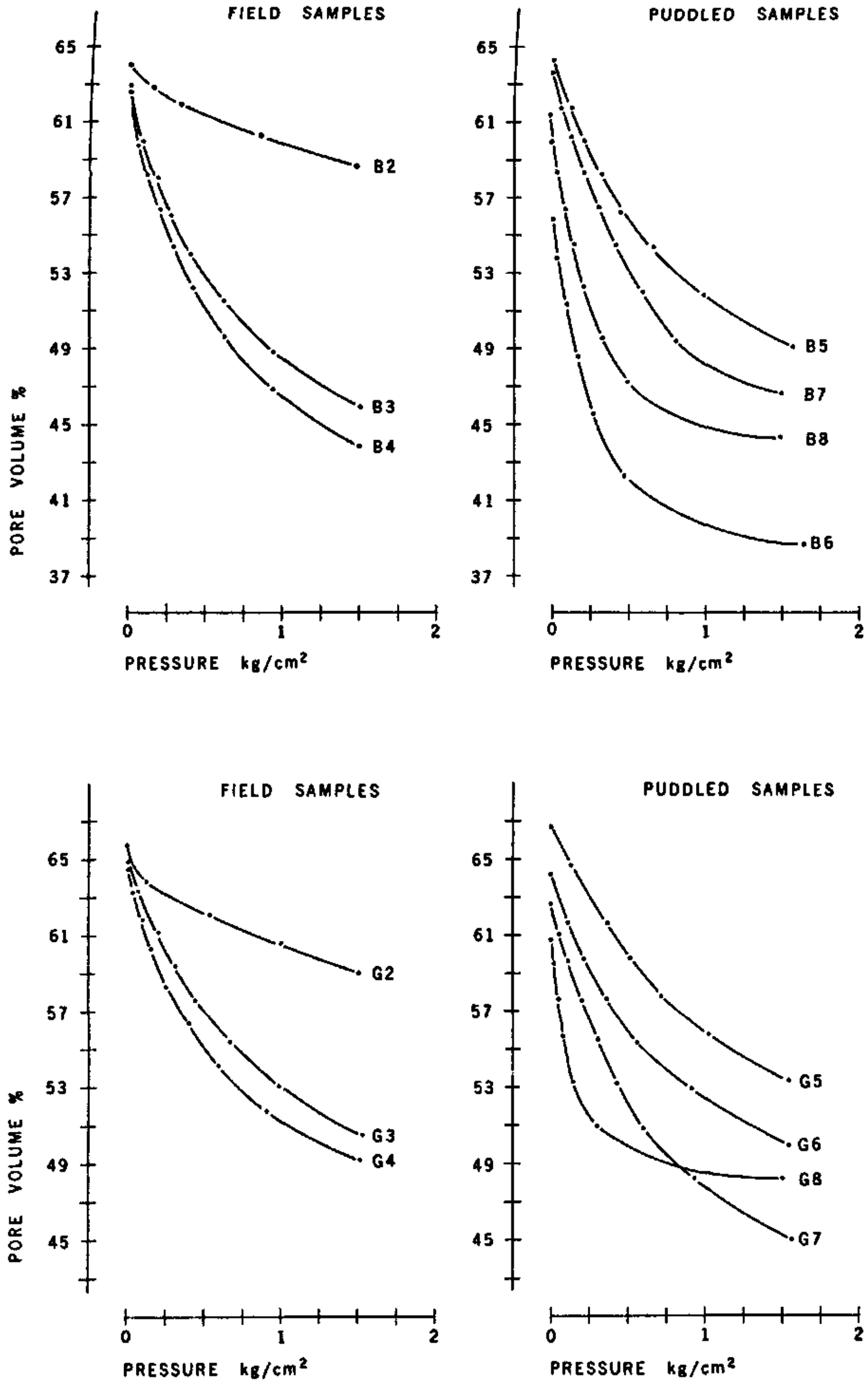


Fig. 25. Compression of aggregate samples.

4. MODEL EXPERIMENTS.

4.1 Pressure

4.1.1 Introduction

The problem of compaction has often been studied in model experiments by compressing standard soil samples under clearly defined conditions (Day & Holmgren, 1953; Kuipers, 1958; Söhne, 1956; Hutter, 1966).

Among others, the aim of such tests is to compare the behaviour of different soils, or of the same soil with different moisture or organic matter contents. All experiments indicate that with increasing moisture content compression is more pronounced. As soon as all pores are filled with water, further compression is only possible by squeezing it out, because it is not compressible (Kuipers, 1958, Söhne, 1956).

Comparison between surface soil and subsoil samples has revealed that higher organic matter content leads to greater stability (Kuipers, 1958; Söhne, 1956). Hutter (1966) has described the formation of larger, rather stable units when aggregates of 1-2 mm are compressed at higher moisture contents. All these data have been collected by physical methods for whole samples, even if they were not homogeneous.

In their study on deformation of aggregates during compression, Day & Holmgren (1953) showed the first micromorphological pictures of compressed aggregate samples with flattened contact areas between the aggregates. The discussion in the previous chapter of puddling processes and the effect of drying suggested that not only remoistened dried samples should be investigated but also samples that were not dried. In addition different microstructures should be studied, such as those occurring in puddled soil as discussed in Chapter 3 and shown in Fig. 18.

With the foregoing in mind, a series of model experiments was devised.

4.1.2 Technical specifications.

Aggregates between 1 and 2 mm were put into a 100 cm^3 5 cm high steel cylinder with the lower opening closed by a thin, detachable, porous piece of cloth. During filling the contents were packed slightly closer by gently knocking the cylinder on the table.

To avoid differences in microstructure all aggregates were obtained by sieving moist soil collected in the field, when necessary slightly dried to a friable consistence (moisture content about 10% indicated by f-sd). Part of these aggregates were dried to a moisture content of about 3% (indicated by f-d).

Series of puddled soils (indicated by p) were also included. To obtain them, the soil was kneaded for a while at a moisture content corresponding with pF about 1.5. Soil material G had about 27% moisture, that of B about 24%. Afterwards pieces were dried to moisture contents of about 10% (indicated by p-sd; Type II in Fig. 18). All aggregates composed of puddled soil were prepared by sieving this moist soil material; again part of them were dried afterwards to a moisture content of about 3% (indicated by p-d; Type III in Fig. 18).

After these procedures, all samples were saturated with water (in vacuum, to avoid rupture of aggregates by explosion of enclosed air), kept in this state during 48 hours to enable free swelling (Koenigs, personal communication), and desorbed to certain pF values (Fig. 28). The following indications were used for the aggregate samples:

B1/G1: natural friable soil with low moisture content, not compressed;

B2/G2: as B1/G1, but compressed;

B3/G3: natural, dried soil, saturated and desorbed to pF 2.0;

B3a/G3a: as B3/G3, but with natural, not dried, friable soil; sampled in autumn.

B4/G4: as B3/G3, but desorbed to pF 1.5;

B5/G5: puddled dried soil, saturated and desorbed to pF 2.0. Afterwards the moisture content was lowered by evaporation to that of B3/G3 as indicated by an arrow in Fig. 28;

B6/G6: Puddled, slightly dried soil, carefully moistened to pF 1.0 on pF sandbox; after a few days a suction corresponding to pF 2.0 was applied; this procedure avoided internal slaking (see Section 4.3). Afterwards the moisture content was lowered as with samples B5/G5.

B7/G7: puddled soil, saturated and desorbed to pF 2.0;

B8/G8: as B7/G7, but desorbed to pF 1.5.

After equilibrium was reached, the samples were compressed at the Laboratory of Soil Tillage under a flat, circular piston with a surface of

20 cm^2 and a constant downward speed of 9 cm per minute, until a pressure of 1.5 kg per cm^2 was reached. The pressure was continuously recorded.

The heights of the sample in the cylinder before and after pressing were very accurately determined, and the pore volume could be calculated at any moment of the procedure from the position of the pressure head, knowing the weight of the core after drying at 105°C and the density of the soil material. (Fig. 25).

The cylinders with the dried sample were impregnated in vacuum (to avoid disturbance by entrapped air) with Vestopal-H (Jongerius & Heintzberger 1963). When hardening, it slightly shrinks thus allowing the removal of the sample without destroying neither sample nor steel cylinder. Finally, a vertical thin section (5 x 5 cm) was prepared for point-counting with a petrographic microscope (see next section). To show the internal structure in the core, an overall picture was also needed. After some attemps, results proved best when the thin section was directly inserted into a photographic enlarger, which gave an image of about one third of the section. This image was directly recorded as a negative on photographic paper: the pores, which did not absorb light, appeared black and the soil particles appeared grey.

4.1.3 Morphometric analysis.

For the morphometric analysis point-counting techniques are used. The samples originally presented a loose assemblage of aggregates. After compression a mass was formed in which the pores were only partly connected in the plane of the section. Physical methods provided values for total pore space in each sample before and after compression.

Morphometric analysis was used to obtain similar values for the larger pores between aggregates. In the aggregates (1-2 mm) very few very fine pores were found (smaller than 0.1 mm).

It was therefore quite easy to distinguish them from intergranular pores, even when the latter were not mutually connected after the application of pressure. They were generally larger than 100 μ.

Point-counting techniques are gradually becoming common practice in micromorphological research (Kubiena, 1966; Milfred et.al., 1967). Details of this method and its mathematical background were described by (Chayes, (1956); Brewer (1964); Van der PLas & Toby (1965); Swanson & Peterson (1942); Alexander & Binnie (1962)) and others.

The method allows the estimation of a volume of a certain component in a sample from a two-dimensional section of the sample. The component should be easily recognizable to ensure reproducible measurements.

Measuring is carried out by projecting a grid of points on the section. The number of points that touch the component to be measured is expressed as a percentage of all points. This is its volume percentage. Van de Plas & Toby (1965) provided a chart indicating the 95% reliability of a count, as a function of the number of points counted.

To apply this method, they emphasize, it is necessary that the distance between two successive points is greater than the average size of the objects to be counted. This can easily be achieved by using a particular magnification. In these experiments a magnification of x 75 was used. In the ocular a grid was fixed with 7 points with an interval of 675 µm. All 1100 points counted were equally scattered over the section. The values given are to be read as ± 2%, with 95% probability. It proved desirable to check the values by another method. Homogeneous samples had to be chosen for this experiment (G1 and B1). With an apolar liquid the internal porosity of the aggregates (sizes 3.4 - 4.8 mm) in a dry state was determined by McIntyre's (1956) method, as described by Kuipers (1961). (Table 6).

Table 6. Percentages pore volume (kerosene method) in dry aggregates between 3.4 and 4.8 mm from field samples and from puddled soil.

	Sample G					Sample B			
Field samples	37.1	36.3	36.7	36.2	av.36.6	33.0	33.2	33.3	av.33.2
Puddled and dried samples	38.3	39.2	37.8	38.7	av. 38.5	37.6	37.8	37.0	av.37.5

Measured by Mr. B. Kloesbergen.

The result was 36.6% with s = 0.4 (sample G1). Morphological values obtained by point counting will be compared with figures obtained by physical methods.

Total pore volume: 63.6% (physical analysis). Counted volume of large pores: 39% and so 61% aggregates. These aggregates contain pores and solid particles. According to the kerosine method: 36.6% pores and so 63.4% solid.

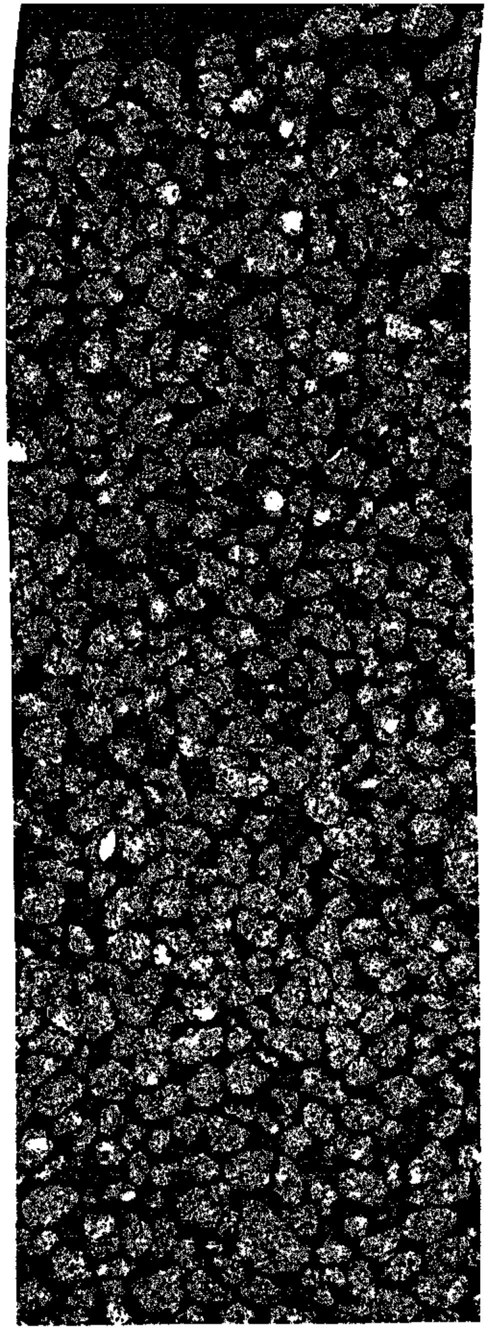


Fig. 26a (x 4).
Sample G_1:
standard,
39 % large pores.

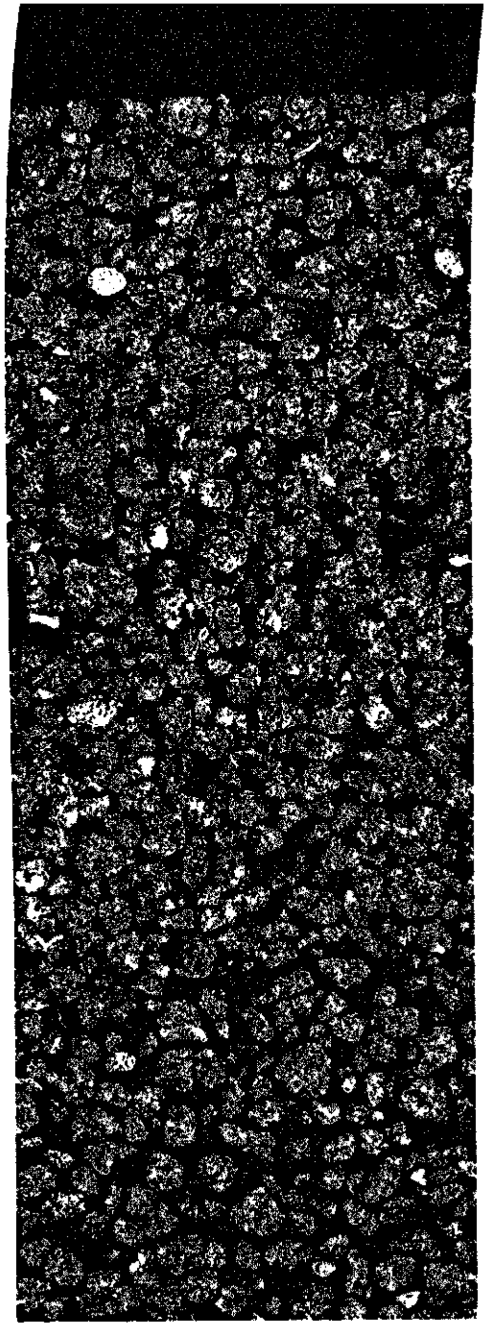


Fig. 26b.
Sample G_2 (Gf-sd):
1.5 kg/cm², 14.2 % moisture,
36 % large pores.

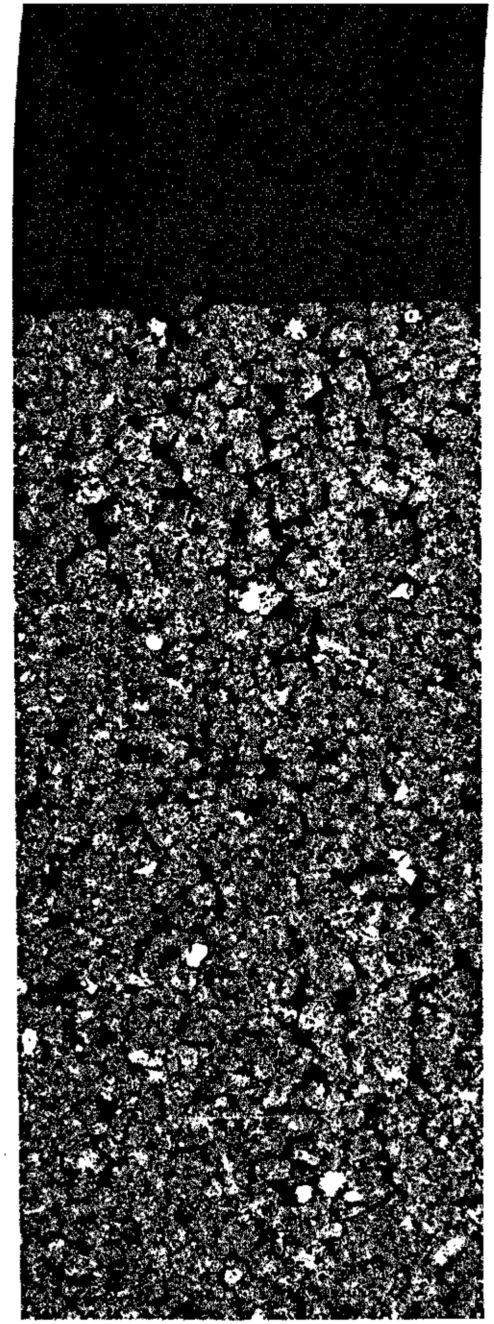


Fig. 26c.
Sample G_3 (Gf-d):
1.5 kg/cm², 23.4 % moisture,
pF 2.0,
18.3 % large pores.

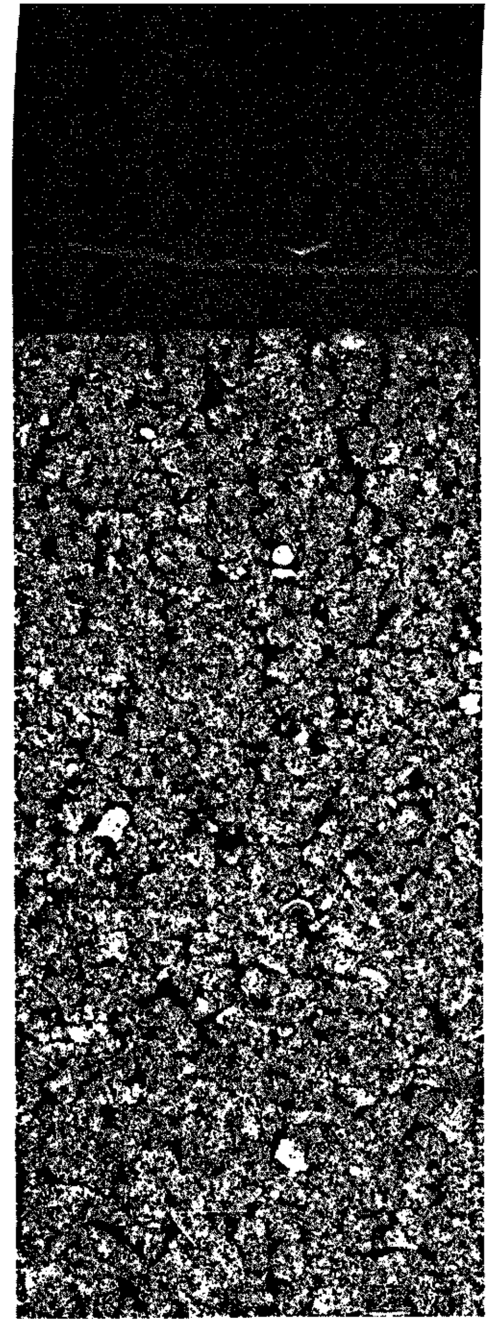


Fig. 26d.
Sample G_4 (Gf-d):
1.5 kg/cm², 27.6 % moisture,
pF 1.5,
17.4 % large pores.

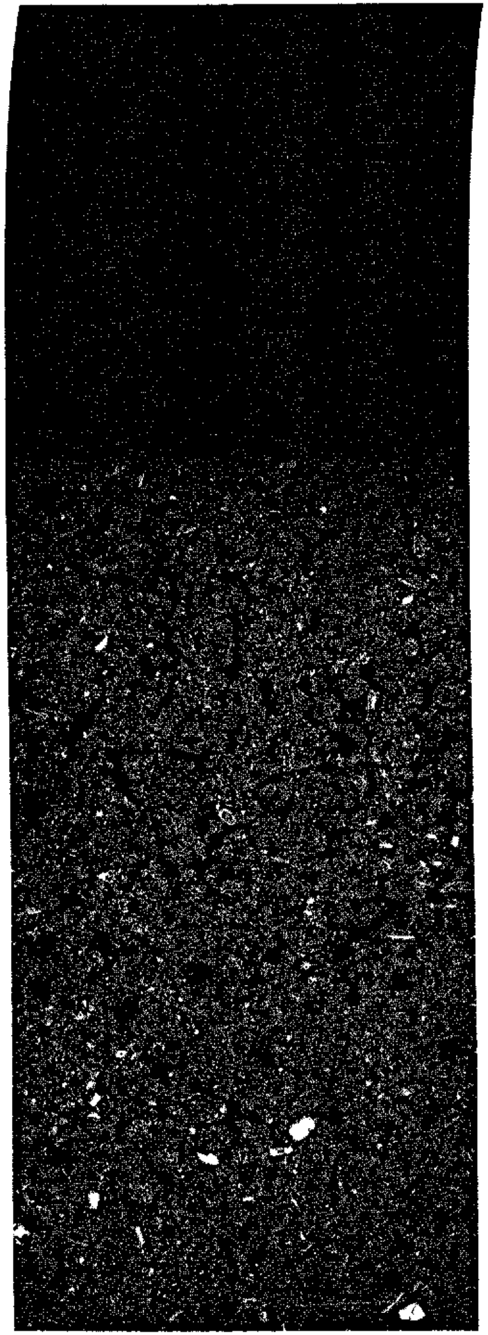


Fig. 26e.
Sample G_6 (Gp-sd):
1.5 kg/cm², 23.4 % moisture,
pF 2.0 ↓,
16.4 % large pores.

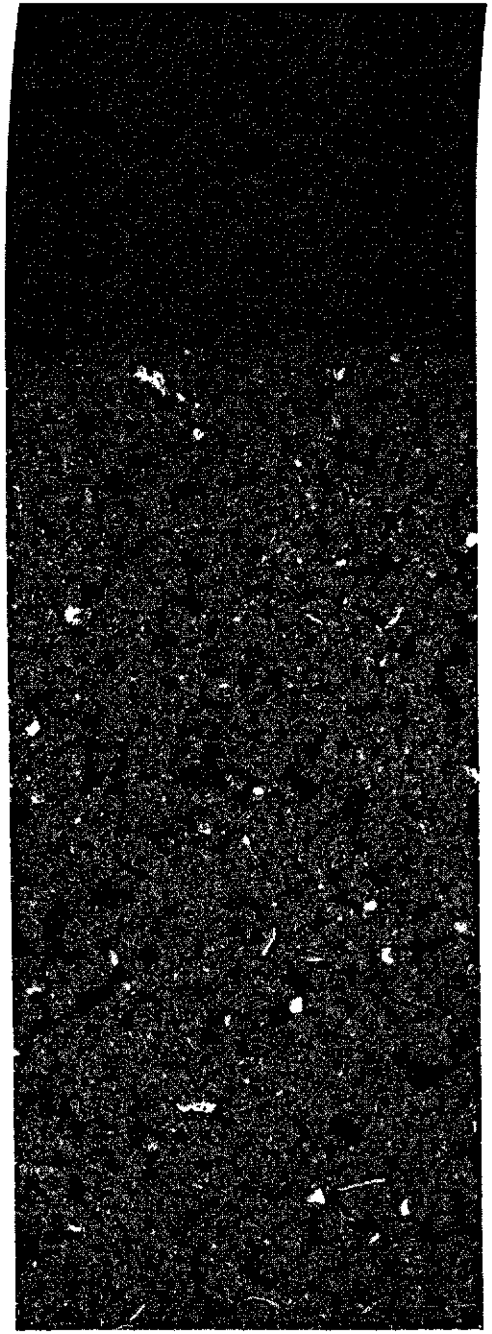


Fig. 26f.
Sample G_5 (Gp-d):
1.5 kg/cm², 23.4 % moisture,
pF 2.0 ↓,
19.4 % large pores.

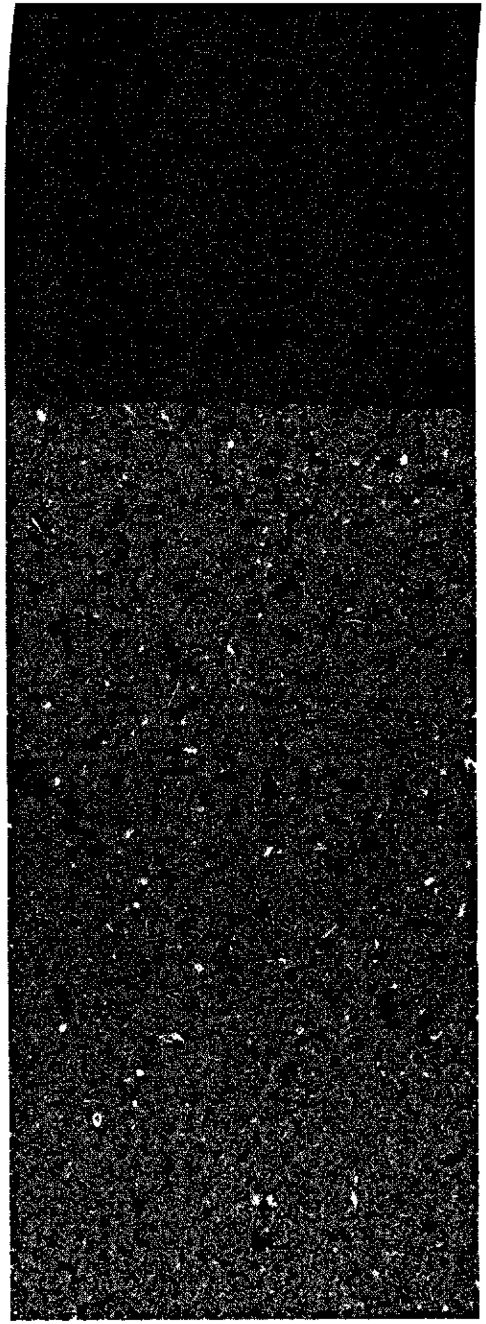


Fig. 26g.
Sample G_7 (Gp-sd):
1.5 kg/cm², 25.1 % moisture,
pF 2.0,
14.9 % large pores.

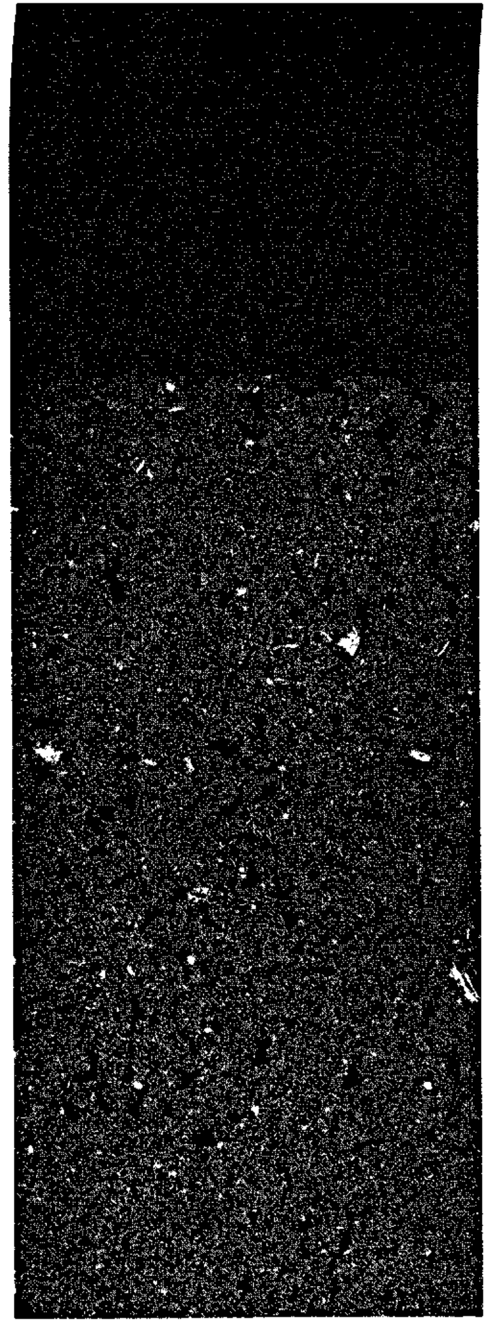


Fig. 26h.
Sample G_8 (Gp-sd):
1.5 kg/cm², 33.9 % moisture,
pF 1.5,
10.2 % large pores.

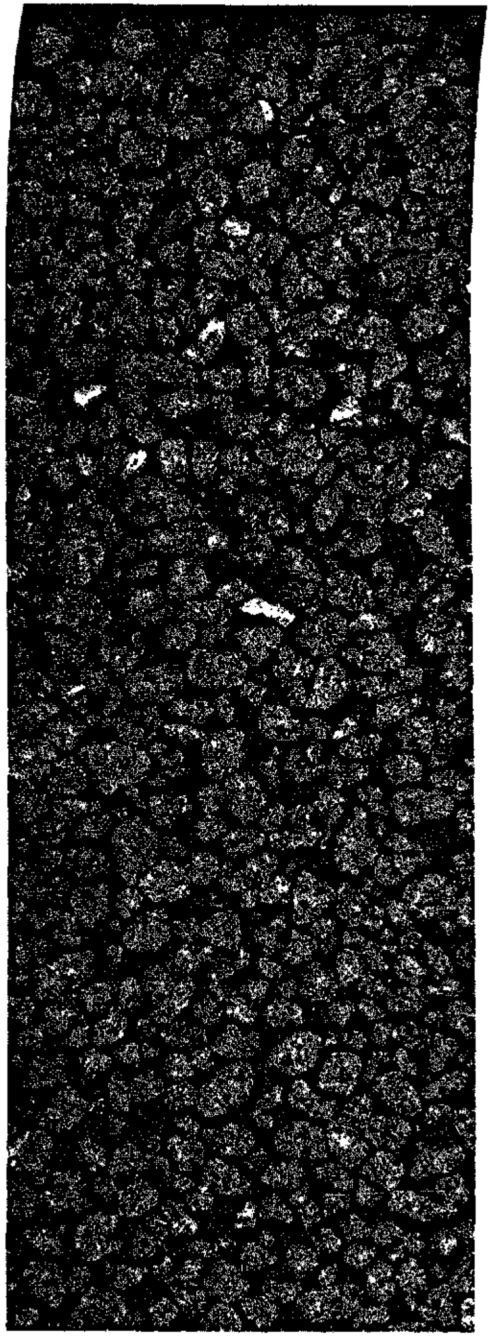


Fig. 27a (× 4).
Sample B_1:
standard,
43.0 % large pores.

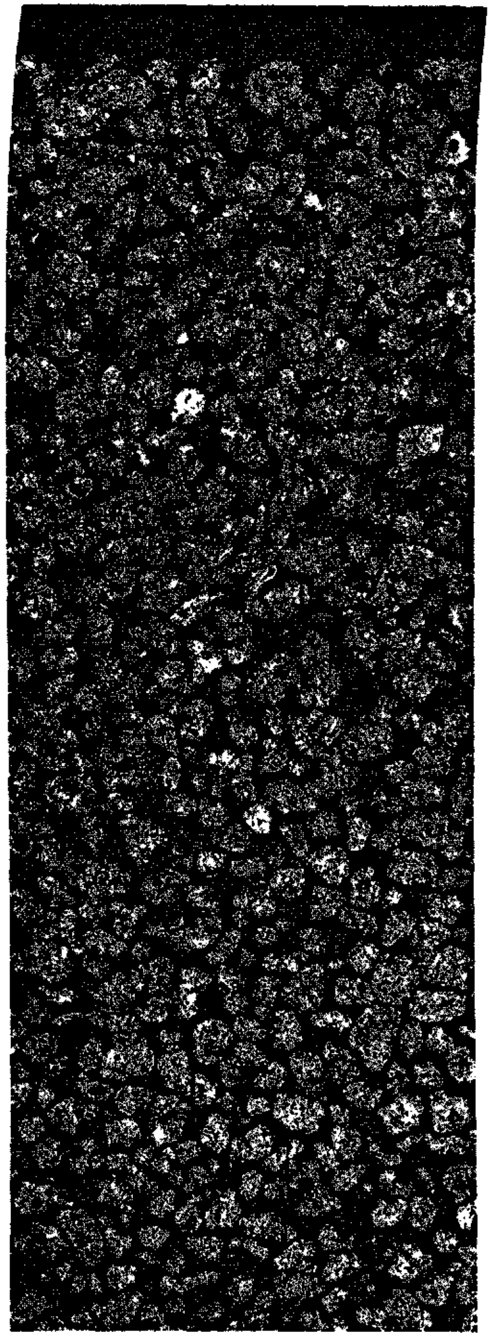


Fig. 27b.
Sample B_2 (Bf-sd):
1.5 kg/cm², 12.7 % moisture,
38.0 % large pores.

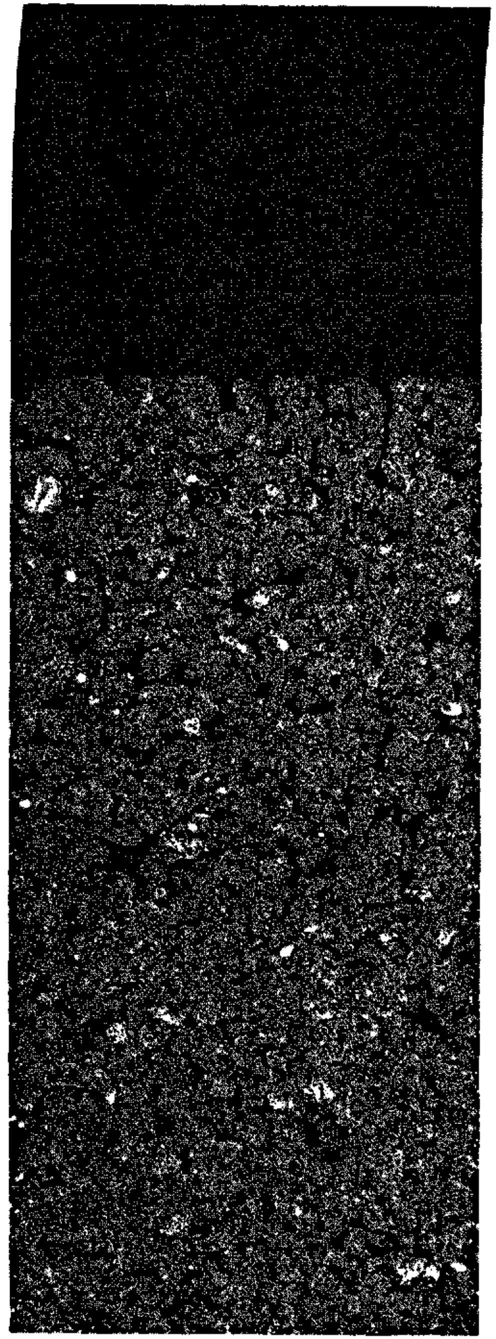


Fig. 27c.
Sample B_3 (Bf-d):
1.5 kg/cm², 21.1 % moisture,
pF 2.0,
15.4 % large pores.

Fig. 27d.
Sample B_4 (Bf-d):
1.5 kg/cm², 24.6 % moisture,
pF 1.5,
11.5 % large pores.

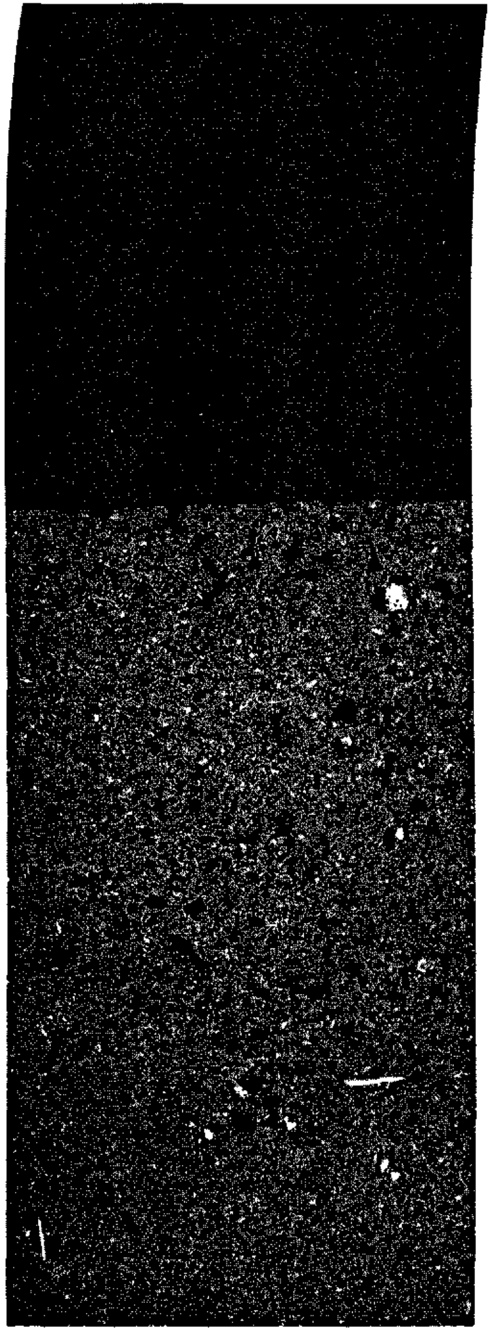


Fig. 27e.
Sample B_6 (Bp-sd):
1.5 kg/cm², 21.1 % moisture,
pF 2.0 ↓,
9.2 % large pores.

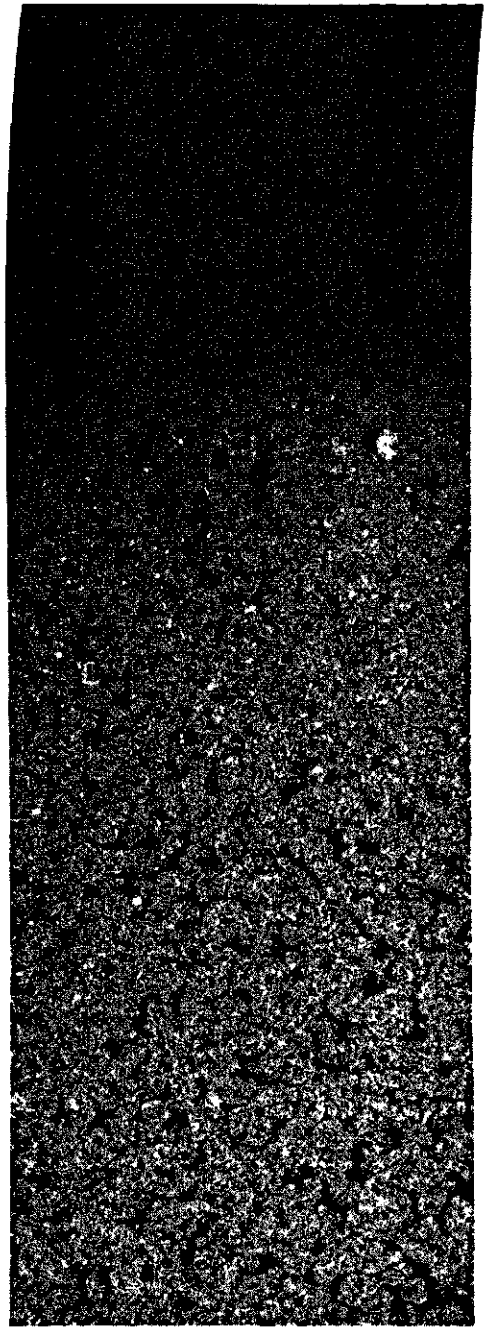


Fig. 27f.
Sample B_5 (Bp-d):
1.5 kg/cm², 21.1 % moisture,
pF 2.0 ↓,
17.7 % large pores.

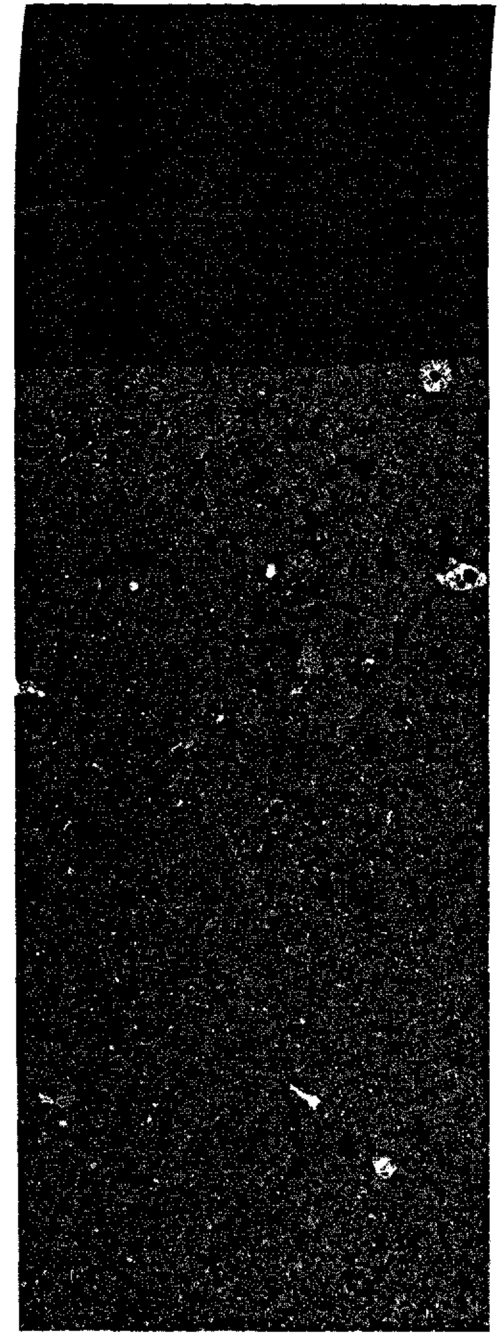


Fig. 27 g.
Sample B_7 (Bp-d):
1.5 kg/cm², 23.1 % moisture,
pF 2.0,
11.4 % large pores.

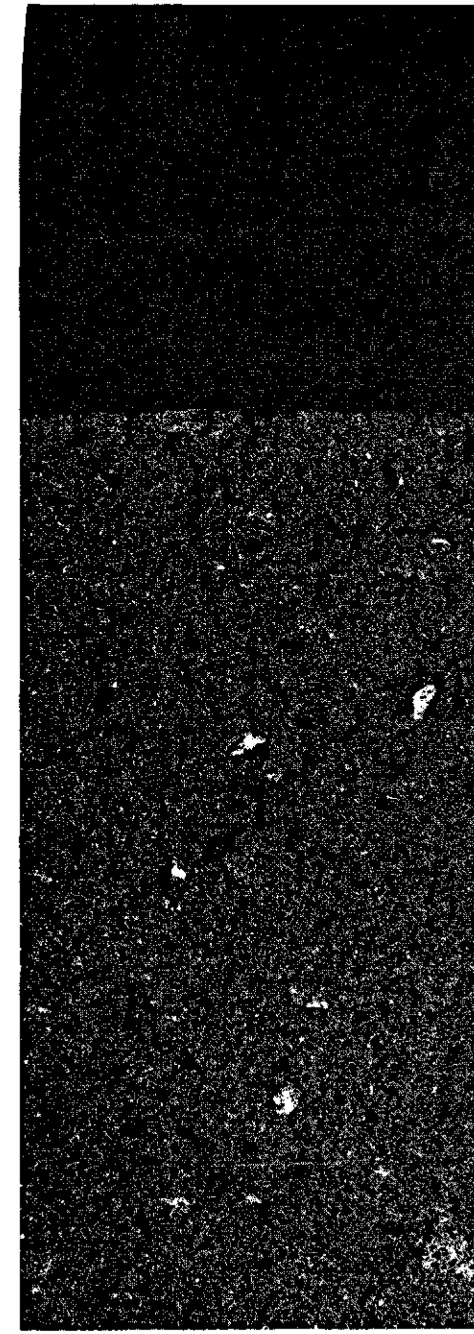


Fig. 27h.
Sample B_8 (Bp-d):
1.5 kg/cm², 27.4 % moisture,
pF 1.5,
9.6 % large pores.

In the original system these values become: 61/100 x 36.6 = 22.3% and 61/100 x 63.4 = 38.7%. Thus total pore space would be 22.3 + 39 = 61.3%, that is about 3% from the value actually measured (63.6%).
Sample B1: Values were calculated as above. The kerosine value was 33.2%, s = 0.4. The calculated pore volume amounts to: 18.9 + 43 = 61.9%. The determined value was 62.4%, a difference of about 2% which is considered acceptable.

Assumed that the measurements with kerosine are correct, the calculations show that morphometric data are sufficiently accurate to be used here next to physical data. They provide essential information.

Fig. 25 shows the relation between pressure and pore volume in field samples and puddled samples. Figs. 26 and 27 the corresponding photographs with the percentages intergranular pores as determined by point counting. The diagram in Fig. 28 gives pore volume before and after pressure as well as the percentage moisture in the sample; pore volumes before compression are in the first column of this figure.

4.1.4 Discussion of results.

Comparison of the dried samples at pF 2.0 (B3/G3) and at pF 1.5 (B4/G4) with the low moisture samples (B2/G2) in Fig. 25 shows that compaction increases with moisture content and that samples B4/G4, with most moisture, are most compacted. The volumes of large pores show the same tendency as apparent from Figs. 26 and 27. These photographs also indicate that compaction implies a plastic deformation of the aggregates leading to a larger contact surface. But until pressure exceeds cohesion no deformation of aggregates will occur. With higher pressure, aggregates will be modified until equilibrium is reached again: in a larger area of contact pressure is lower (Day & Holmgren, 1952). Below the lower plastic limit, as in samples B2/G2, there is very little plastic deformation. At moisture contents corresponding with the same suction, compaction in soil material B is more pronounced than in soil material G, although the moisture content of B is lower. Nevertheless aggregates B are less stable and therefore more compacted. Since they differ only in organic matter content, the difference must be due to larger and more stable bridges between the skeleton grains in soil material G and to differences in consistence. Noteworthy is the greater compaction of sample B4 as compared with G4 especially true for the larger pores. In sample B4 the moisture content at pF 1.5 (25%) is equal to the upper plastic limit (25%), but in sample G4 at pF 1.5 (28%) it is well below it (31%), resulting in a relatively greater stability (for consistency values see Fig. 58 in Chapter 6). The greater compaction at pF 2.0 of sample B3, as compared with G3, can be better explained by considering the lower plastic limits. For sample B3 (21% moisture) it is about 18%, for sample G3 (23% moisture) it is about 22%. This means that the plasticity of soil material B must be higher, resulting in greater compaction, as indeed observed. In samples G3a/B3a, with moisture contents of 23.4 and 21.1% respectively the upper level of the aggregates in the cylinder sank slightly because of swelling when moistened before desorption to pF 2.0 (see next Chapter).

After compression at pF 2.0, the pore volumes were for G3a: 49% (large pores, point count: 20%) and for B3a: 46% (ibid. 17%). These values are almost equal to those of the samples previously dried in the laboratory before remoistening (B3: and G3). It demonstrates the effect of drying in the field.

The series of the puddled samples (B7/G7) had at the same suction higher moisture contents than those of the field samples. The plastic deformation during puddling led to the formation of a homogeneous system with only very fine pores. Measurements with kerosine revealed that the total pore volume after drying of these puddled samples was higher than in the field samples (table 6). Most of these pores were finer than 30 μ (Fig. 20), and, at pF 2.0 were therefore filled with water. This also follows from physical analysis. Slightly dried puddled samples had also higher moisture contents at pF 2.0 (see Fig. 26 and 27). Compaction, a function of the moisture content, was therefore more pronounced.

The puddled samples were also compared with field samples of similar moisture contents. Samples B5/G5 and B6/G6, with more moisture at pF 2.0 after puddling, were exposed to the air until the moisture content had dropped to that of the samples B3 and G3. To re-establish a regular distribution of the moisture, the sample cylinder was closed for five days before compressing. Before remoistening, the aggregates of the puddled soil in samples B5/G5 were dried at the air to about 3% moisture (type III of Fig. 18). With slight drying, as in samples B6/G6, the aggregates remained friable at a moisture content of about 15% (Fig. 28; in fact type II of Fig. 18).

The effect of pressure was striking: samples B5/G5 were highly resistant, even more so than the field samples with the same moisture

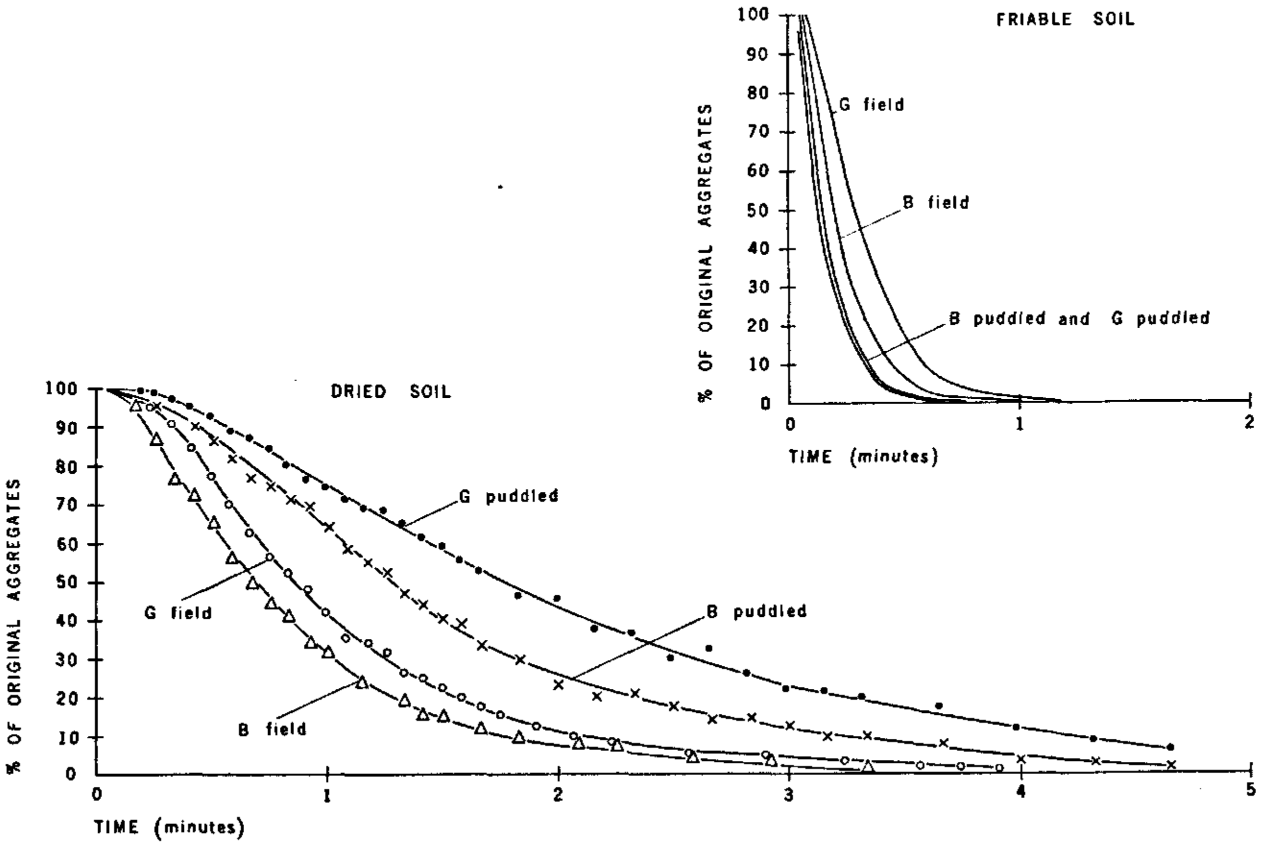


Fig. 29. Resistance of aggregates to waterdrop impact.

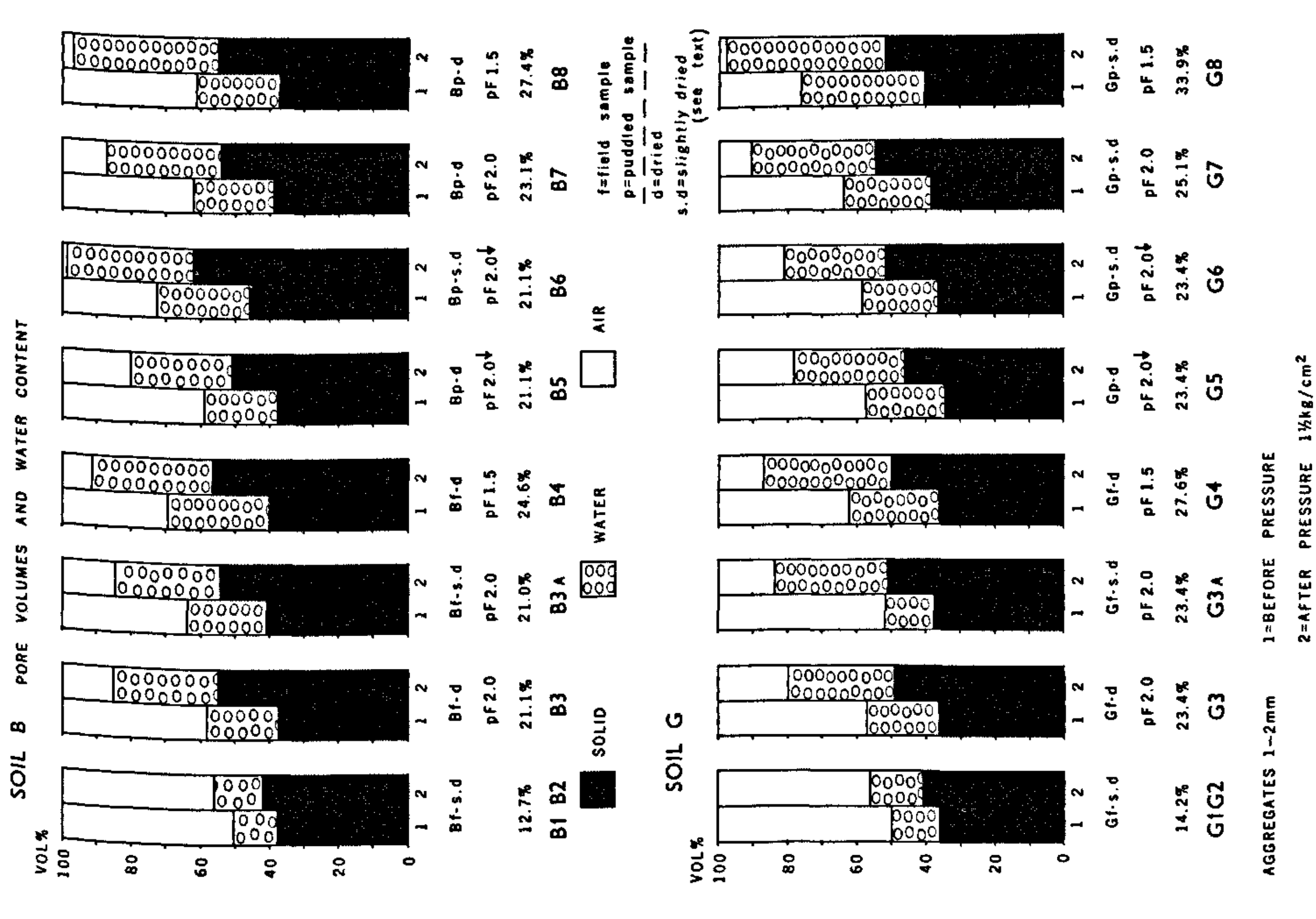


Fig. 28. Diagrams with the effects of pressure on pore volume and water content.

content (compare B5 with B3 and G5 with G3). But in slightly dried samples resistance was very low (compare B6 with B3), even though moisture content and pressure were the same! Between G6 and G3 the difference was not so pronounced. These results again demonstrate the greater stability of soil G and the devastating effect of puddling on stability.

At higher moisture content (pF 1.5) the puddled samples were easier compressed. Previous treatment had also played a part here, as G8 was not dried before remoistening and B8 was.

The pressure curve (Fig. 25) and the diagram (Fig. 28) show that after compression almost all pores in sample G8 were filled with water. The same was true of samples B8 and B6. This is demonstrated by the lack of response of volume to increasing pressure (Fig. 25).

In addition a natural, undisturbed sample of 100 cm^3 from the Ap2 of pedon G and from the subsoil immediately below the Ap of pedon B were compressed at pF 2.0. Only at pressures exceeding 5 kg/cm^2 compaction occurred!

The conclusions from the preceding paragraphs:

1. Compression increased with moisture content for both soil materials.
2. Soil material G was more stable than soil material B.
3. Compression appeared to be determined not only by moisture content and pressure, but the microstructure of the aggregates before moistening was an essential factor.
4. Puddled soil material showed a higher moisture content at pF 2.0 than unpuddled material, also after drying. This higher moisture content led to higher compressibility.
5. Drying increased soil stability. An increase in stability of puddled soil as a result of drying was reached when the soil became air-dry.
6. Samples composed of aggregates showed a higher compressibility than natural samples.

   Puddling of the soil, frequent in farming when the soil is worked at moisture contents corresponding with pF around 1.5, may form unstable, easily compactable structures difficult to regenerate. Only drying can have a favourable result. Tillage of not dried puddled soil to improve its structure, will have the reverse effect.

4.2 Aggregate stability as determined by impact of water droplets.

4.2.1 Technical specifications

Methods to determine soil aggregate stability have been discussed by various authors (Baver 1956; p. 173; de Boodt, 1961; Cernuda et.al., 1954; Henin 1938; Emerson, 1954; McIntyre 1958a and b; Tochet et.al., 1965). In these methods air-dry aggregates were remoistened and subjected to various procedures.

In this experiment aggregates between 4.5 and 4.8 mm were sieved from moist soil from the field and from slightly dried puddled soil, prepared in the laboratory (moisture around 10%). Part of the aggregates was dried, and immediately but slowly remoistened to saturation. Also the slightly dried aggregates were saturated. Saturation lasted for 48 hours. To estimate the effect of water droplets, the equipment of the Soil Tillage Laboratory could be used. On a sieve with square 4 mm meshes, 100 saturated aggregates were put. One meter above the sieve a water tank with small holes in the bottom was fixed. The flow of water could be interrupted. Droplets had a weight of 80 - 100 mg. During the experiment the sieve slowly rotated. Each 10 seconds a counting was made of the number of aggregates that had remained on the sieve so that the number of demolished and consequently disappeared aggregates could be calculated.

For relatively stable aggregates this number will decrease slowly; weak aggregates will soon be washed away. In graphs a curve with a gentle slope indicates unequal stability of the soil material in the aggregates: if all aggregates had about the same stability a sharp drop would have appeared after a certain time. The latter is not the case, partly also because of a certain range in sizes (4.5 to 4.8 mm) and of irregularities in shape. Three replicates have been made of each determination. The resulting values were quite close so that solely averages have been included in the figures.

4.2.2 Discussion of results.

The results (Fig. 29) show a greater stability of the aggregates of both soil materials after drying. The dried aggregates of the previously puddled soil are more stable than those from the field, which must be

4.3 The occurrence of internal slaking.

4.3.1 Introduction.

After ploughing in autumn at a moment the moisture content of the soil is favourable, an assemblage of fragments is present separated by relatively large compound packing voids. As demonstrated very well by Andersson & Håkansson (1966), the creation of these larger voids implies a rise of the soil surface. Kuipers & Ouwerkerk (1963) also mention measurements of total pore volumes in tilled layers and they indicate a downward movement of the soil surface during winter, a process occurring even without application of any external pressure. This downward movement results from a plastic deformation of the soil fragments leading to narrower voids.

During the field study the impression was that this downward movement did not always proceed regularly throughout the plough layer. Observations on Pedon B in December 1966, strongly suggested a more pronounced deformation in the lower parts of the Ap. This was also shown by the pore volume (Fig.3). The same observation was made by Sekera (1951). This would have important consequences as up till now, and in the methods used to estimate the total pore volume in the ploughed layer as mentioned by Andersson & Håkansson, this part of the soil has been considered as a unit, and data on sinking have been reported as averages for the whole plough layer. But if this process proceeds mainly in the lower parts of this layer, a situation may occur that is worse than suggested by the average.

4.3.2 Experimental procedure and results.

Aggregates of 1-2 mm were sieved from moist field samples and from puddled soil that had been dried to a friable consistence. In addition, air-dried aggregates were prepared of both soils. The procedures were the same as those mentioned in 4.1.2.

The steel cylinder of 100 cm^3 was loosely filled with aggregates, moistened in the two following ways.

a. To dry and moist aggregates from the field sample and the puddled sample a vacuum was applied during a few hours before a thin layer of air-free water was added. Investigations on some samples revealed that this vacuum did not change the arrangement of the aggregates in the cylinder.

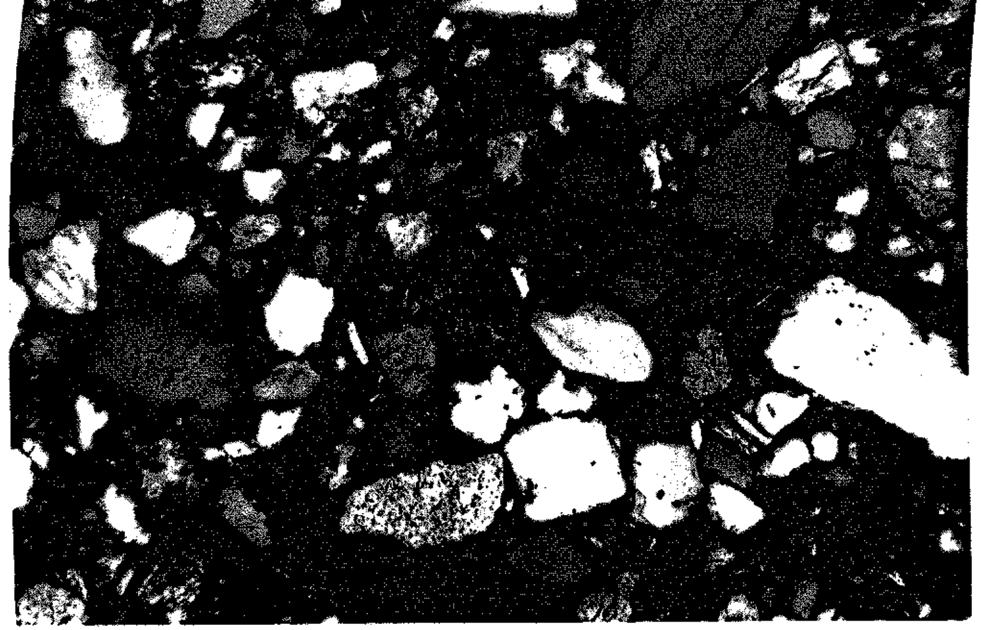


Fig. 30. A representative picture from the Ap of Pedon G, showing a high microheterogenity. See also Fig. 14 where this phenomenon is still more pronounced. Natural soil material from the Ap of Pedon B shows a similar picture (× 160).

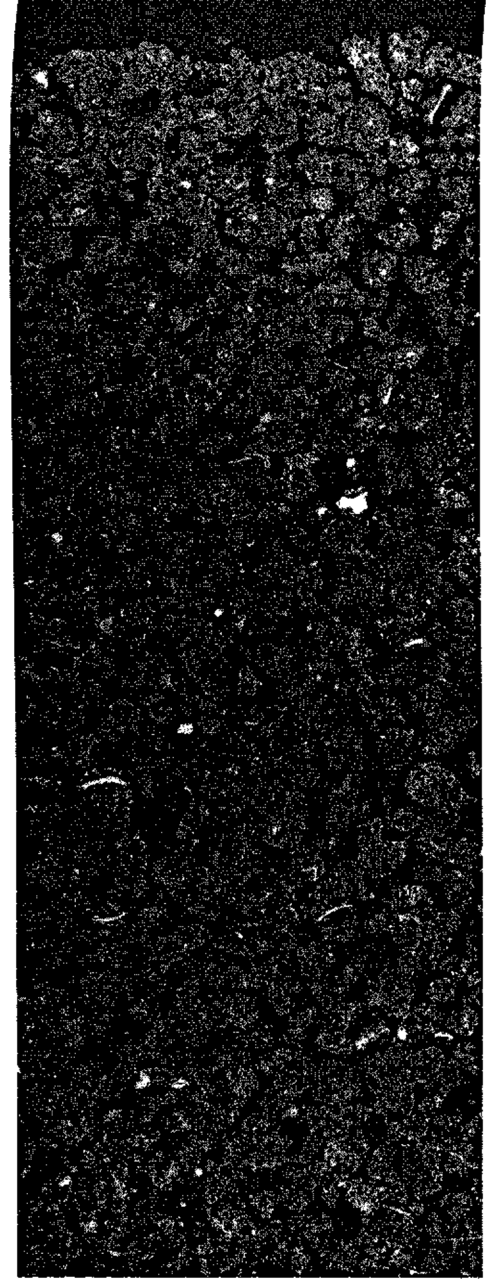


Fig. 31.
Gf-sd (12.3 %): after saturation in vacuum (48 hours), 4 × desorbed to pF 2.0, 3 × saturated.

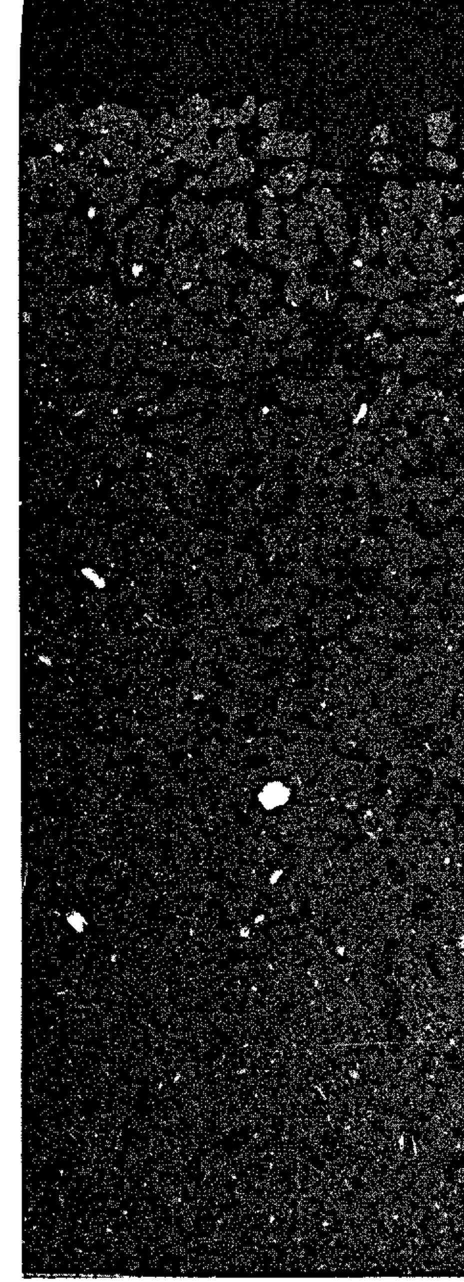


Fig. 32.
Gp-sd (8 %): after saturation in vacuum (48 hours), 4 × desorbed to pF 2.0, 3 × saturated.

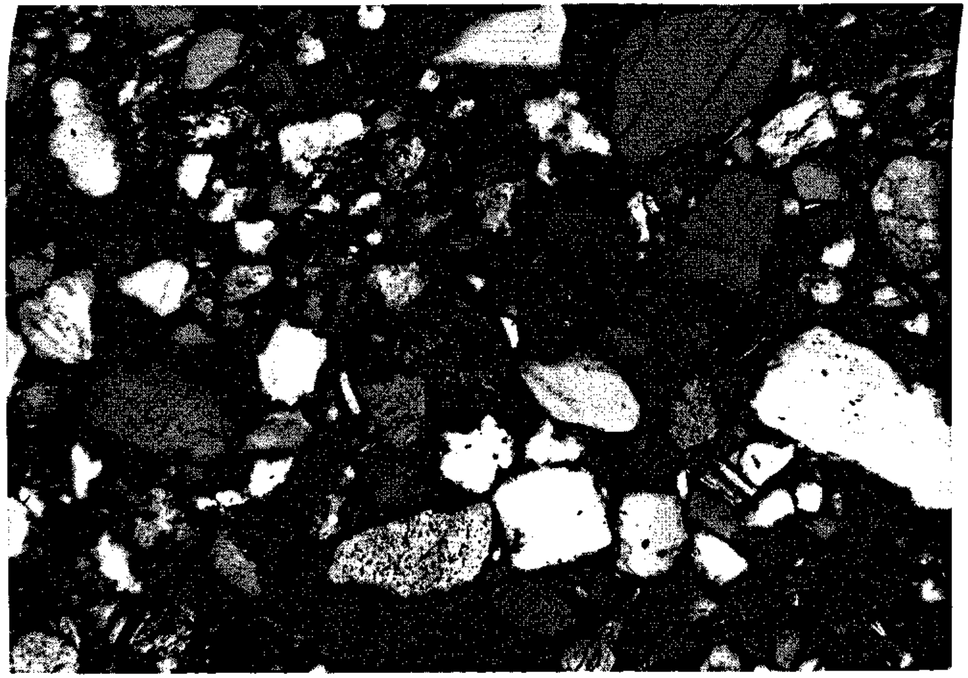


Fig. 30. A representative picture from the Ap of Pedon G, showing a high microheterogenity. See also Fig. 14 where this phenomenon is still more pronounced. Natural soil material from the Ap of Pedon B shows a similar picture (x 160).

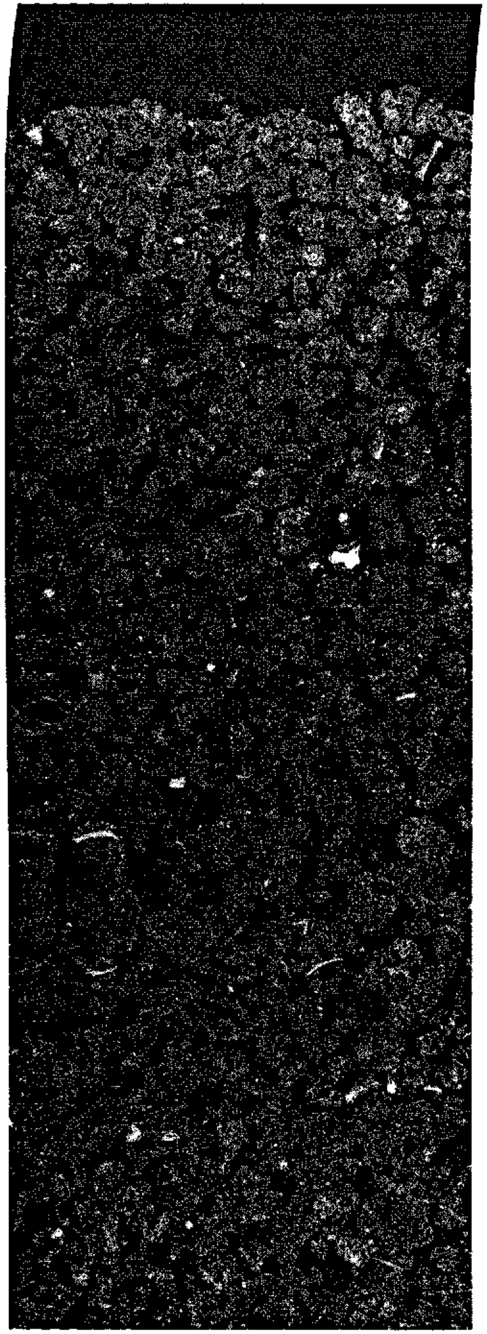


Fig. 31.
Gf-sd (12.3 %): after saturation in vacuum (48 hours), 4 x desorbed to pF 2.0, 3 x saturated.

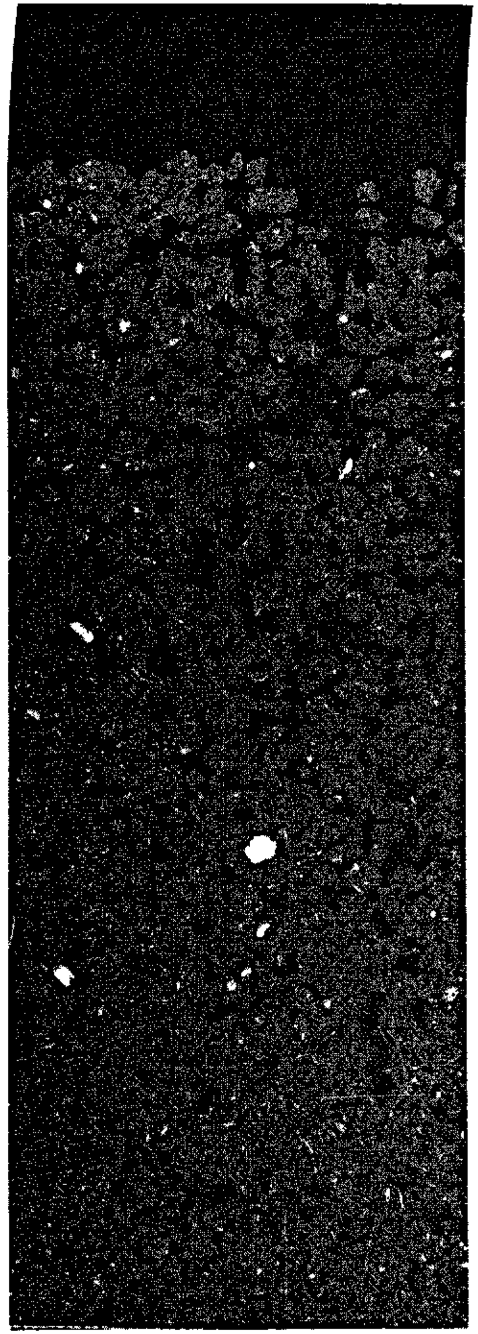


Fig. 32.
Gp-sd (8 %): after saturation in vacuum (48 hours), 4 x desorbed to pF 2.0, 3 x saturated.

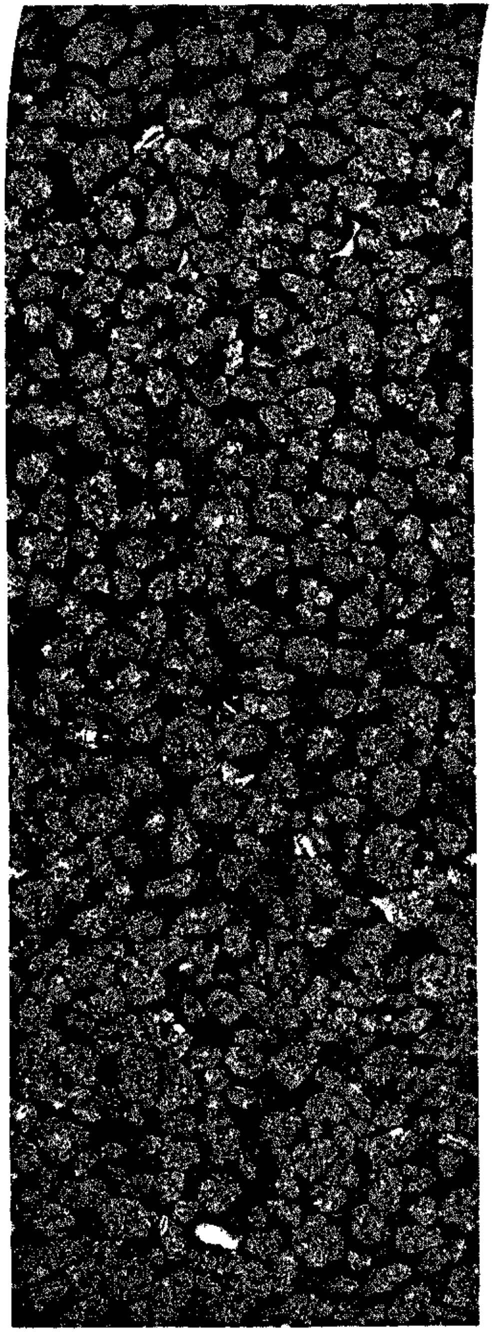


Fig. 33.
Gf-d (3 %): after saturation
in vacuum (48 hours),
4 × desorbed to pF 2.0,
3 × saturated.

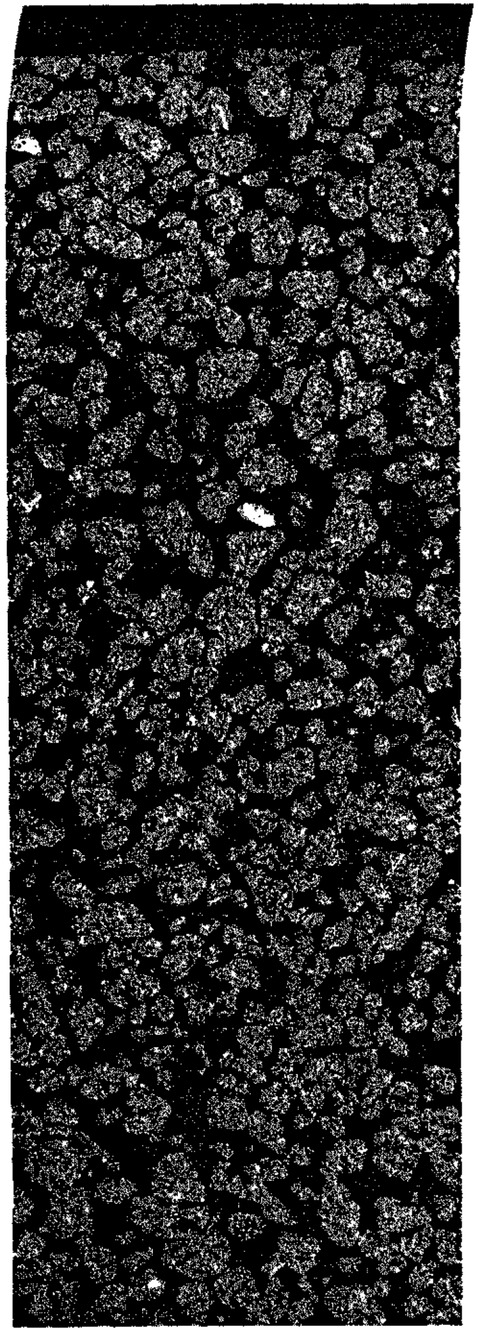


Fig. 34.
Gp-sd (16.7 %);
4 × adsorbed to pF 1.0,
4 × desorbed to pF 2.0.

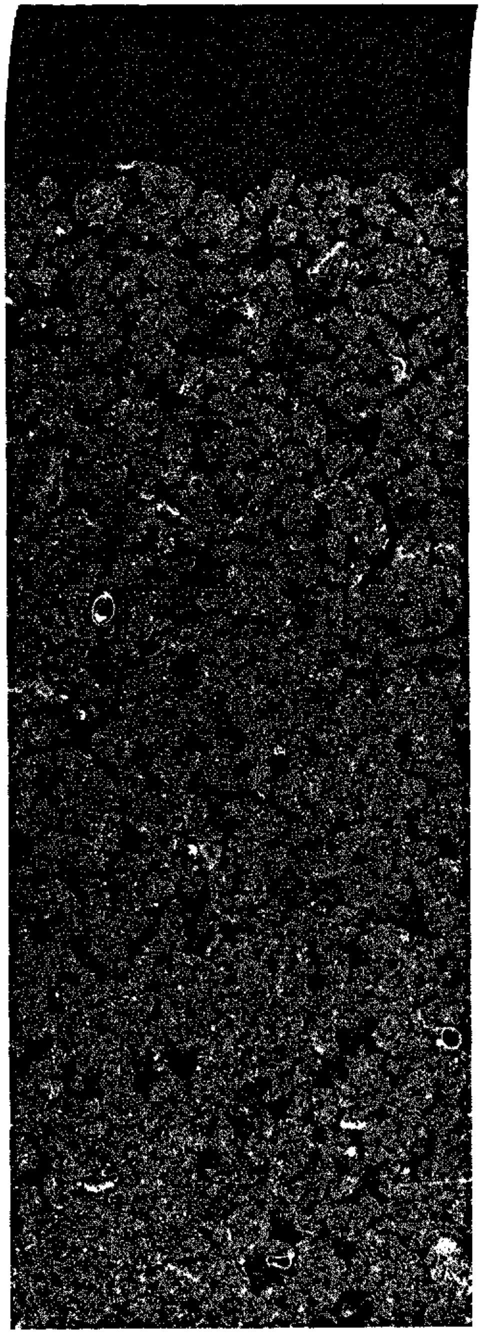


Fig. 35.
Bf-sd (7 %): after saturation
in vacuum (48 hours),
4 × desorbed to pF 2.0,
3 × saturated.

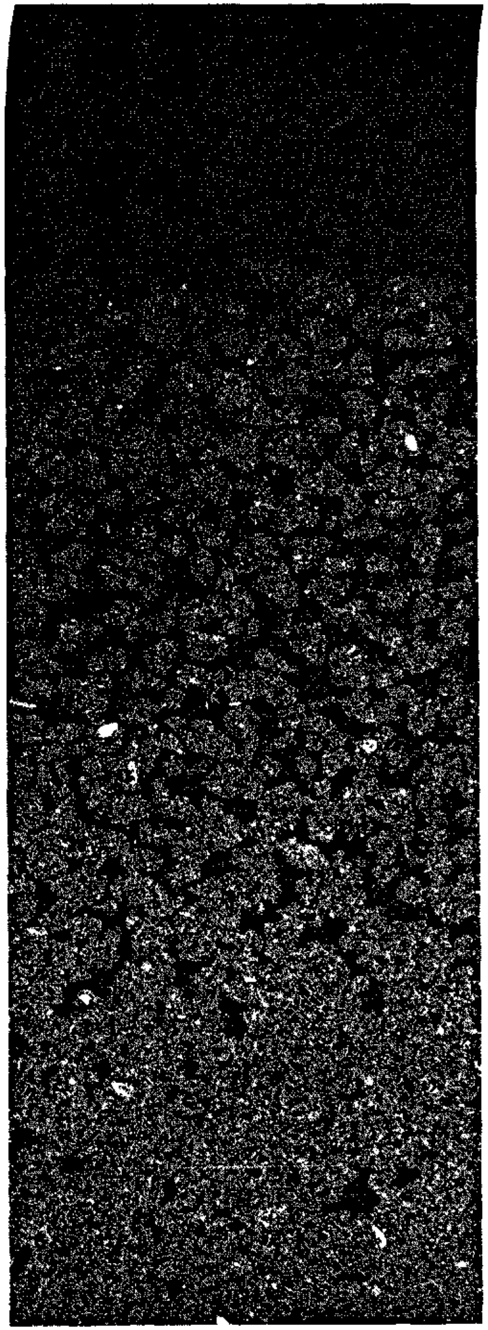


Fig. 36.
Bp-sd (11 %): after saturation
in vacuum (48 hours),
4 × desorbed to pF 2.0,
3 × saturated.

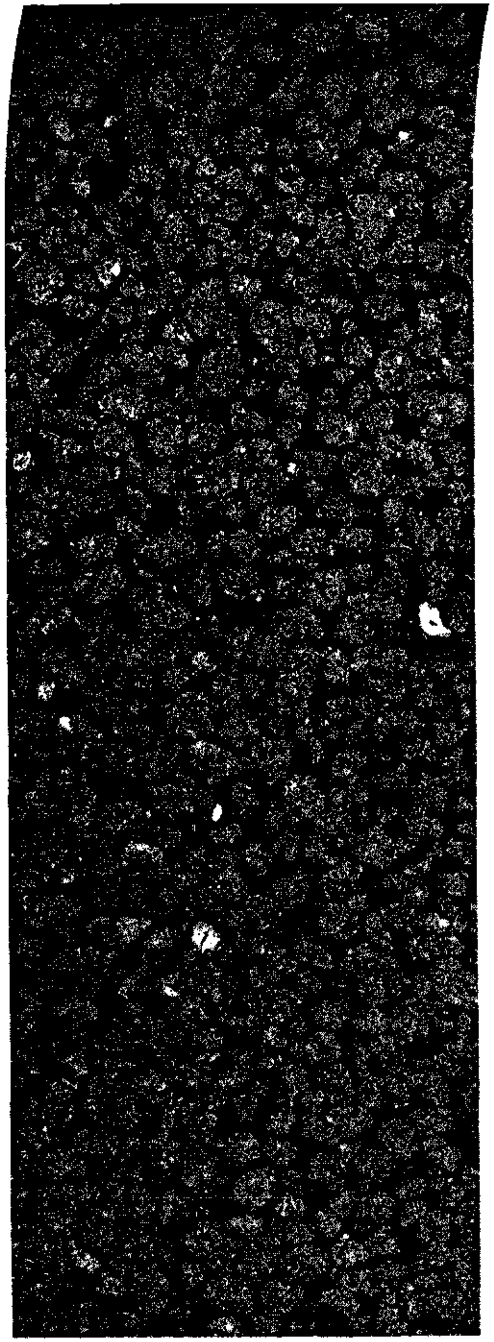


Fig. 37.
Bf-d (2 %): after saturation
in vacuum (48 hours),
4 × desorbed to pF 2.0,
3 × saturated.

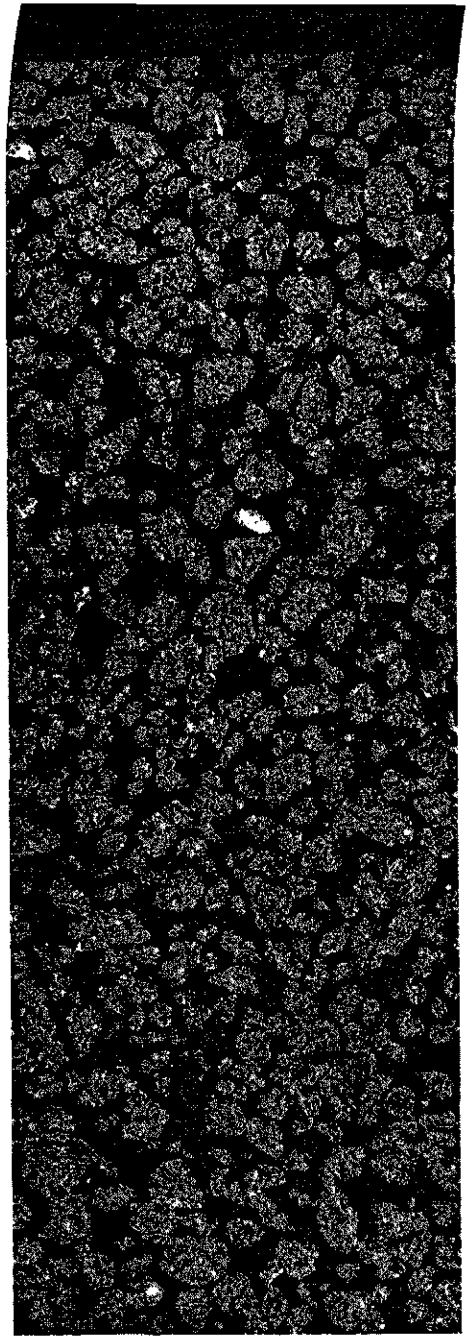


Fig. 38.
Bp-sd (14.7 %);
4 × adsorbed to pF 1.0,
4 × desorbed to pF 2.0.

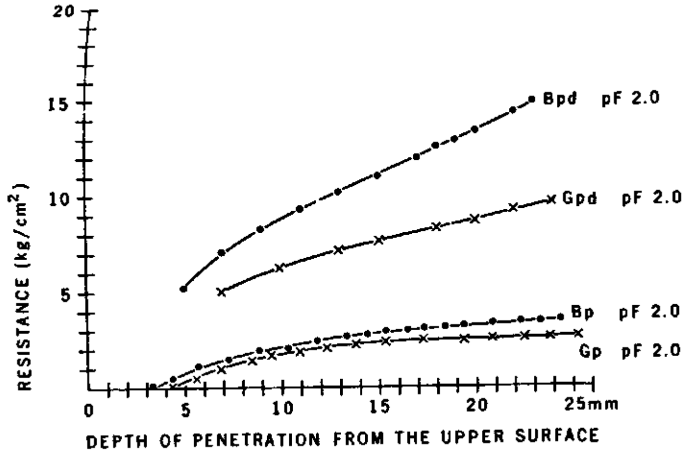


Fig. 39. Cone penetration in puddled soil.
p = puddled; d = air dried (3 % moisture), later remoistened and desorbed to pF 2.0.

Afterwards saturation* took a few hours.

b. Moist aggregates from field soil and puddled soil were carefully provided with water on a sandbed of a pF box with a suction corresponding to -10 cm (pF 1.0). This process took about two days; after that the moisture content did not increase anymore.

In both cases the samples were left for 48 hours and then, abruptly, a suction corresponding to pF 2.0 was applied during four days. This sequence of adsorption and desorption was repeated four times. After that, the samples were dried. Finally a vertical thin section was prepared through the centre of the cylindrical core. The results are shown in Figs. 30-37.

In the beginning the aggregates formed a loose assemblage. Fig. 31 shows that, as a result of the treatment, in the originally moist samples deformation took place, especially in the lower part of the core. Simultaneously the upper level of the aggregates in the core lowered. Henceforth this process will be called 'internal slaking'. Aggregates composed of puddled soil material show a greater deformation than those of the field soil (Figs. 32 versus 31, and Fig. 36 versus 35). Dried aggregates (Figs. 33 and 37) did not show any deformation: the aggregates remained visible as discrete entities throughout the core after the treatment.

Moist aggregates wetted only to moisture contents corresponding to pF 1.0 did not show any deformation with repeated desorption to pF 2.0 (Figs. 34 and 38). Again all aggregates remained visible. The ultimate picture is comparable with that of dried samples saturated with water before each desorption. Although the procedure of adsorption and desorption had been repeated four times, the changes occurred after the first saturation when the upper level of the aggregates in the cylinders was observed to sink.

Deformation of aggregates, as occurring in the lower parts of cores, will be a function of soil stability. So it is not surprising that dried aggregates do not show deformation after saturation, whereas not dried samples show a pronounced structural change in the lower parts, especially

---

* It should be emphasized that the term 'saturated' is used here to characterize a moisture content that is established when a cylinder with aggregates is placed in a box with a layer of about 1 cm water on the bottom.

the moist aggregates prepared from puddled soil. Deformation is thought to arise from swelling of aggregates upon saturation. In the lower part of the cylinder all pores are filled with water. Theoretically in the upper part the suction corresponds with about 4 cm water when a core of 5 cm is placed in 1 cm water. Then, packing pores between aggregates will not be filled with water. Water is found in the aggregates and between them as thin films at the points of contact, exercising capillary forces.

Not only the microstructure, however, is of importance with regard to the mechanism of internal slaking. Also the moisture content of the system is very important. When moist soil aggregates in the core are not saturated but only slowly adsorbed to moisture contents corresponding to pF 1.0, before desorption to pF 2.0, no observable deformation is found.

Moisture contents in the lower part of the core never exceed values corresponding to a suction of 7.5 cm (A suction of pF 1.0 is being calculated from the middle of a cylinder with a height of 5 cm.

It may be concluded that internal slaking will occur mainly when relatively high moisture contents, approaching saturation, are present. This will occur when tillage leads to processes of puddling as in pedon B in december 1966. In this soil free water was found in pockets throughout the Ap horizon. A second reason of high moisture contents may be formed by the occurrence of a relatively impermeable traffic sole below the Ap. Then, saturation may periodically be found in the Ap soil material on top of it. Internal slaking is only avoided in this case when all fragments in the Ap would have been air dry before. This situation, is rather improbable under natural circumstances. Besides, in such a theoretical situation permeability values of the subsoil would probably be so high that saturation with water in the Ap was rather improbable.

In view of this experiment, it is clear that the occurrence of a relatively impermeable layer below the Ap is very unfavourable. This layer may be formed when pressure and shear forces are applied to the bottom of the ploughed layer by wheels of tractors at such moisture contents that puddling may occur.

Creation of a compacted or puddled layer at that depth may result in pronounced processes of internal slaking later in the year. Compound packing voids between fragments will then be closed, and permeability of the soil will be reduced. This decrease of permeability will accellerate similar phenomena in layers on top of it.

4.4 Mechanical resistance

4.4.1 Introduction.

Soil structure descriptions made in the field, note the occurrence in the plough layer of weak, plastic soil formed after tillage operations or as a result of mechanical pressure exercised by the wheels of agricultural machinery. On the contrary, after drying in summer the soil has a firm or brittle consistence even after remoistening. This difference in mechanic behavious could be attributed to the internal arrangement of soil particles (section 3, fig. 18). In this section it was attempted to obtain some numerical values for the mechanical resistance of puddled soil (Stage I Fig. 18) and puddled soil that had been dried before remoistening (Stage IIIw Fig. 18) (see table 7 samples Bp/Gp and Bpd/Gpd). The moisture content at the moment of determination correspond to a suction of pF 2.0, that was obtained by desorption of saturated samples.

4.4.2 Experimental procedure and results.

To measure mechanical resistance a cone was pressed into samples that filled 100 cm^3 steel cylinders. The cone, with an apical angle of 90^o and a base of 10 mm diameter had a constant downward velocity of about 5 mm per minute in all experiments. The force, necessary to maintain this velocity was registrated by a hydraulic compression outfit at the Laboratory of Soil Tillage.
Physical properties of the samples used for the determination of mechanical resistance are given, in table 7.

Table 7.

	Volume cm^3	Moisture content w/w %	Pore volume %	Air volume %
Original puddled soil				
B	100	23.7	40.8	3.4
G	100	27.6	44.0	4.2
After desorption to pF 2.0:(fig.39)				
Bp	96	21.0	38.3	3.8
Gp	96	24.1	42.0	5.6
After air-drying to 3% moisture, saturation for 48 hours, desorption to pF 2.0:(Fig.39)				
Bpd	94	20.5	37.2	3.0
Gpd	94	23.2	40.6	4.6

The table shows that after drying and remoistening the soil does not swell back to its original volume. By wrapping a piece of filterpaper around the dried soil sample, before remoistening,a close contact between the sample and the core could be achieved at the moment of measurement. The previously dried samples have a higher resistance to cone penetration than those not-dried (Fig. 39).

It should be stressed that moisture contents in both cases are quite near for each soil material. For the dried samples not a constant, but an increasing value of resistance has been measured. For soil B this is partly the result of a loss of water from the sample during compression. Lower moisture contents lead to a higher resistance. In soil G no water was pressed out during compressions. However, during penetration, the soil next to the hole is compressed. Since pore volume is low, and most pores are filled with water that cannot be compressed, the soil has to be moved upwards to the open end of the core. Flowing of soil occurs easily when it is weak after puddling. It is not produced as easily here, because of a relative high cohesion that results from the intergranular bonds formed by drying. With increasing depth of penetration the amount of relative cohesive soil that has to be moved upwards increases, and so does the required force. Besides, the soil will move upwards along the wall of the cylinder. This resistance counts as well.

Here, however, it is sufficient to observe a clear relative difference in resistance between the two types of microstructure: dried and not dried, for each soil material. The numerical values as such are, after all, not so important for our purpose since the absolute value of measurement is a direct function of the size and shape of the cone as well as its velocity.

4.5 Permeability measurements.

4.5.1 Introduction

The accumulation of water at the surface of the soil during winter and early spring caused by insufficient permeability was the starting point of this study. The rather simple measurements of saturated soil permeability values in field samples from the Ap (Section 2.3 and Appendix III) yielded very variable results. Some cores of soil B did not conduct any water with the commonly applied hydraulic head of one inch (measurements in December 1966). Neither did compacted samples of Soil G, obtained in the autumn of 1967 (Type III). But such figures are insufficient for a general discussion of the permeability problem.

Pedons B and G, used for investigations were well drained by pipes. Throughout the year the groundwater was maintained at about one metre implying that, at equilibrium and without evaporation, the surface soil had a moisture content corresponding to a suction of pF 2.0. After rainfall it will take some time before this equilibrium is reached, depending on the permeabilities of all layers between soil surface and watertable. Evaporation and transpiration will complicate such a picture. In summer, when evaporation exceeds precipitation (Section 3.1) various patterns of water movement are found and water content in the surface soil may be lower than pF 2.0. But stagnation of water on the surface of the soil occurs mainly in a period when rainfall exceeds evaporation. Then the surface soil has, as an average a moisture content corresponding with pF 2.0, or the moisture content is higher during the desorption to this suction. The actual moisture content determines the stability of the soil material to pressure (section 4.1) the greatest stability being present at relatively low contents. So, not just the moisture content at equilibrium, but also the time it takes to reach it, is important since during this time the still higher moisture content makes structure more susceptible to deterioration.

Moisture contents of the surface soil were measured throughout the year Relatively high suctions proved to be present (Fig. 3): in summer and autumn near pF 2.0, in December and March though more water was present, hardly below pF 1.5. Only Pedon B showed (in December 1966) a high moisture content.

According to the capillary model of soil structure (Section 4.5.4) this implies that voids larger than 100 µm - corresponding with pF 1.5 - are only periodically used for the transport of water. Water movement from pF 1.5 to pF 2.0, using voids between 30 µm, is most common.

The phenomenon, that in a natural soil under natural conditions movement of water also occurs through the fine pores, has been emphasized by several authors (e.g. Biggar & Nielsen, 1962; Nielsen & Bigger, 1961, 1962; Horton & Hawkins, 1965). They demonstrated that the rate of addition of water and the capillary conductivity of the soil material will determine whether water will flow through larger voids. This flow only occurs when capillary conductivity is not sufficiently high to conduct all moisture. They also showed that movement of water through fine pores implies a transplacement of water that was already present in these pores before simulated rainfall was applied.

Two aspects have therefore been stressed in the following experiments: the time necessary to reach a moisture content corresponding to pF 2.0, and the permeability of samples in equilibrium at this suction. First, specific microstructure as discussed in the foregoing chapters will be tested; the treatment of undisturbed field samples will follow.

4.5.2 Technical execution

Various measuring methods for permeability in soils have been described (e.g. de Boodt et al., 1967). The present experimental design was based on equipment used by Butijn & Wesseling (1959).

Before filling the steel cylinder of 100 cm^3 as mentioned before, its wall was waxed to avoid movement of water around the sample after filling. For the same reason the upper edge around the samples was waxed. The cylinder was placed in a funnel on a 5 mm thick plate (Fig. 40) with pores between 1.7 and 1.9 µm. The base of the funnel was connected with a rubber tube to which a burette with a scale was attached that could be moved vertically to regulate suction. Outflow of water from the sample raised the water level in the burette. By keeping the water level 100 cm below the middle of the soil sample, suction was kept constant at pF 2.0. The readings of the flow were accurate to 0.1 cm^3. Evaporation was avoided by covering the parts that were exposed to the air with permanently soaked cloth.

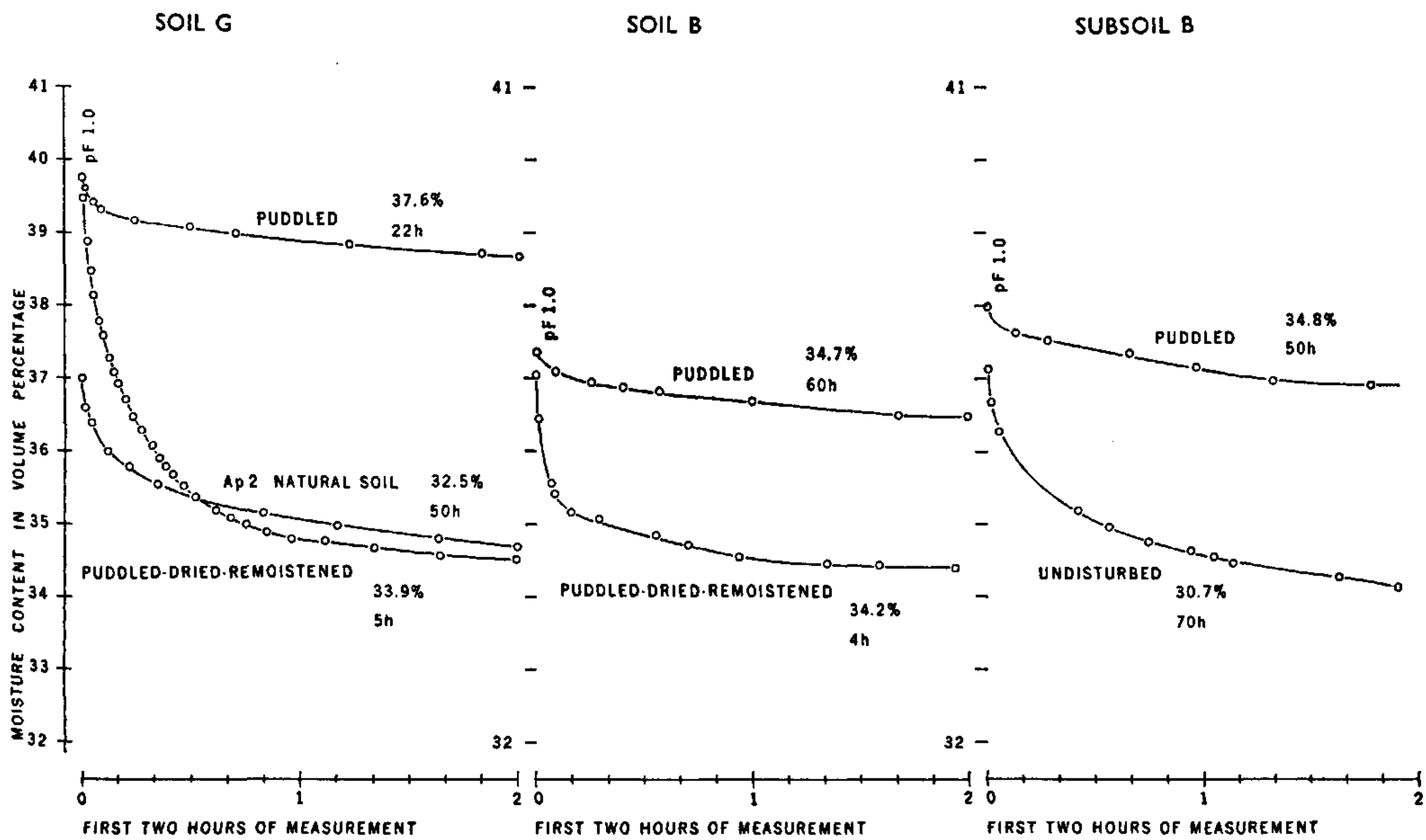


Fig. 41. Permeability of natural and artifical soil samples from pF 1.0 to pF 2.0.

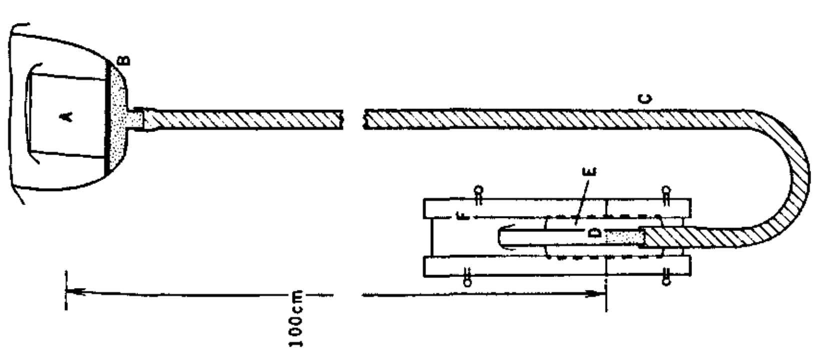


Fig. 40. Apparatus for estimating soil permeability. A = soil sample in steel cylinder of 100 cc; B = porous plate; C = rubber tube filled with water; D = glass tube with scale; E = segment with D, movable along F.

In the literature pF values are frequently used to characterize physical processes (Kuipers, 1961a, 1961b; Boekel, 1965). Here emphasis will be put on the time necessary to reach the moisture content corresponding with a certain pF value.

Puddled samples were prepared of both soils (Stage I, Fig. 17; for physical data, see Section 4.4). Moistening to pF 1.0 took 5 days on a sandbed in a standard pF apparatus (Section 2.2.2). Afterwards the sample was placed in the apparatus at a suction of pF 1.0 until equilibrium. Then, suddenly the suction was lowered to pF 2.0. The resulting outflow was recorded, giving a graph with outflow versus time. When the water level in the burette had been constant for a period of at least 8 hours, it was supposed that the new equilibrium had been reached.

Next, the same sample was dried at 30°C for some days to about 3% moisture. The now dry and hard sample was carefully remoistened in vacuo and left to swell for the next 48 hours.(Stage IIIw, Fig. 18). Then it was again desorbed to pF 1.0, followed by a similar procedure as described above. In a second series of experiments similar samples were used but they were desorbed to pF 2.0 in the funnel. Then, 4 cm^3 water was suddenly poured over their surface into a second core fixed with wax on top of the original one. The rate of outflow was measured against time.

Experiments were made with puddled, and with puddled and dried samples, and in addition to the 4 cm^3 (a water layer of 2 mm) the results after addition of 3, 6 and 9 cm^3 were noted.

4.5.3 Discussion of results

Fig. 41 shows the results of the experiments in which the samples were moistened to pF 1.0. As most data showed a relatively rapid decrease during the first two hours, the later data were not included. The moisture content at equilibrium (pF 2.0) has been indicated in each graph as a volume percentage with the time needed to reach it.

Obviously puddling led to a higher moisture content at pF 2.0 (see also 3.2). After drying this content decreased (Soil G: from 37.6% to 33.9%; Soil B: from 34.7% to 34.2%). Striking differences were found between the times necessary to reach equilibrium: for the puddled sample of soil G it took 22 hours to reach a moisture content corresponding with pF 2.0, but after drying only 5 hours were needed to reach a considerably lower value. For Soil B the moisture contents at pF 2.0 did not differ very much but the time to reach them did: 60 hours for the puddled, 4 hours for the puddled and dried sample. These differences should be attributed to the microstructure of the samples (3.2.3), as in the puddled soil the simple packing voids were filled with plasma with a relatively high water retention capacity, especially in the sample of Soil G with the highest organic matter content. After drying and remoistening, capillary pores were present between the skeleton grains and the plasma was concentrated around these grains (Fig. 18 IIIw). The differences in capillary conductivity resulted from the occurrence of these voids: in the puddled samples only fine pores were found (apart from some larger vesicles and other not interconnected voids formed during the preparation of the sample).

In addition, two field samples were tested. The first was a sample from the Ap_2 of Pedon G, with channels (see profile description and 2.3). The moisture content at pF 1.0 was considerably lower than that of the puddled samples, due to the occurrence of large voids, partly of biological origin. At a suction of pF 1.0 these voids (>200 μm) were filled with air. The pore system was less uniform than in the puddled samples so that the capillary conductivity was relatively high at moisture contents near pF 1.0. Ultimately, after two days, a moisture content of 32,5% was attained at pF 2.0, but after 8 hours already 34% had been reached, the equilibrium quantity of the dried puddled sample.

From 5 cm below the Ap of Pedon B an undisturbed sample was taken. It strongly resembled that of the Ap_2 in Pedon G: it also contained channels. After puddling the sample, the same differences were observed as between the Ap_2 of pedon G and the puddled soil G: moisture content at pF 2.0 is higher after puddling, as is the content at pF 1.0 due to the absence of large biogenic voids.

Drying of the puddled soil samples to around 3% moisture (air dry; type III: Fig. 18), forming fine pores between skeleton grains, is more pronounced than drying under natural conditions at some depth in the soil profile. So are the effects of drying. Equilibrium at pF 2.0 in samples of the Ap_2 of pedon G and the subsoil of pedon B, is therefore reached after a longer time than in the puddled and dried samples.

Fig. 42 gives the results of the experiments in which permeability was determined after desorption to pF 2.0. A regular outflow of water occurred for the puddled samples as long as free water was present on the surface of the sample. It is possible to calculate a K_i value (in cm^2)

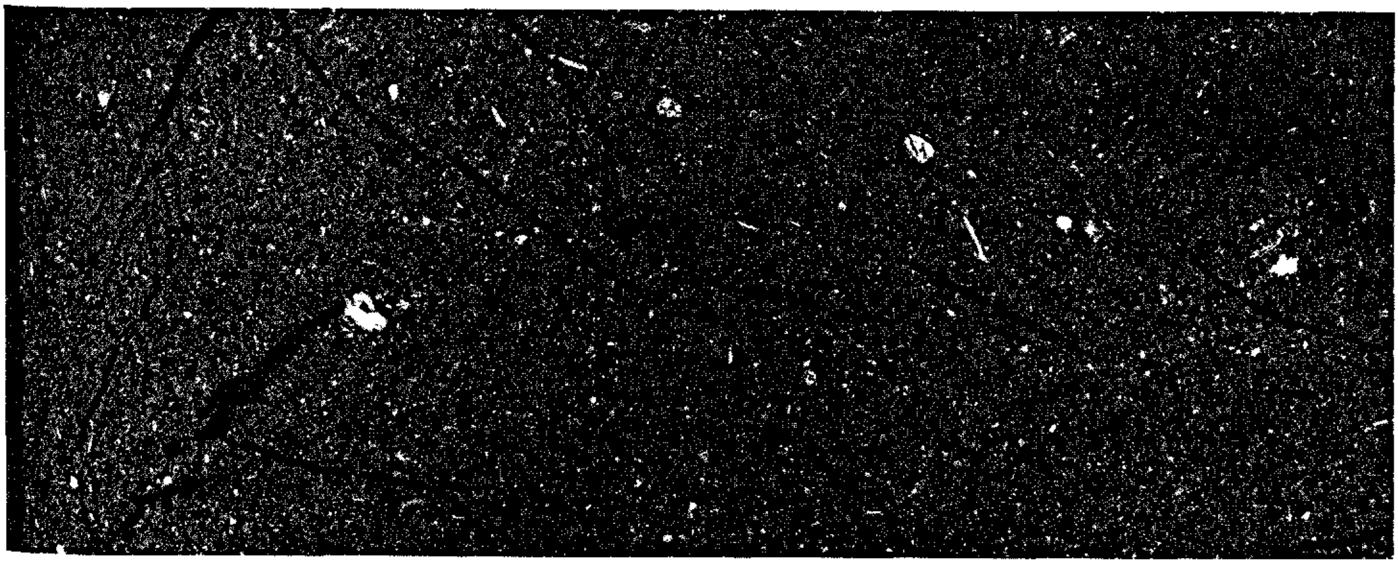


Fig. 44. Puddled soil B at pF 2.0, frozen at −8°C. After evaporation of the ice from the wedges, planar voids remain (section 4.6.2) (×4).

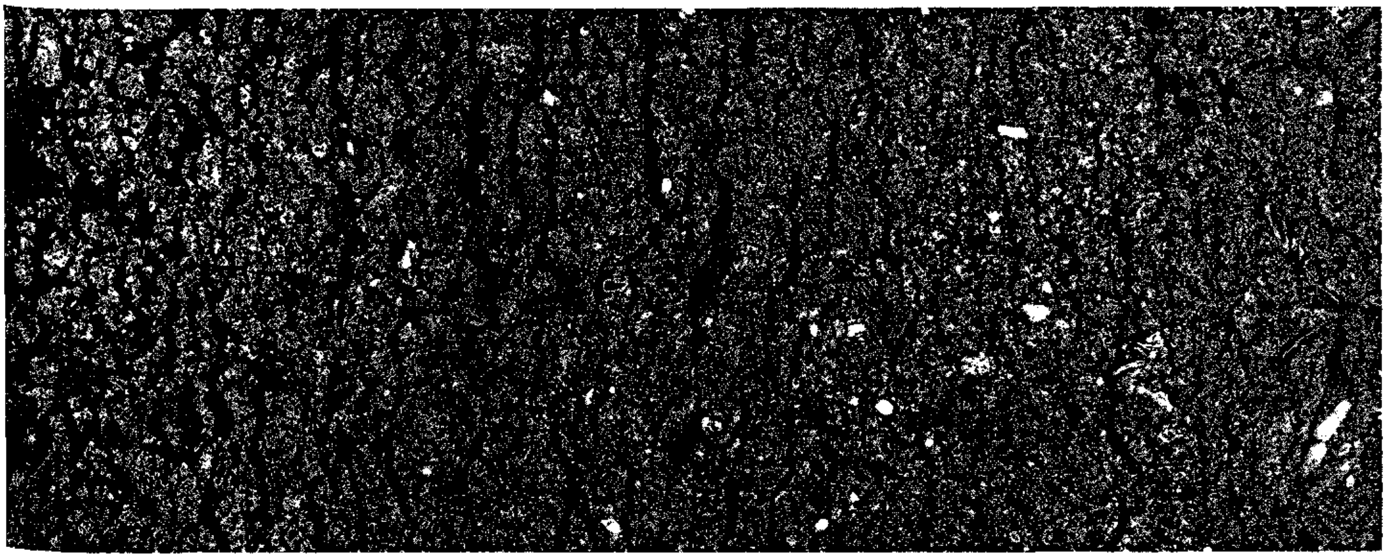


Fig. 43. Topsoil of Pedon G in February 1968. Joint planes were left after evaporation of ice from planar wedges (×4).

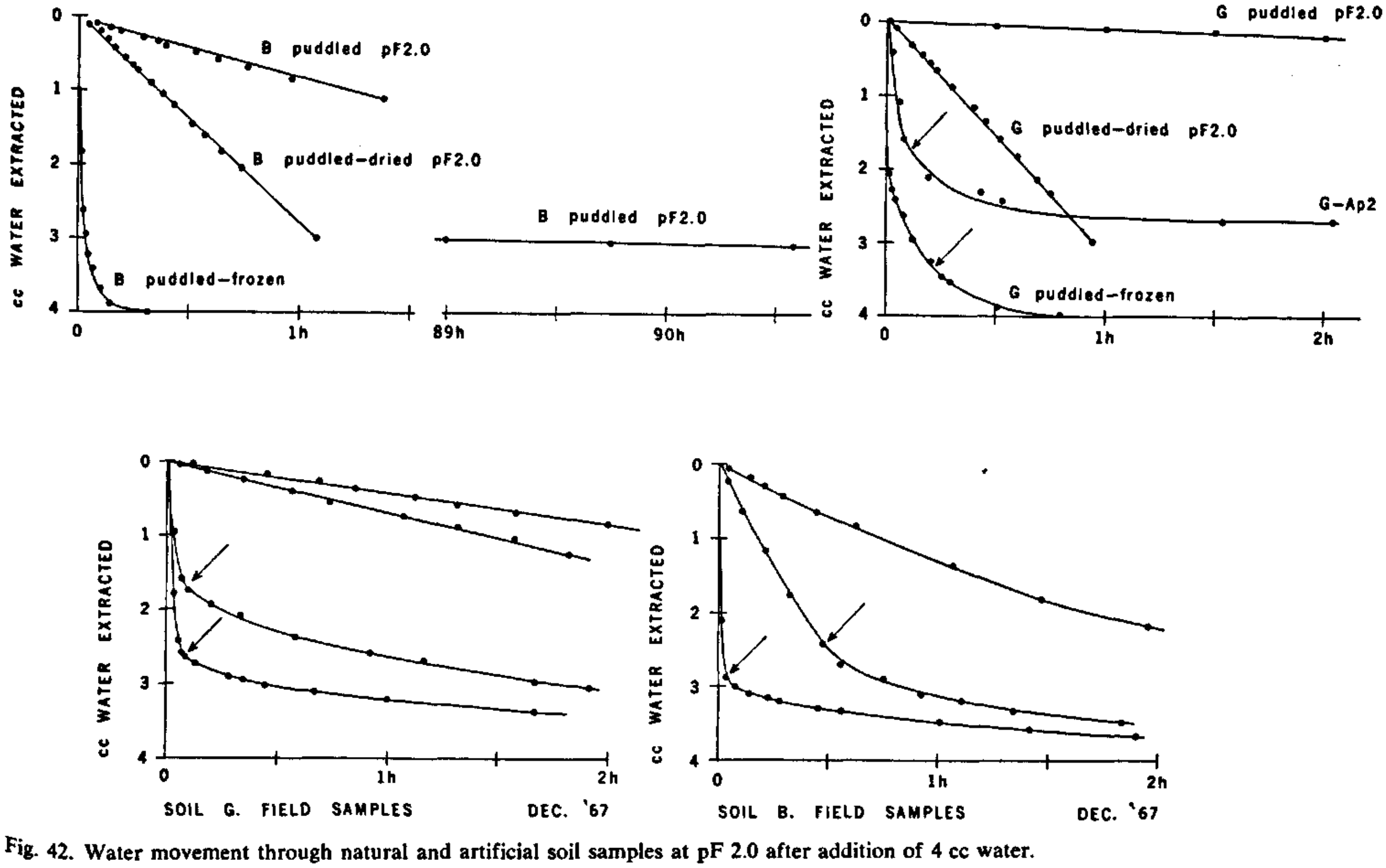


Fig. 42. Water movement through natural and artificial soil samples at pF 2.0 after addition of 4 cc water.

from Darcy's well known formula assuming saturated flow:

$$V = \frac{K_i}{\eta} \; \frac{(P_2 - P_1) + \rho g\,(h_2 - h_1)}{l} \quad (1) \qquad V = \frac{Q}{A}$$

In which: Q = amount of outflow per sec. ($cm^3\ sec^{-1}$) A = crossection of sample (cm^2). l = length of sample (cm).
P = hydrostatic pressure ($dn\ cm^{-2}$). ρ = density of water ($gr\ cm^{-3}$).
g = accelleration due to gravity ($cm\ sec^{-2}$).
h = height in gravity field (cm) η = viscosity ($dn\ cm^{-2} sec$).
Indice 2 gives the upper part of the sample, indice 1 the lower part. As soon as the water had disappeared from the surface, the difference in pressure between bottom and top became less than 97.5 cm and this simple formula could not be used anymore.

Adding 4, 8 and 9 cm^3 water did not result in other permeability values, as could be expected since the layer of water on the sample was very thin as compared with the applied suction. This was different for the puddled soil B: here at pF 2.0 the permeability of the puddled sample decreased with increasing persolation. The first two hours, a K_i of 5.0 x $10^{-12} cm^2$ ≈ 0,5 mm/day) was measured; after 8 hours it had decreased to 2.0 x 10^{-12} and after three days to 2.6 x 10^{-13} (≈ 0.02 mm/day). This probably was the result of swelling during percolation. In the puddled Soil G K_i was constantly low at 7.2 x 10^{-12} (≈ 0,7 mm/day).

After drying and remoistening, K_i values were considerably higher: for G 2.0 x 10^{-11} and for B 1.9 x $10^{-11} cm^2$ (≈ 2 mm/day). This, again, was caused by the formation of larger micropores between the skeleton grains during drying (see Figs. 18, 20 and 21).

An undisturbed sample of the Ap_2 of Pedon G was included in this experiment to demonstrate the effect of root channels on permeability. After adding 4 cm^3 water to a sample of 100 cm^3, only about 2 cm^3 passed very rapidly, as long as water was visible on the surface (as indicated by arrows in Fig. 41). The remainder was as slowly desorbed as that in the puddled sample. The original sample was in equilibrium at pF 2.0; therefore it could be expected that the 4 cm^3, added to it, would be desorbed rapidly through previously drained pores. The 2 cm^3 that remained longer in the soil apparently flowed into pores larger than those filled with water at pF 2.0. Since desorption of this water took place with the same velocity as in the puddled soil, it seems justified to assume that water flowed into larger channels and voids not penetrating the core over its total depth. This water was later slowly desorbed through small voids between skeleton grains. These small voids, therefore, determine in fact the permeability of the soil sample.

Frozen puddled soil (Fig. 42) shows the same pattern, but here vertical frost planes (Fig. 44) result in a much stronger initial permeability. Natural samples from the Ap, taken in December from both pedons, showed varying results. The effects of compaction on Pedon G (Type III, Novemeber 1967) were still obvious from the low permeability of two samples (Fig. 42) that resemble the graph for puddled soil G.

The results of the other field samples showed that, with free water at the surface (indicated by an arrow in Fig. 42) water was first conducted through the larger vertical continuous voids, resulting in strong desorption in a short period. In the meantime water also flowed into not continuous large pores not filled with water at pF 2.0. Downward water movement from these pores continued when the large continuous pores had become empty, through very fine pores filled with water at pF 2.0.

It should be realized, that cylinders with a height of 5 cm were used for the experiments. In some of them vertical continuous larger pores were present between fragments, as indicated by the permeability data, whereas in others they were not. As a sample becomes longer, the chance that a large pore is vertically continuous throughout becomes smaller. In fact, the real sample is not a core of 5 cm but an Ap with a depth of 25 cm or more. Thus, capillary conductivity data, calculated for the basic fabric of the soil material and based on a morphological analysis of microstructure forms an important soil physical characteristic.

Total infiltration can be estimated for a theoretical Ap of 30 cm, composed of puddled soil material at pF 2.0, and of puddled and dried material remoistened to pF 2.0. In both cases groundwater is supposed to be at 1 m. In this hypothetical case no macropores are present. If at 30 cm depth suction is 70 cm (as there was a permanent suction of 97,5 cm below the porous plate in the second experiment), the following infiltrations can be calculated with Darcy's formula; also considering the gravity effect:

Puddled Soil B:	1.4→0.07 mm/day
Puddled Soil G:	0.21 mm/day
Puddled, dried and remoistened Soil B:	5.4 mm/day
Puddled, dried and remoistened Soil G:	5.8 mm/day

When water moves down through the soil, the suction at 30 cm depth will normally be different from 70 cm, the exact value being determined by the permeability of the subsoil. When at the other limit, suction is zero at 30 cm depth and water moves only by forces of gravity, the following values are obtained:

Puddled Soil B:	0.4 - 0.02 mm/day
Puddled Soil G:	0.06 mm/day
Puddled, dried and remoistened Soil B:	1.6 mm/day
Puddled, dried and remoistened Soil G:	1.7 mm/day

The true values calculated for this simplified system considering only water movement and neglecting the occurrence of air will be between these two limits. When larger voids are present, not only permeability will be increased (at least when these pores have a vertical elongation up to the surface of the soil) but in addition a temporary storage of moisture is made possible.

4.5.4 Pore size distribution and permeability.

The law of Poisseuille gives the relation between the width of a capillar tube (2r) and the velocity (v) of a liquid with viscosity η moving through the tube as a result of a pressure gradient dP/dx (Marshall 1958).

$$v = - \frac{r^2}{8\,\eta} \cdot \frac{dP}{dx}$$

If the cross section through a porous material shows a portion ε to be made up of cross sections of tubes of radius r_t, the velocity V' in this portion will be equal to V"/ε, where V" is the apparent linear velocity for the porous medium as a whole.

Hence: $V'' = - \frac{\varepsilon\, r_t^2}{8\,\eta} \cdot \frac{dP}{dx}$. Since $V'' = - \frac{K_i}{\eta} \cdot \frac{dp}{dx}$, it follows:

$$K_i = \frac{\varepsilon\, r_t^2}{8}$$

With this equation an 'effective pore diameter' r_t can be calculated for the soil materials, substituting calculated K_i values. For the puddled, dried and remoistened soil materials a r value of 0,4 μm is obtained (ϵ = 0.12 as determined by point count, $K_i = 2.0 \times 10^{-11}$ cm^2).

Morphological pictures (Figs. 20 and 21) show, however, that many voids in thin sections are larger. Except for some larger ones their diameters are as a rule about 30 to 40 μm. Corresponding with r about 15 μm, When this general value of visible pore size is substituted, a K_i of 3,4 x $10^{-8} cm^2$ is found.

In continuous irregular pore systems permeability will be determined by the smallest pores. Therefore, the measured permeability is much lower than the theoretical value corresponding with a pore diameter of 30 μm.

Marshall (1958) studied in sandy soil material the relation between permeability and size distribution of pores, the latter derived from pF curves. Each suction corresponded with a certain pore size. He supplied a theoretical calculation, based on the probability that certain 'necks' between larger pores will be found in a pore system. Following his procedure, in which more emphasis is given to smaller pores, the relation between permeability and pore sizes is more complex:

$$K_i = \epsilon^2 n^{-2} \{ r_1^2 + 3r_2^2 + 5r_3^2 + \ldots\ldots\ (2n - 1) r_n^2 \} : 8$$

in which ϵ is the porosity and n the number of equal classes of the pore volume each with a specific pore size r.
In this equation $r_1 > r_2 > r_3 > r_n$.
The numerical examples given by Marshall were based on pF curves of sands. His data on pore size distribution were obtained mainly between suctions of 10 and 50 cm, corresponding with pore diameters of 300 and 60 μm calculated from

$$r = 2\ \gamma/\rho g h$$

in which r is the pore radius, γ the surface tension of water, ρ the density of water, h the suction in cm water and g the acceleration due to gravity.

According to microscopic point counting at x 250 magnification, the rather homogeneous sample of the puddled and dried soil material considered here (sample B) had much finer pores. They were present as more or less discrete entities between the skeleton grains (fig. 20). The size of a pore hit by a point was measured by estimating the diameter of a circle with the same surface. A count of 1500 points, randomly distributed over the section, was made. The results were:

15 - 30 µm : 5% of the volume
30 - 50 µm : 4% of the volume
50 - 80 µm : 3% of the volume

The measurement offers problems:

1. Very fine pores (< 15 µm) cannot be well distinguished and measured at normal magnifications in a thin section with a normal thickness of ± 20 µm.
2. When very fine pores, equal to or slightly greater than the thickness of the section (20 µm) are measured, a 'neck' effect is introduced. A pore is seen because it is black under crossed polarizers and remains so when the microscope table is turned. Only the few pores whose walls make right angles with the surface of the section show their true cross sectional size, while all others, with oblique walls, show their smallest dimensions in the plane of the thin section. When pores have sizes over (say) 50 µm, as in many sands, the relative error is so much smaller, that counts are well possible.
   Total pore volume (soil material B) was 36% (section 4.6). At pF 2.0 some swelling occurred, giving a pore volume of 38%(moisture content at pF 2.0 = 23%, all pores are assumed to be filled with water, density of soil material = 2.67).

   The volume of pores from 0-15 µm was thus estimated at 38% - 12% = 26% (that is 68% of total pore volume!). Based on Marshall's calculation method, the above size distribution resulted in a K_i of 2,5 x 10^{-9} cm^2. (for ε = 0,38 η = 10 and r_1= 25, r_2 = 13, r_3 = 6, r_4 = 3, r_5 = 2, r_6 = 1, r_7, r_8, r_9 and r_{10} < 0.5 µm).

   This value is considerably higher than the measured one (2.0 x 10^{-11} cm^2). This is because pores larger than 30 µm still occupy 7% of pore volume. However, the size of the 'necks', where the skeleton grains contact each other, determines permeability. After drying, the plasma is concentrated at these points of contact, giving a small 'neck' and increasing the size of the intergranular packing void, that hardly contributes to permeability. The morphometric analysis of a thin section is thus not particularly useful in estimating permeability from size distributions of very fine pores. However, the micromorphological picture is essential to 'translate' a grain size distribution, based on weight percentages into a structural pattern.

4.6 Morphological aspects of drying by frost.

4.6.1 The formation of ice crystals

The effect of freezing depends on such factors as moisture content, temperature and capillary conductivity of the soil material, and on the speed with which the temperature is lowered. As a comprehensive study of these subjects is beyond the scope of this text, attention is confined to the occurrence of ice crystals in natural soil and in artificial samples and the effects on soil structure after evaporation or thawing of the ice.

Water in large pores will more easily freeze than that in small pores. In large voids, at temperatures just below zero, concentrations of ice are formed that grow by attracting moisture from finer pores still filled with water. The water in the small pores will not freeze before a lower temperature is reached (Scheffer-Schachtschabel, 1966, pp. 215, 251). Then very fine crystals are formed, as with freeze-drying. In February 1968, a frozen sample from the Ap of Pedon G, containing wedge-shaped ice crystals, was taken to the laboratory. The soil between the dominantly horizontal ice wedges was still moist. After thawing and drying, a vertical thin section was prepared (Fig. 43). It showed that, after thawing, a platy structure had remained and that the ortho-joint planes (Brewer, 1964) were locally inter-connected. Near the soil surface, where temperatures had been most extreme, the soil material had been divided into small aggregates and plates had become thinner. Normal drying at the air of this originally compact soil would have resulted in cohesive dense fragments.

Movement of water into ice crystals or wedges leads to stabilization of the soil material from which the moisture has been extracted. But this is true only, if low moisture contents are reached, perceptible from the light dry colour of the soil.

Freeze drying results in the formation of many very fine crystals. After evaporation, the shape of these crystals is still visible from the arrangement of the plasma that previously surrounded them.

Drying, caused by extraction of moisture from the plasma, resulted in orientation (see Fig. 45). Comparison with Fig. 20 of a puddled and dried soil suggests the occurrence of a lower pore volume in the s-matrix of the latter soil. If true, it could be important for the mechanical stability of the soil material, a higher pore volume resulting in a lower stability. To investigate this phenomenon aggregates of 3.4 - 4.8 mm were

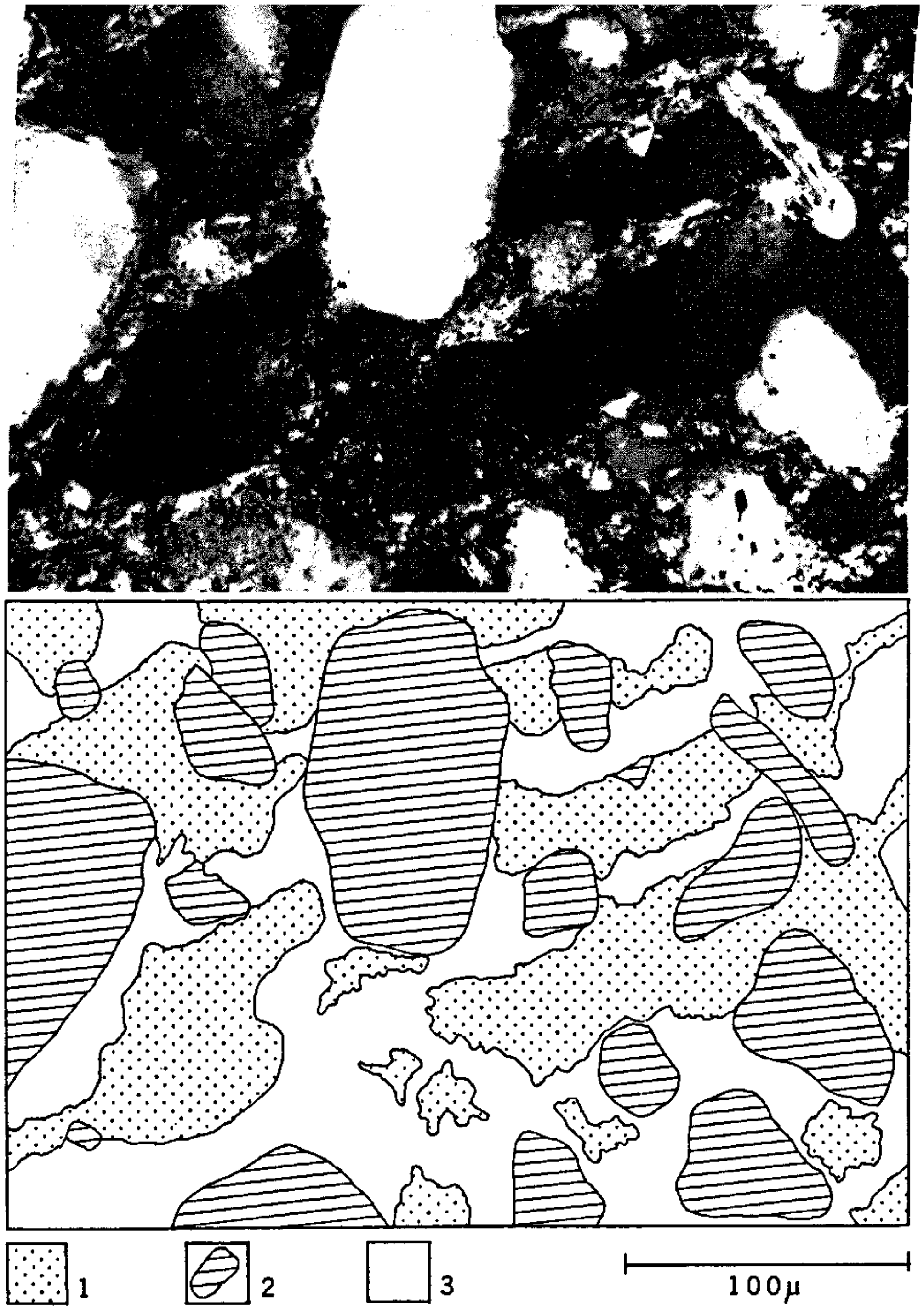


Fig. 45. During freeze drying of a puddled soil many fine ice crystals are formed. After evaporation of the ice their imprint is left; oriented clay particles are found in between.
1 = voids; 2 = skeleton grains; 3 = plasma.

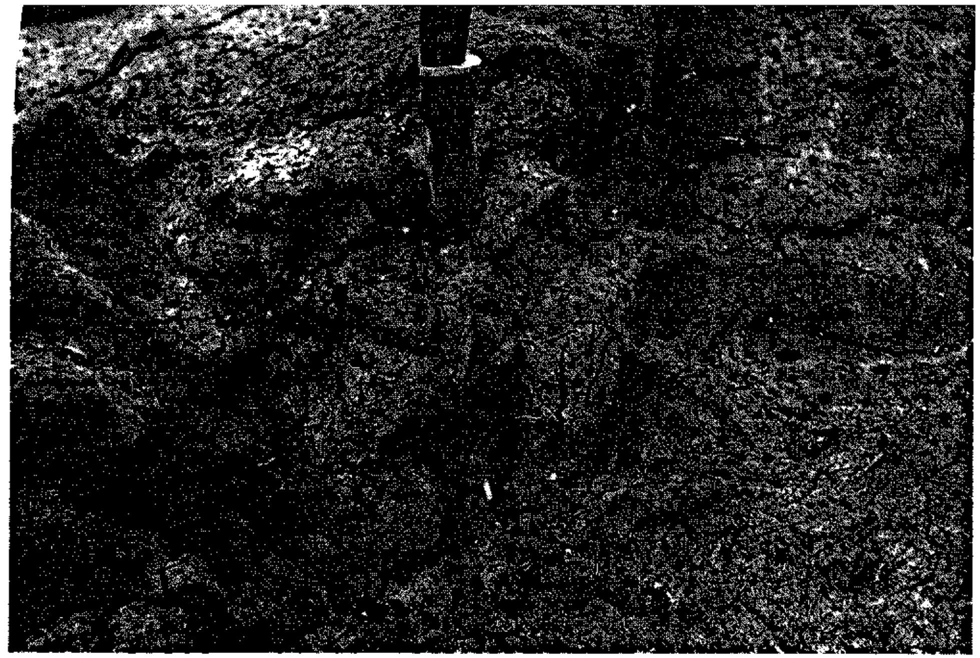


Fig. 46. Vertical ice wedges, penetrating the crust on Pedon G (February 1968).

prepared from puddled material of both soils that had been dried to a friable consistence. The resulting aggregates were carefully remoistened on a sand-bed of the pF apparatus to pF 1.5. This resulted in relatively low moisture contents after two days: soil aggregates B 20%, soil aggregates G 25%. Next, a part of the aggregates was dried to air (B: 1.7% moisture G: 2.4%); the remainder was freeze dried and reached moisture contents of 2.5%(B) and 3.5% (G). Table 8 gives the pore volumes, estimated with the method described in section 4.

Table 8. Pore volume in puddled soil materials B and G after air-drying and after freeze-drying (averages from 10 estimates).

Profile B		Profile G	
dried to air	dried by freezing	dried to air	dried by freezing
36.3±0.24	36.5±0.30	36.8±0.19	39.2±0.28

Measured by Mr. B. Kroesbergen.

For the aggregates of Soil G, pore volume was indeed significantly higher after freezing, but this was not so with the other aggregates, probably because of their relatively low moisture content (20 against 25%). Ice crystals had formed here, too, but the amount was not sufficiently high as to produce a significant higher pore volume.

4.6.2 Permeability of puddled and frozen samples

A puddled sample of each soil, prepared as in 4.4, was desorbed to a moisture content corresponding to pF 2.0. Then the core was placed in a refrigerator at -8°C for about 14 days. This resulted in low moisture contents (Soil B: 2.8%, Soil G: 4.2% by weight). The ice had evaporated, leaving planar voids. After careful remoistening in vacuum, the sample was again desorbed to pF 2.0 and permeability was measured according to the procedure discussed in 4.5. As shown in Fig. 42 permeability of the frozen sample had strongly increased. The vertical thin section through the soil in the sample cylinder revealed distinct interconnected planar voids, stretching in various directions (Fig. 44) and resulting in a higher permeability. A puddled sample dried to air showed a quite different

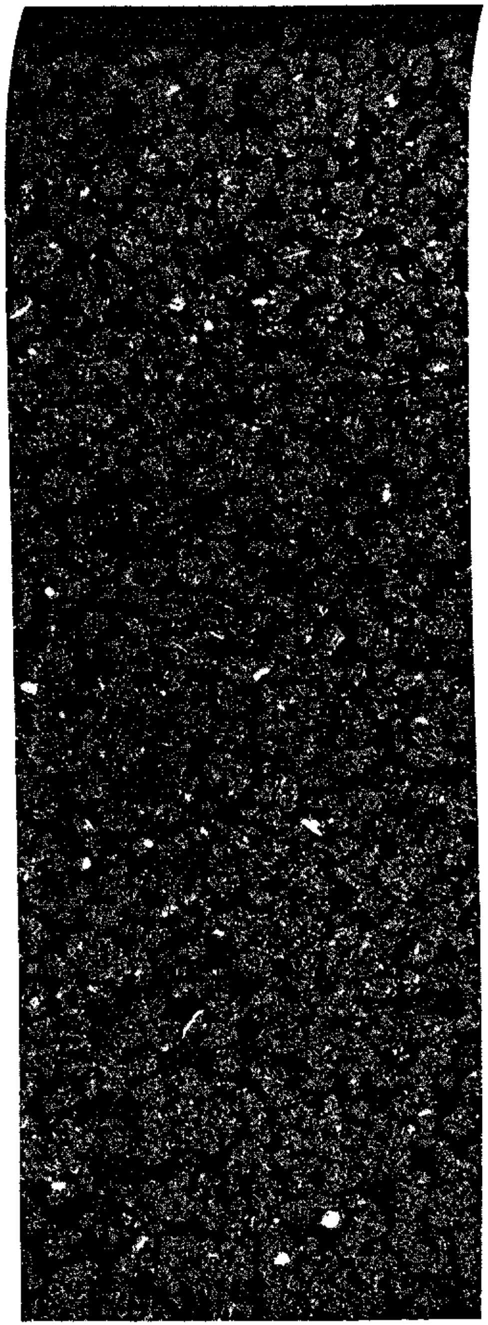


Fig. 47.
Gp-sd (12 %), absorbed to pF 1.5,
freeze dried to 3 %,
saturated in vacuum (48 hours),
4 x desorbed to pF 2.0,
3 x saturated.

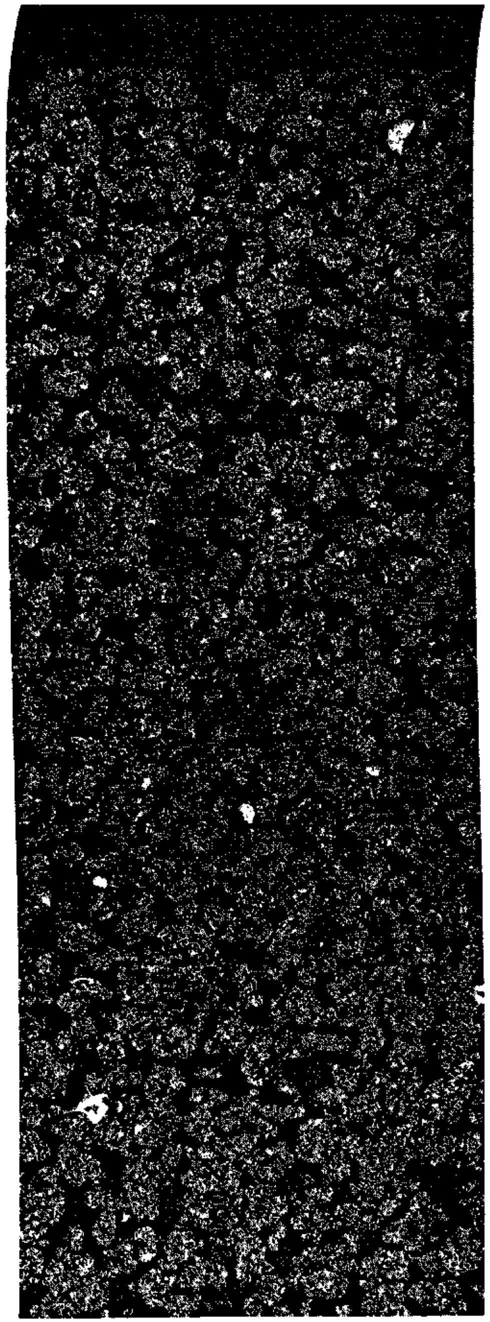


Fig. 48.
Bp-sd (8 %), adsorbed to pF 1.5,
freeze dried to 3 %,
saturated in vacuum (48 hours),
4 x desorbed to pF 2.0,
3 x saturated.

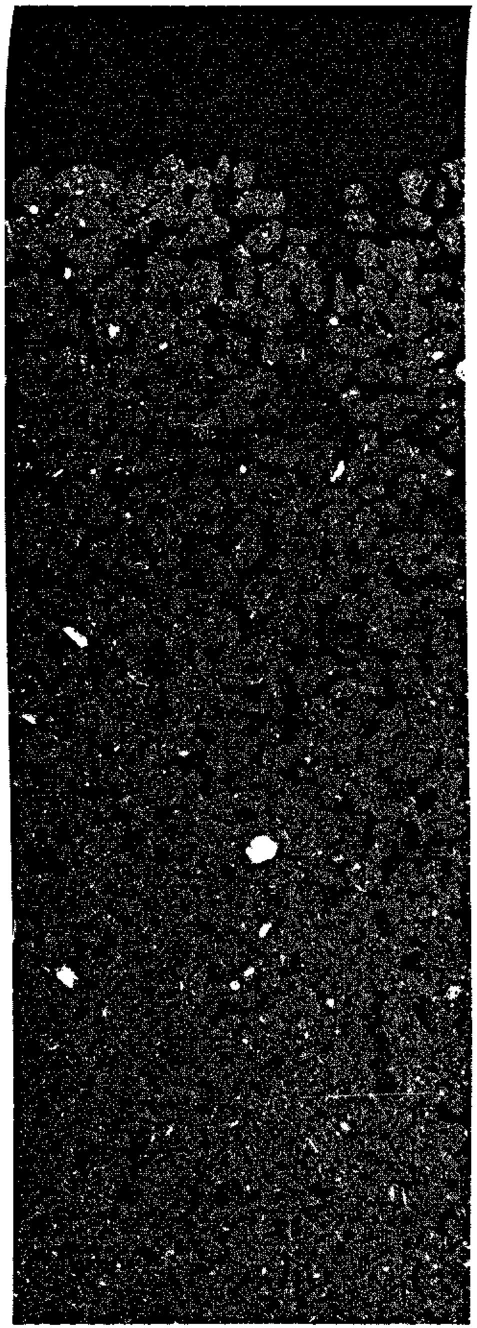


Fig. 49.
Gp-sd (12 %): after saturation
in vacuum (48 hours),
4 x desorbed to pF 2.0,
3 x saturated.

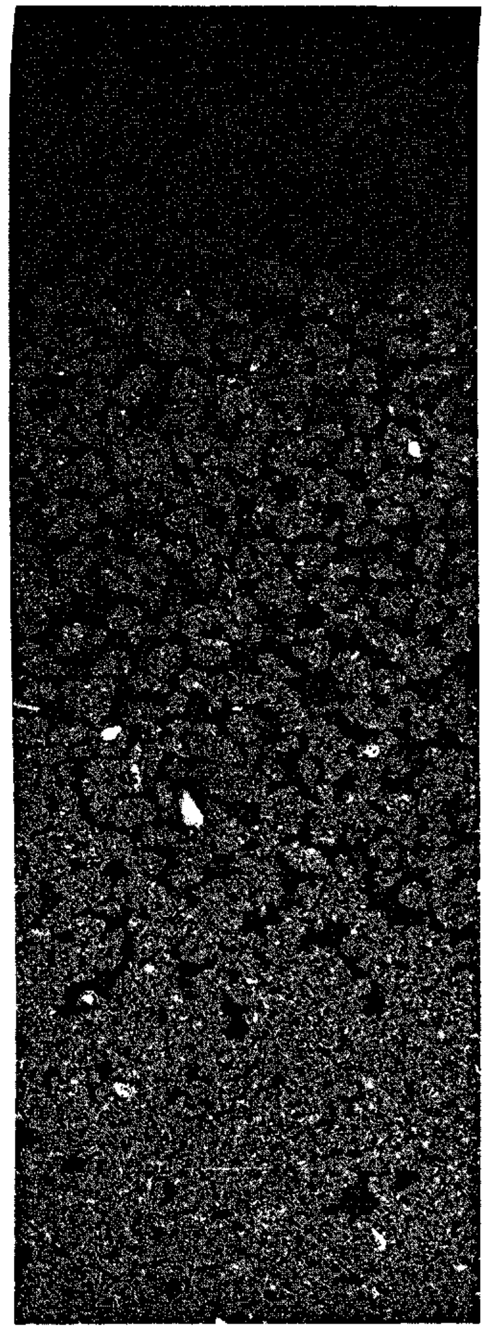


Fig. 50.
Bp-sd (8 %): after saturation
in vacuum (48 hours),
4 x desorbed to pF 2.0.
3 x saturated,

picture: here only fine pores were present (Fig. 20) and no planar voids, resulting in a much lower permeability (Fig. 42).

In the field, vertical ice wedges penetrating the crust have been observed (Fig. 46).

4.6.3 Increase of stability after freeze drying.

Ice crystals tend to grow by attracting moisture from the surrounding soil so that, ultimately, a dry soil is left between the ice concentrations. It may be expected, that this mechanism also leads to a higher structural stability of the soil material, as does drying to air. The larger pores in the aggregates after freezing (4.6.1) may, however, have a weakening effect.

To investigate this stability factor, some of the methods of the previous sections have been used. Here, the results of the experiment on internal slaking (4.3) will be recorded. Aggregates of 1-2 mm were prepared from puddled soil that was dried to a friable consistence. Careful remoistening to pF 1.5 on a sandbed was followed by freeze drying. Then the aggregates were air-dry (B: 2.3%, G: 3.8% moisture). A 5 cm high steel cylinder of 100 cm^3 was filled with those dried aggregates and remoistened in vacuum. In addition, cylinders filled with moist aggregates from puddled soil were saturated in vacuum. To swell, in both cases the cylinders were placed during 48 hours in a box with a water layer of about half a centimetre. A cycle of adsorption and desorption was followed as in 4.3. Then the cores were dried and vertical sections were prepared. Figures 47-50 show the results: a more pronounced deformation occurred in samples which had not been dried by freezing before remoistening. The stabilization effect is obvious.

5. SOME EXPERIMENTS ON PLANT DEVELOPMENT

5.1 Introduction.

Studies on soil structure are usually made from an agricultural point of view. The soil is judged as a medium for plant root development. Roots absorb soil moisture containing nutrients. In the laboratory excellent growth can be achieved when plants grow in an aerated nutrient solution with only a relatively small root system. For crops growing in the field, however, the situation is quite different. Here, the nutrients are distributed over an irregular pore system.

The average distance between roots will be relatively small when a well branched root system is present. As a consequence the nutrients in the soil solution, notably ions like NO_3'' (Wiersum 1962), will be relatively well available. This factor, however, depends on the capillary conductivity of the soil material as well. The higher its value, the greater the possible transport distance at equal root suction in a certain time. In this case a less well branched root system may be able to absorb as much, or even more, soil moisture than a very well branched one in a soil with a relatively low capillary conductivity.

It is difficult to describe the properties of an optimal root system. This will vary among plant species and it will be a function of climate, of the fertility level and of agricultural management. Besides, a profound discussion of the plant physiological aspects of the problem are beyond the scope of this text. The essential point, however, is the fact that at the start of plant development a volume of soil is found with nutrients, at least a part of which must be transferred into the roots. Therefore roots have to penetrate the soil. In literature, discussing root development as a function of soil physical conditions, three factors are usually stressed:

a. The density of the soil material
b. The rigidity of the soil material
c. The amount of oxygen available for root growth

According to Trouse & Baver's review (1962) the critical upper bulk density for root growth varies with the nature of the soil and herein its aeration plays an essential part. How these factors interact has been clearly demonstrated by Rickman et al. (1966): in their experiments root growth continued in dense, compacted layers when oxygen was injected until O.D.R. values over 20 x 10^{-8}g $cm^{-2}min^{-1}$ were reached in cases where without O_2 addition no growth occurred. In general, a higher correlation was found between O.D.R. values and root growth than between bulk density and root growth.

Stolzy & Letey (1964) also reported a high correlation and they mentioned that at O.D.R. values below 20 x 10^{-8} roots did not grow at all. Rosenberg in his review (1964) arrived at a parabolic relation with bulk density; critical densities for root development ranged from 1.5 to 1.9, depending on soil conditions, especially aeration. That bulk density does not provide a satisfactory boundary value for root growth is because usually a soil is no rigid system. Wiersum (1957) showed that roots cannot grow into rigid pores with a diameter smaller than their own. Barley (1963) also demonstrated the effect of rigidity. In his experiment root elongation stopped at an applied overall pressure of 0.6 kg/cm^2 at the sides of a core with glas beads of silt size. Roots can penetrate well aerated non-rigid systems, even when only small pores are present (Wiersum, 1957).

In the following sections some experiments will be described based on the factors described above. All relevant soil material was taken from the Ap of Pedon G.

5.2 Experimental procedure.

Of soil material from the Ap of Pedon G three series of puddled soil were prepared with microstructures as pictured in fig. 18 (1) to study the penetration of roots (2) to compare the growth of wheat plants and (3) to study the effect of fertilization of puddled soil on the growth of wheat plants.

Series 1: Soil from the Ap was puddled at about 27% moisture and balls with a diameter of 3 cm were prepared. Three treatments were followed:

A: desorbed to pF 2.0 (25% moisture); (Type 1 Fig. 18)

B: dried at 30°C for 3 days (3% moisture), remoistened in vacuum, saturated for 48 hours, desorbed to pF 2.0 (25% moisture); (Type III w Fig. 18)

C: superficially perforated with a needle of about half a millimetre thick to a depth of about 3 mm, afterwards treated as B (Microstructure as B).

From each series 10 balls were packed in a net hung in a black plastic contained (Fig. 51) under a small sieve filled with moist sand in which 8 selected pregerminated seedlings were placed. Their roots reached the balls after about one day. Only water in the balls was available for plant growth.

Series 2: Samples of 690 g, composed of puddled soil with 27% moisture shaped to the lower part of the container (Fig. 52) were treated in three ways (in 3-fold):

A: original puddled soil; desorbed to pF 1.0

B: dried, remoistened in vacuum; saturated for 48 hours and desorbed to pF 1.0;

C: perforated with a needle over the total depth to about 8 holes per cm^2, afterwards dried, remoistened and desorbed to pF 1.0 as sample B.

The samples were put in the same kind of containers as mentioned above. Small sieves filled with moist sand and with 15 plants about 3 mm high and roots about 4 mm long were put on top of them.

Afterwards this was covered with about 3 cm dry sand to restrict evaporation (Fig. 52). The containers were placed in a conditioned room at the Institute for Biological and Chemical Research on Field Crops and Herbage (IBS) at a temperature of 16°C and a relative humidity between 55 and 65% under TL lamps at a distance of about 1 m (corresponding with a light intensity of 5 x 10^4 erg $cm^{-2}sec^{-1}$) burning during 16 hours a day. Leaf measurements were usually carried out in the morning. Only water present at pF 1.0 at the start of the experiment (see vertical ax of Fig.49) was available for plant growth. Additional water was not supplied.

Series 3: Samples of 480 g composed of puddled soil with 27% moisture, were puddled in two ways (in 2-fold):

A: with tap water, afterwards desorbed to a moisture content corresponding to pF 2.0 (25%).

B: with a nutrient solution (40 g ASF-grains N:P:K = 16:22:27 in one litre water), afterwards desorbed to pF 2.0.

In each sample 10 plants were grown as in the experiment of series 2. Again they were placed in a conditioned room, but now the temperature was 20°C and the light was more intensive, provided by three high pressure mercury lamps at about 60 cm distance, resulting in an intensity of 10 x 10^4 erg $cm^{-2}sec^{-1}$. As in the experiment of series 2 no additional water was supplied.

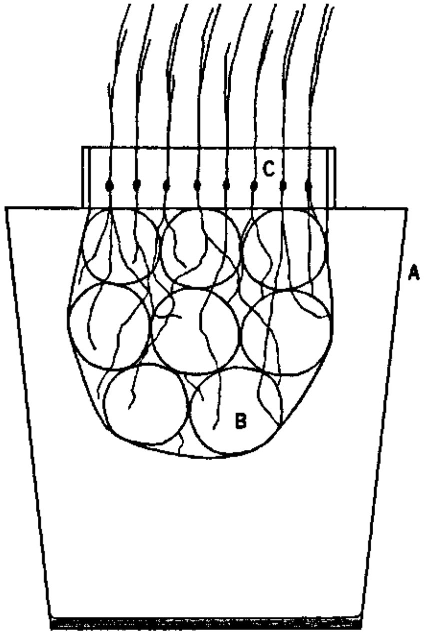


Fig. 51. Experiments of series 1. A = plastic container with some water on the bottom; B = soil balls; C = plastic ring with moist sand and young wheat plants.

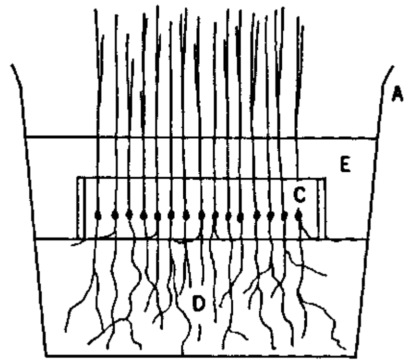


Fig. 52. Experiments of series 2 and 3. A = plastic container; C = plastic ring with moist sand and young wheat plants; D = soil material; E = dry sand.

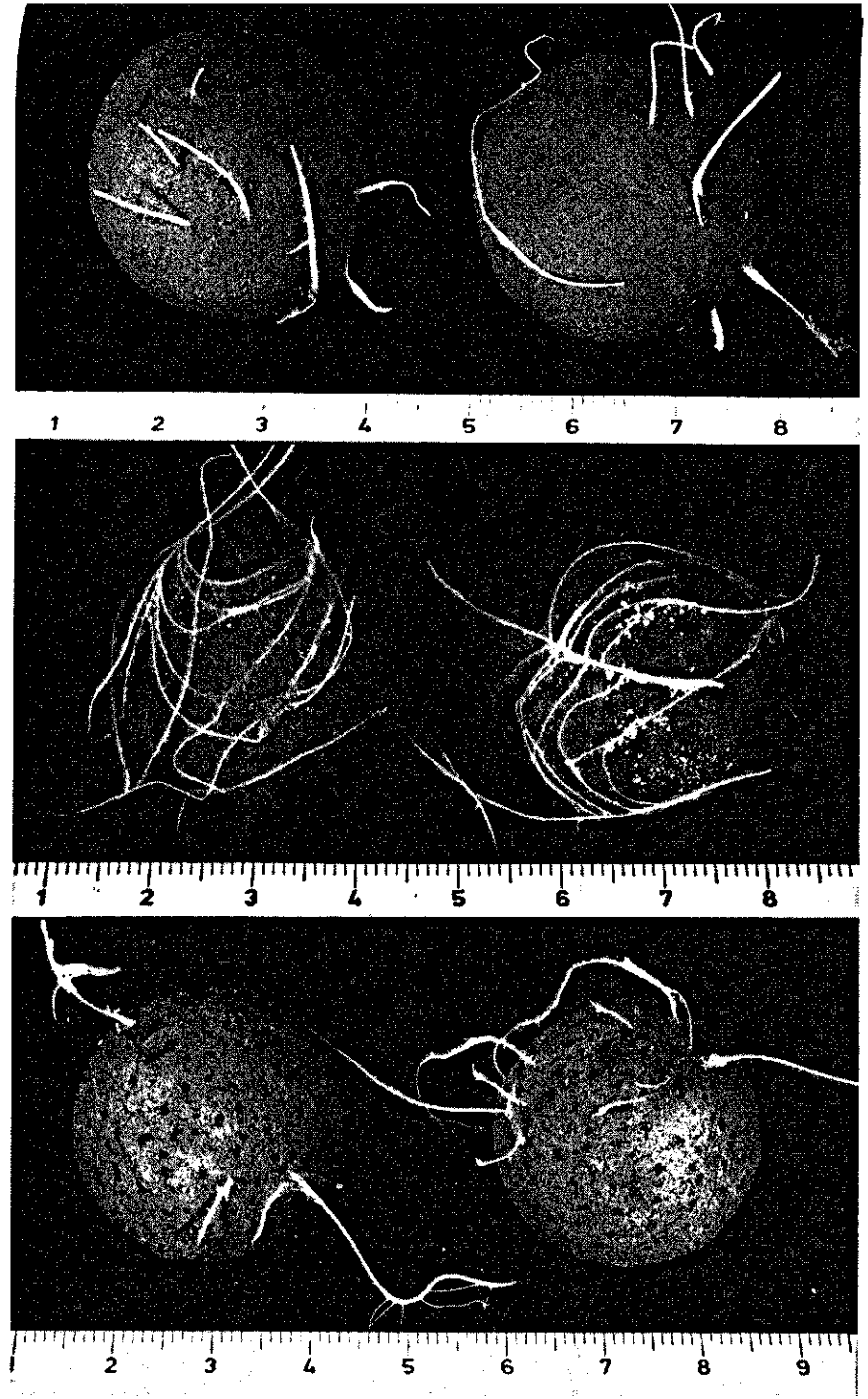


Fig. 53. Experiments of series 1. Top: Type A, puddled soil. Middle: type B: puddled-dried and remoistened. Bottom: as B, but superficially perforated.

5.3 Discussion of results

The experiments with the earth balls (Series 1; Figs. 53) show that drying and remoistening (1B) made it impossible for the roots to penetrate. Roots penetrated the balls of types 1A and 1C. O.D.R. values can be used to estimate whether or not a certain soil material will be penetrated by roots. With the kind assistence of Mr. van der Wey (Dept. of Soils and Fertilizers), they have been measured in samples with a moisture content corresponding with pF 2.0 according to the procedure described by Letey et al. (1964). Table 9 gives the results.

Table 9. O.D.R. values (in 10^{-8} gr. cm^{-2} min^{-1}) in samples (series 2) with moisture contents corresponding to pF 2.0.

Treatment A		Treatment B		Treatment C	
10	16	4	4	8	24
6	3	10	8	8	14
10	2	2	18	8	10
6	3	2	6	4	24

At pF 2.0 pores in these samples are still filled with water. Therefore except for two measurements of structure 1 C, all data are well below the critical value 20 x 10^{-8}g $cm^{-2}min^{-1}$ (Stolzy, 1964). So rootgrowth is improbable in all cases, except when oxygen would be supplied through the roots from above or along the roots after penetration. Roots do penetrate sample A that is relatively non rigid (section 4.4). At the point of contact with the balls the root tips are somewhat thicker, suggesting some initial difficulties at penetration.

In 3.2.3 and 4.4.1 it is already remarked, that the difference in consistence between 1A and 1B at the same moisture content can be attributed to differences in microstructure.

Structure 1B is ralatively rigid (section 4.4). Together with a lack of pores at the surface exceeding the size of the root tips (Wiersum, 1957) this prevents penetration. The artificial shallow pores at the surface of 1C remove this difficulty. Besides, the roots continue to grow beyond the ends of the holes, whereas the treatment of the soil has been the same as in 1B.

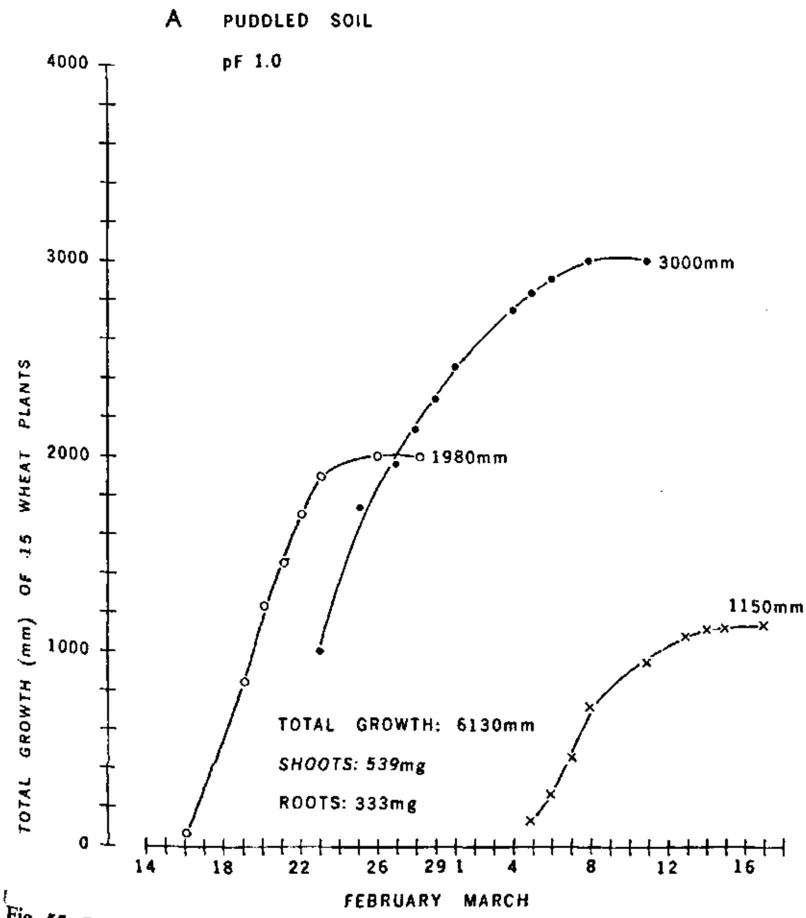


Fig. 55. Experiments of series 2.

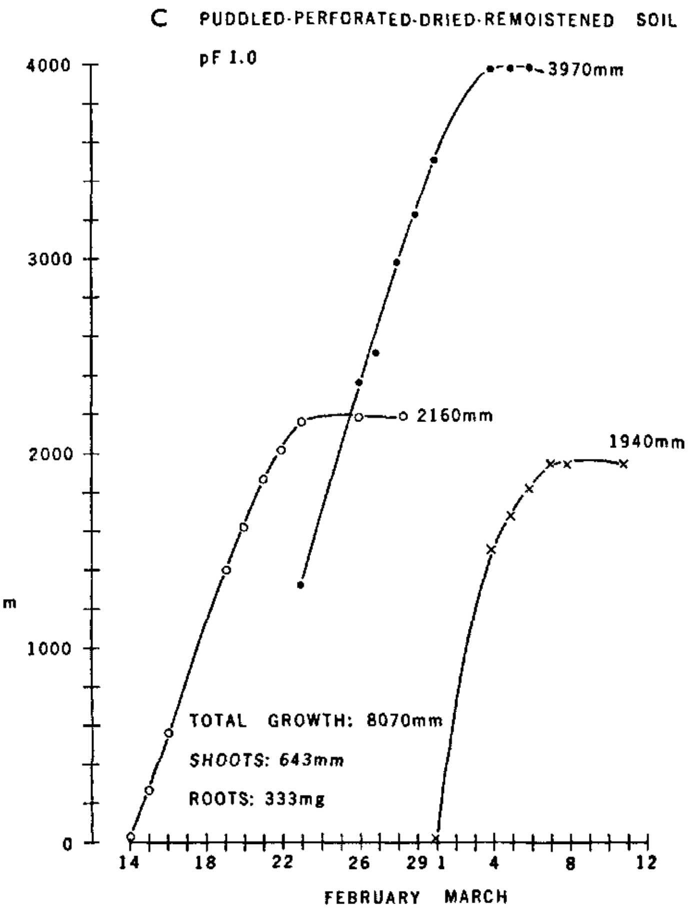
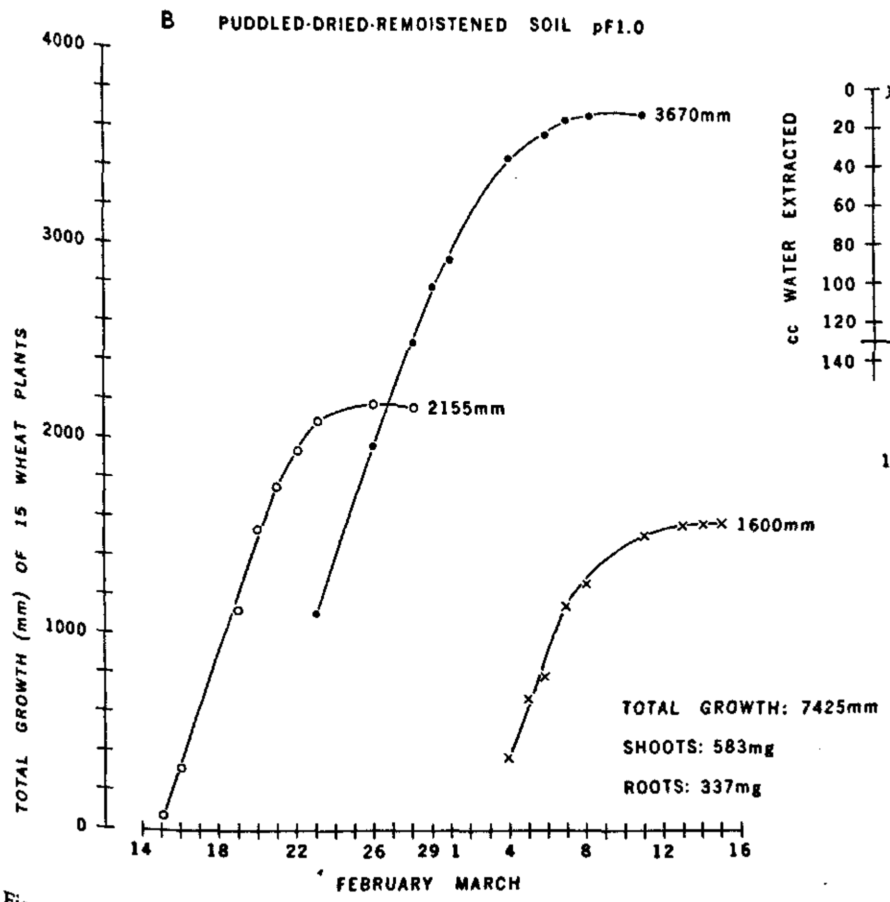


Fig. 56. Experiments of series 2.



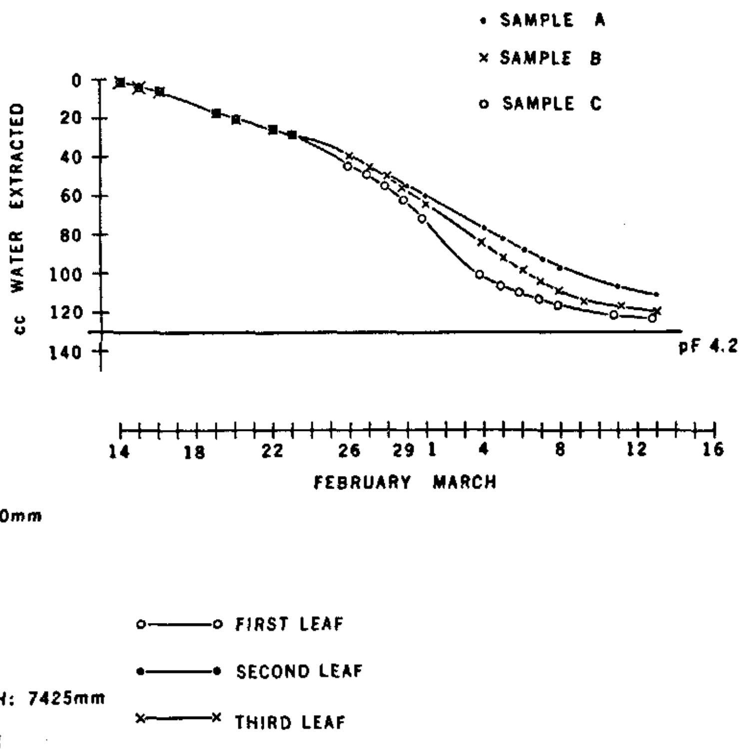


Fig. 54. Experiments of series 2.

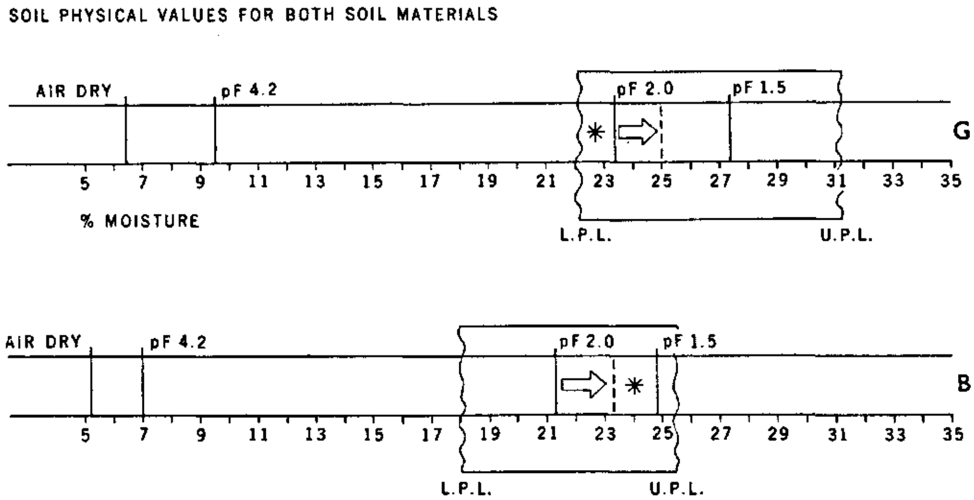


Fig. 58. Soil physical values for both soil materials. l.p.l. = Lower Plastic Limit. u.p.l. = Uupper Plastic Limit. After puddling the moisture content at pF 2.0 increases; this is indicated by an arrow in the figures. The asterisk gives the moisture content at the moment of tillage in 1966.

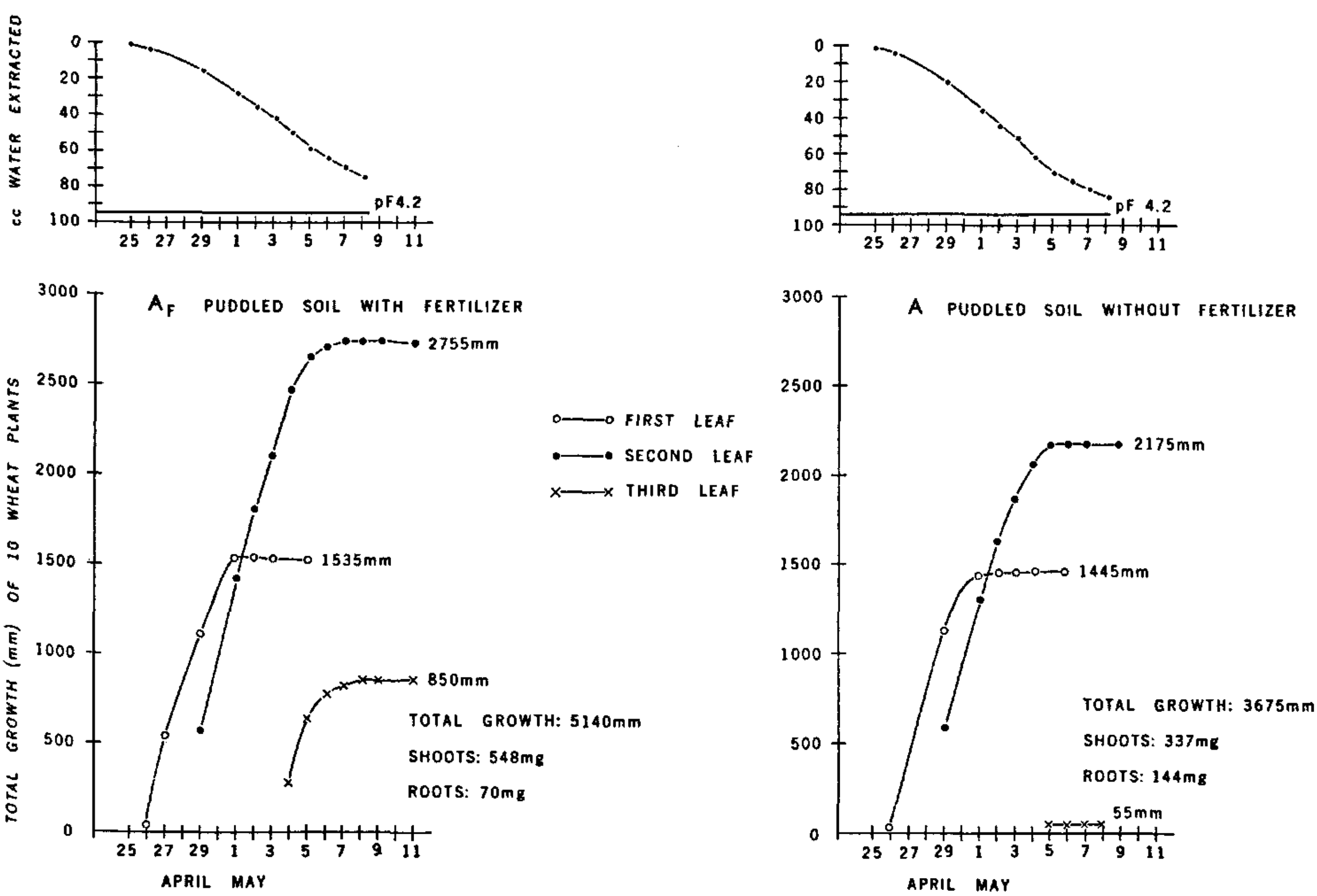


Fig. 57. Experiments of series 3.

This proves that mechanical resistance in sample 1B as such is not the limiting factor. Only when no pores larger than the root tips are present at the surface the rigidity of the soil material prevents the penetration by roots. For the experiments of series 2, leaf growth in mm has been recorded for all 15 plants, for the first, second and third leaves (vertical scale Fig. 54, 55 and 56). The horizontal scale lists the days of measurement. One of the three samples of each treatment has been chosen for graphical expression. When growth had stopped after about four weeks, the dry weight of shoots and roots was determined of two samples of each treatment. The average values are expressed in the figures. It can be seen that total growth in mm is highest for sample C. This is also true for the production of dry matter. Sample A on the contrary is lowest in both aspects.

This difference becomes only visible after the development of the first leaf, The total amount of roots is about the same for each sample. In sample B roots were only found around the sample. In samples A and C about half of the total amount was found inside the fragments. In sample C roots followed the artificial channels.

Sample C shows the greatest development in the shortest period. Growth ended here on March 7, whereas for sample A growth was still observed till March 14. Finally, the values for water extraction (Fig. 54) show that extraction in sample C was considerably more pronounced than in sample A. Also here, sample B has intermediate properties.

Two facts are important for the discussions of the results: (1) the dried and remoistened samples (B and C) have a relatively high capillary conductivity, whereas in sample A this value is relatively low, (section 4.5) and (2) the roots penetrated A and C whereas in sample B they remained at the surface. The latter implies that the average distance of diffusion to the roots in samples A and C was smaller than in B. Development was best in C, however, with its relatively high capillary conductivity.

The difference between A and B suggests that, under the given conditions, capillary conductivity has a greater influence than the pattern of root distribution. During the development of the second leaf, growth in sample A was already retarded. This must have been due to a stronger adsorption of water to the soil particles in this puddled soil that lacks larger micropores, which are formed after drying and which cause a relatively high capillary conductivity.

The nutrient content of the soil solution in the three experiments was not known, but since sampling was done in autumn, it will have been rather low.

The total lengths of the first leaves formed by the plants was about similar in all three experiments (Table 10 first column). This was due to the equal moisture content (17 cm^3) of the sand in the three experiments. Later on, the influence of differences in treatment of the samples became obvious. Less water could be extracted from A because of its low permeability, and from B because of the long way of diffusion. A smaller quantity of soil solution contains less ions, resulting in less growth.

Above, total growth values have been compared. It is necessary also to estimate them at a moment when the amount of available moisture becomes critical at values of pF >3.5 (Vervelde, personal communication). This point was estimated to be reached after extraction of 100 cm^3 moisture. The figures in Table 10 thus derived lead to similar conclusions as the totals included in Figs. 54 - 56.

Table 10. Summed leaf length of all plants in mm after extraction of 100 cm^3 moisture.

	Total length of			
	first leaves	second leaves	third leaves	total
Experiment A	1980	3000	800	5780
Experiment B	2155	3670	800	6625
Experiment C	2160	3970	1450	7580

Since capillary conductivity of the soil material seems to play here a dominant part in growth processes, it is reasonable to assume a distinct influence of the nutrient content of the soil solution, especially of mobile anions (Wiersum, 1962).

Experiment 3 confirmed this.

In the puddled sample A of experiment 2, the amount of soil solution that could be adsorbed by the roots in a certain time, seemed the limiting growth factor. Drying would have a favourable effect. If followed by remoistening, a sample would have been obtained similar in properties to B, with a better plant development. Without drying, improvement can be reached only by adding nutrients to the soil solution. This will increase the number of ions available to be absorbed from the soil in a certain time.

The experiments indeed show a pronounced increase in production for the fertilized sample (Fig. 57). The shoot/root weight ratio is 7.3 with and 2.3 without fertilizers. This pronounced increase of efficiency, especially attributed to nitrogen, has been described before for grasses (Oswalt et al., 1959).

6. DISCUSSION OF RESULTS.

6.1 Introduction.

The properties of both pedons were discussed in sections (1 and 2). They belong to the same mapping unit (Pgb. Haans 1954), and have a similar granulometric composition.

Differences in organic matter and lime content of both surface soils could be attributed to affects of soil management. The structure of the subsoil has a more permanent character than that of the surface soil which structure is frequently changed after tillage operations and after driving over the soil. The surface soil structure observed on a certain moment is a direct function of soil management.

When structure is favourable, it should be realized that this fact is only indirectly resulting from properties of the soil recorded in the standard profile description. With a bad management a very poor structure might have been present in the surface soil of the same profile.

At the start of plant growth, roots have to penetrate the soil to absorb nutrients. The structure of the soil material, that is: its physical constitution as expressed by the size, shape and arrangement of the solid particles and voids (Brewer, 1964) governs this process, as was demonstrated (chapter 5). In a study of soil structure the profile, here especially the Ap, is described as an arrangement of particles, and voids, that governs the movement of soil solution and air as well as the stability.

As explained (2.2) macrostructure in Ap horizons is complex and changing with time. Its stability, is a function of microstructure (chapters of section 4). A sandy loam can only have a limited range of different microstructures, determined by different treatments (Fig. 18). Soil materials with the boundary values of microstructure (Type I and Type III w: Fig. 18) have physical properties that can be measured, as was done in the previous chapters.

6.2 A discussion of soil structure.

Considering soil structure, two factors are emphasized:

a. soil structure in the profile should be favourable towards root development and activity.
b. soil structure should possess a maximal mechanical stability and resistance.

To a certain degree these two conditions are contradictory, so that a suitable balance between both has to be found. Several arrangements of plasma and skeleton grains will now be discussed from this point of view using results from the field study and from modal experiments.

As the soils studied here show only a very limited range of micro-structures, all comparisons are relative: in the following the use of the words 'high' and 'low' should thus be interpreted in a relative and not in an absolute sense.

The mechanical stability of a certain assemblage of aggregates is a function of (a) microstructure, (b) moisture content, and (c) plasticity of the soil material as expressed by the Atterberg consistence values. Drying of the sandy loam soil material has two effects, observed after remoistening: (1) a high capillary conductivity, and (2) a high stability. The first point means that addition of moisture as occurs in nature by rain leads to an equilibrium, estimated here at pF 2.0, in the shortest possible time (4.5). During this time stability is lower.

For the sandy loam considered here it has been shown, that, at equilibrium, stability is high because of previous drying (4.1 and 4.4). Therefore, from the point of stability and resistence to mechanic pressure, a profile would be most favourable when consisting of puddled and dried soil material. But evidently such a soil is highly unfavourable for root growth with its pore volume of about 40%, its air content after remoistening at pF 2.0 of about 4%, and an O.D.R. below 20×10^{-8} g cm^{-2}min^{-1}. Besides roots would not penetrate such a theoretical soil (section 5).

Larger cavities therefore have to be present, conducting and containg moisture and air. Three types of these occur: channels and other biogenic voids formed by roots and animals (for convenience to be called system I), pores between peds formed as natural aggregates in the soil (III) pores between fragments formed by tillage (system II) and As peds are weakly developed in this soil material because of the rather low clay content, a choice has to be made between systems I and II. Of system I good examples were found during the field work in the Ap_2 of Pedon G ('verlassene Krume') and in subsoil samples. They had pore volumes of about 43% and the air content at pF 2.0 varied between 10 and 13% (section 2). The capillary conductivity in such samples shows a special pattern (4.5). After addition of water, channels cause a high initial permeability, at least when they are sufficiently long in vertical direction, as is common with root channels. But dominantly water has to be transferred through fine pores between not interconnected larger ones. Besides, at suctions from pF 1.5 to pF 2.0 water will only flow through fine pores <100 µm. When the soil material has once been dried, capillary consuctivity will be high. The storage capacity of this soil material is considerable (12 vol % air at pF 2.0). It is easily accessible to roots because of the presence of channels (section 5). Furthermore the high capillary conductivity makes the soil solution easily available for the roots (section 5), and the resistance to pressure is relatively high (see 4.1).

The latter appeared from small experiments in which cores of 100 cm from the Ap_2 of pedon G and from the subsoil of pedon B were compacted at a moisture content corresponding to pF 2.0. Compaction occurred only at pressures over 5 kg/cm^2. This, however, was a static force. In the field shear forces are more prominent and dangerous.

One example was described in November 1967 on pedon G, showing that no compaction was found of the Ap_2 (25-35 cm) whereas the surface soil, sharply separated from it, was very much compacted. This demonstrates the stability of the Ap_2 under natural conditions. It remains a question how a layer with the biogenic structure of the Ap_2 would behave if present up to the surface of the soil.

The porosity of type II is caused by tillage. The plow exercises shear forces. The effect depends on soil moisture: if it is higher than that corresponding to the Lower Plastic Limit, plastic deformation and puddling may occur (Soil B in December 1966 (section 2)) resulting in an unfavourable, unstable soil with a low permeability. If ploughed at moisture contents near or below the Lower Plastic Limit, effects are favourable as shown by an increase in air content at pF 2.0 (Pedon G, December 1966 and December 1967). A green manure crop in autumn may help to create a lower moisture content by its transpiration in a time when precipitation exceeds evaporation. In the months after ploughing internal slaking may occur, especially at moisture contents approaching saturation (see 4.3). When during ploughing puddling occurs in the subsoil bordering the Ap_1, a temporary stagnation of water on top of it later in the season is probable The internal slaking will close the pores between fragments and the results of ploughing are nullified. Again the danger of driving with the tractor through the open furrow has to be stressed, notably when moisture contents are high, or when no provisions are made against wheel spin.

These risks of tillage can be reduced when tillage is done at a moment when moisture content is sufficiently low. Assuming good tillage (for example: Pedon G, December 1966) also the resistance to pressure of a soil with large pores formed by tillage has to be considered.
As mentioned before, for a sandy loam with channels (biopores) this resistance is high. A sample consisting of aggregates, representative for an Ap composed of fragments, is more easily compacted (see 4.1).

This applies especially for the plastic range above the Lower Plastic Limit, when movement of soil particles is more easily produced in the system composed of aggregates.

Experiments on compaction have demonstrated a strong deformation of aggregates at moisture contents higher than those corresponding with pF 2.0 (4.1). In aggregates in nature moisture will have to move down from aggregate to aggregate along their points of contact when they are not saturated. This results in a flow considerably smaller than in a compact sample with channels, and the etablishment of equilibrium will take more time. Observations on Pedon G in November 1967 demonstrated the consequences of higher moisture contents, thus created: the surface soil (0-25 cm), tilled the previous year with favourable results, now showed a high compaction after the mechanical pressure exercised by machinery. This compaction was not observed in the Ap_2.

As usually pressure and shear forces decrease gradually with depth (Gill and van den Berg, 1967), the sharp boundary between the two layers at 25 cm is of special interest. In indicates a difference in stability due to differences in macrostructure: aggregates versus compact soil with channels. It shows there is a greater sensitiveness to deformation and puddling when aggregates are present.

The two systems have been tested for their mechanic behaviour under various circumstances during the year by considering suitability for root development and stability. When only these two factors are taken into account system I, without tillage, but with green manuring, is to be preferred. It offers an optimal combination of a high mechanical stability and a favourable root environment. Favourable affects of tillage for weed control are not considered here. For the given soil material a better combination seems hardly possible. But if machinery causes shear forces in the surface soil strong enough to disturb even this optimal arrangement, other decisions have to be considered. Then two possibilities arise:
(1) The management system is changed; driving over the soil is restricted to moments when the moisture content is sufficiently low or forces of sheer and compaction are lowered by the use of other tires or lighter machinery.
(2) Only the very upper part of the profile, where the optimal arrangement is disturbed is tilled. The thickness of this layer has to be determined by a comparison of the mechanical forces, that decrease in intensity with depth, and of the resistance of the soil material. For the conditions described for pedon G in November 1967 this layer could be less than 25 cm deep. Tillage of a thin layer of soil may have other advantages. If puddling occurs, regeneration by drying will be more prominent near the soil surface than deeper in an Ap horizon.

The discussion of systems I and II was based on soil material with the granular composition of a sandy loam. Deffirences in organic matter content between soil materials B and G were not discussed, though they are very important as they have a distinct influence on the mechanical behaviour of the soil materials at different moisture contents. (Baver 1956, Boekel 1965). In modal experiments (e.g. section 4.1) aggregates of soil G, with most organic matter, proved to be more stable than those of soil B. A higher organic matter content leads to greater stability; the Lower Plastic Limit (L.P.L.; see section 3) is found at higher moisture contents. For our soils this is shown in Fig. 58.

The difference between moisture content at pF 2.0 that increases with organic matter content, and moisture content at the plastic limits has been used by Boekel (1965) to characterize the susceptibility of a soil material to puddling and slaking. Moisture content at pF 2.0 of soil material G is closer to its L.P.L. value, than that of soil material B suggesting a greater resistance to puddling.

The moisture contents at the Upper Plastic Limit (U.P.L.) show a more pronounced difference between the two soils, again illustrating the relatively low stability of soil material B. Next to the estimation of these static values and differences also an analysis is necessary (see section 4.5) introducing permeability as an important factor determining the length of the period in which the soil has not yet reached equilibrium at pF 2.0.

The analysis of plasticity should be taken into account when discussing alternative structure models. A management leading to higher contents of organic matter is favourable. It reduces the susceptibility of the soil material to puddling.

Samenvatting.

Twee middelzware zavelprofielen, liggend in verschillende delen van de Haarlemmermeer, maar behorend tot dezelfde bodemkundige eenheid Pgb, (Haans 1954) zijn gedurende anderhalf jaar onderzocht met behulp van fysische en morfologische methoden (1). De bewerkte laag in het ene pedon (G) had een iets hoger gehalte aan organische stof dan dit in de andere (B), als gevolg van een regelmatige organische bemesting gedurende vele tientallen jaren. De granulaire samenstelling van beide profielen was dezelfde. De proefplekken zijn zo gekozen, dat in beide gevallen het grondwater steeds op ongeveer één meter diepte werd aangetroffen.

De landbouwkundige waardering van het perceel waarin pedon B lag, was aanzienlijk minder dan van het perceel met pedon G. In een nadere analyse is de beoordeling van de grond door de boer vergeleken met die door de bodemkundige. Daarbij spelen in het eerste geval economische en bedrijfstechnische aspecten een belangrijke rol. Van de bodemkundige wordt niet slechts een analyse van een toestand gevraagd, maar ook uitspraken en adviezen betreffende te verwachten effecten bij het gebruik van de grond als landbouwkundig produktiemiddel.

Het beschrijven van de macrostructuur in bouwvoren volgens de bestaande schema's (Soil Survey Manual 1961, Jongerius 1957 en Brewer 1964) levert vooral voor lichte zavelgronden moeilijkheden op (2.2.1). Als gevolg van het relatief lage kleigehalte van de grond (13%) zijn verschijnselen als zwel en krimp weinig uitgesproken; de vorming van structuurelementen is derhalve zwak. De aanwezige fragmenten in de bouwvoor zijn gevormd door het uitoefenen van krachten tijdens de grondbewerking, en zij zijn qua grootte, vorm en onderlinge rangschikking bepaald door het hanteren van werktuigen onder zeer gevarieerde omstandigheden. Bovendien is het macrostructuurbeeld niet min of meer permanent, zoals in het natuurlijke ongestoorde profiel. Door zakking en door hernieuwde bewerkingen of door berijden van de grond treden steeds veranderingen op. Voor het karakteriseren van de bodemstructuur in bouwvoren is daarom, zeker in deze gronden, het gebruik van fysische methoden, die veel informatie verschaffen ten koste van relatief weinig werk, te prefereren.

Tijdens het veldonderzoek (2.3) bleek dat het ploegen een zeer averechts effect kan hebben. Een van de doelstellingen is het creëren van poriën tussen te vormen fragmenten. Na de grondbewerking in 1966, waarbij de tractor door de open voor reed, was dit doel niet bereikt in pedon B. Het hoge vochtgehalte van de grond tijdens de bewerking leidde tot sterke slip van de tractor. De bewerkte laag was week en had een plastische consistentie. Het vochtgehalte bij pF 2.0 bleek sterk te zijn gestegen. Het porienvolume daarentegen was vrijwel constant gebleven, waardoor het luchtgehalte bij pF 2.0 sterk was afgenomen. Dit patroon werd in feite het volgende jaar, zij het in veel minder sterke mate, teruggevonden. Deze bewerking vond onder drogere omstandigheden plaats. Ook nu was er echter nauwelijks een stijging van het poriënvolume. Een maximale waarde van 45% werd nooit overschreden (Fig. 3 en 5). Opvallend was het verschil in consistentie vóór en na de bewerking. De onbewerkte grond had een vrij harde, enigszins brosse consistentie bij ongeveer hetzelfde vochtgehalte waarop de grond na bewerken plastisch bleek te zijn. Fysisch bleek dit verschil in beide gronden, gekoppeld aan een stijging van het vochtgehalte bij pF 2.0 na bewerking.

Op pedon G werd na de grondbewerking, waarbij niet door de open voor werd gereden, wel een duidelijke stijging van het poriënvolume na bewerken waargenomen. Ook hier waren de consistentieverschillen in de bewerkte laag vóór en na bewerken duidelijk aanwezig. In dit pedon is een laag aangetroffen (de Ap_2) die vroeger wel steeds mee geploegd werd, maar sinds ongeveer 1950 niet meer (een zgn. 'verlassene Krume'). Door de op dit perceel steeds toegepaste groenbemesting, waardoor ook de wormactiviteit in de grond toenam, bevatte deze laag nu vrij veel biogene gangen. De consistentie was steeds vrij hard in vochtige toestand. Een sterke compactie ontstond in de bovengrond van pedon G tijdens de aardappeloogst. Dit gebeurde alleen in de laag die een jaar daarvoor met gunstig resultaat was bewerkt. Een scherpe grens was aanwezig tussen deze laag en de onderliggende Ap_2, hetgeen er op wijst, dat deze laatste laag duidelijk stabieler was. Het voorkomen en de aard van oppervlakkige verslempingskorsten (2.3.3) en minerale inspoelingshuidjes (2.3.6) is afzonderlijk behandeld.
Wanneer een analyse wordt gemaakt van de processen die zich in de bouwvoor gedurende het jaar afspelen (3.1 Fig. 16) valt op dat in alle gevallen in principe gesproken kan worden van verplaatsingen van de elementaire minerale bestanddelen, al of niet aanwezig in afzonderlijke fragmenten, ten opzichte van elkaar.

De mate van verplaatsing zal een funktie zijn van de uitgeoefende krachten enerzijds en van de cohesie van het bodemmateriaal anderzijds.
Het micromorfologische beeld van natuurlijke monsters leert dat de fijnere bodembestanddelen, met daarbij inbegrepen de organische stof, voorkomen rond de minerale korrels.

In een gedroogd monster is in dit bodemmateriaal niet voldoende plasma aanwezig om alle ruimten tussen de zandkorrels op te vullen (3.2). In dit droge bodemmateriaal worden de korrels samengekit door het plasma. De bindingen hierin berusten op directe wederzijdse krachten, op randplaat bindingen en op bindingen door organische stof (Koenigs 1963). Bij bevochtigen zal de neiging tot zwel van de kleiplaatjes voor een groot deel worden gecompenseerd door de cohesiekrachten. Het uitoefenen van energie op zo'n grond, waarbij de kleiplaatjes onderling worden bewogen, zal tot zwel leiden. Plastische vervorming treedt globaal gesproken pas op boven het vochtgehalte van de uitrolgrens (Lower Plastic Limit). Bij iets hogere vochtgehaltes, globaal overeenkomend met pF 1.5, kan in dit bodemmateriaal door kneden al een volkomen versmeerde, zeer weke en plastische grond ontstaan. Deze heeft een relatief hoog poriënvolume en vochtgehalte bij pF 2.0. In deze versmeerde grond vullen de fijnere bodembestanddelen als een pasta de holten tussen de zandkorrels op (Fig. 18, I en Fig. 19). Na gering indrogen tot vochtgehalten overeenkomend met een pF van ongeveer 3 wordt een rulle consistentie waargenomen (Fig. 18, II). Bij herbevochtiging wordt als gevolg van zwel opnieuw een weke, plastische grond gevormd (Fig. 18, II w). Wanneer echter tot luchtdroog wordt gedroogd is de grond hard. Zij blijft vrij hard en bros na herbevochtiging. Tijdens het drogen concentreert zich het plasma rond de zandkorrels, waardoor fijne holten ontstaan (Fig. 18, III en Fig. 20), die ook na herbevochtiging aanwezig blijven (Fig. 18, III w en Fig. 21 + 22).

De microstructuur kan, gezien de gegeven hoeveelheid van ieder der componenten, slechts in vrij geringe mate variëren (Fig.18). Dit is een belangrijk verschil met de zeer variabele macrostructuur. Bovendien is de microstructuur een duidelijke functie van de behandeling, waardoor het een goede basis vormt voor de studie van de bodemdynamiek. Een serie modelproeven, die zijn gebaseerd op de verschillende zich in de bouwvoor afspelende processen (Fig. 16), werd uitgevoerd op basis van dit micromorfologische concept. Daarbij zijn steeds uiterste waarden van het traject in Fig. 18 met elkaar en met natuurlijke monsters vergeleken. De resultaten kunnen als volgt worden samengevat.

4.1 Drukproeven.

De samendrukbaarheid van uit aggregaten samengestelde monsters neemt toe met het vochtgehalte. Aggregaten uit de bouwvoor van pedon G bleken duidelijk de hoogste weerstand te bezitten, vooral bij iets hogere vochtgehaltes (pF 1.5). Niet slechts het vochtgehalte en de druk bepalen echter de samendrukbaarheid. Vooral ook de microstructuur speelt een belangrijke rol. Aggregaten bestaande uit versmeerde grond bleken zeer zwak. Na droging tot luchtdroog en herbevochtiging werd een veel grotere stabiliteit bereikt bij eenzelfde vochtgehalte.

Een natuurlijk monster uit de Ap_2 van Pedon G had een zeer hoge resistentie. Bij de analyse werd gebruik gemaakt van morphometrische technieken.

4.2 Regenproeven.

Gedroogde en herbevochtigde natuurlijke aggregaten van beide gronden bleken een minder grote resistentie te bezitten dan de overeenkomstige versmeerde aggregaten. Dit is toegeschreven aan de grote heterogeniteit op microschaal in de natuurlijke grond, die gedeeltelijk wordt veroorzaakt door het ieder jaar onderploegen van oppervlaktekorsten.

Het bleek niet mogelijk het verschil in stabiliteit tussen natuurlijke en versmeerde monsters te verklaren uit een verschil in de mate van orientatie van het plasma.

4.3 Verslemping in de bouwvoor.

Het in elkaar zakken van de bouwvoor na het ploegen is nagebootst in een monsterring gevuld met aggregaatjes. Bij verzadiging in vacuum bleken aggregaatjes, bestaande uit weinig ingedroogde versmeerde grond, instabiel. Gedroogde versmeerde aggregaatjes waren daarentegen stabiel. Natuurlijke aggregaatjes vertoonden ongeveer hetzelfde beeld, waarbij die van pedon B zwakker bleken te zijn dan die van Pedon G. Wanneer echter slechts bevochtigd werd tot pF 1.0, trad geen verslemping op.

Onder de natuurlijke bouwvoor kan door de malende werking van het tractorwiel een versmeerde laag ontstaan, met een zeer lage doorlatendheid. Het hierop stagnerende water kan genoemde verslemping veroorzaken. Het rijden door de open voor biedt daarom risico's, die des te groter zijn omdat de te verwachten vochtgehaltes op ongeveer 30 cm diepte hoger zijn dan bovenin de bouwvoor. Regeneratie door droging daarentegen is minder sterk op grotere diepte. Het rijden over het land, zoals toe-

4.4 Mechanische weerstand.

Het indrogen leidt na herbevochtiging tot een sterke toename van de conusweerstand. Bij eenzelfde vochtgehalte zijn de waarden voor de niet ingedroogde monsters veel lager.

4.5 Waterdoorlatendheid.

De bepaling van de waterdoorlatendheid in verzadigde grond geeft voor ringmonsters uit de bouwvoor misleidende uitkomsten voor toepassing in de praktijk aangezien in deze lagen in de natuur zelden een volledige verzadiging optreedt.

Eēn continue verticale holte in het 5 cm hoge ringmonster zal een hoge doorlatendheid kunnen veroorzaken, terwijl bij de in de bouwvoor normale vochtspanningen (pF 1,5 en hoger), holten groter dan ongeveer 100 µm met lucht gevuld zijn. Bovendien zijn deze grotere holten, vooral wortelgangen en pakkingsporiën, slechts over beperkte verticale afstand in de bouwvoor continu. De voor de stabiliteit zeer belangrijke vochtbeweging in het traject pF 1.5 tot pF 2.0 zal daarom vooral moeten plaatsvinden door de fijne pakkingsporiën tussen de zandkorrels (Fig. 20).

Het meest ideaal is dan een toestand waarbij zo snel mogelijk een zo laag mogelijk vochtgehalte wordt bereikt. Gebleken is dat het versmeerde bodemmateriaal een zeer laag capillair geleidingsvermogen bezit.

Na indrogen en herbevochtiging bleek deze waarde sterk te zijn toegenomen als gevolg van de door droging gevormde fijne poriën tussen de zandkorrels. Een berekening is gemaakt ter vergelijking van morphometrische en fysische meetgegevens (4.5.4).

4.6 Drogen door vorst.

Het droogproces kan ook plaatsvinden bij temperaturen onder nul. Het essentiele verschil in het laatste geval bestaat uit de vorming van ijskristallen, waarvan vorm, grootte en distributie onder meer een funktie zijn van de heersende temperatuur. Bij geringe vorst vormen zich relatief grote horizontale en verticale ijswiggen, waarin het water uit de omringende grond wordt geconcentreerd. Na het verdampen van het ijs blijven spleten achter, waardoor na herbevochtiging van de tussenliggende gedroogde grond het water snel kan worden afgevoerd. Bij lagere temperaturen vormen zich fijne ijskristallen. Als gevolg hiervan is, na het verdampen van het ijs, het poriënvolume in de droge grond hoger dan van dezelfde grond gedroogd aan de lucht. Ondanks dit hogere poriënvolume was een duidelijke stabilisatie opgetreden als gevolg van het vriesdrogen en de daarbij optredende orientatie van de kleideeltjes als gevolg van de vochtonttrekking.

5. Plantenproeven.

De plant beemt via het wortelstelsel voedingsoplossing uit de bodem op. Twee aspecten zijn in de proeven, die zijn verricht met tarweplanten, benadrukt:

a) het doordringen van de wortel in de grond

b) het vochtgeleidend vermogen van de grond

Tarwewortels groeiden in versmeerde grond, hoewel de ODR-waarde lager was dan 20×10^{-8} g/cm^{-2}/min. Na drogen en herbevochtigen gebeurde dit niet bij eenzelfde vochtgehalte en evenlage ODR waarden. Wanneer echter ondiepe perforaties werden aangebracht drongen de wortels wel diep de grond binnen. Hiermee werd aangetoond dat niet de hogere mechanische weerstand als zodanig, ontstaan door het drogen, maar de geringe toegankelijkheid van de grond door het ontbreken van grotere poriën, belemmerend werkte op de beworteling. Uit de experimenten bleek de grote invloed van het capillair geleidingsvermogen op de groei. Zo was op niet doorwortelde grond met een relatief hoog geleidingsvermogen in de proeven de groei beter dan op wel doorwortelde grond met een relatief laag geleidingsvermogen. De nadelige gevolgen van een relatief laag capillair geleidingsvermogen op de groei kunnen worden gecompenseerd door het verhogen van de ionenconcentratie in het bodemvocht door bemesting. Bovendien bleek dat in dit geval minder wortels bijdroegen tot de vorming van meer bovengrondse dalen, hetgeen resulteerde in een sterk gestegen spruit/wortel verhouding.

6. Discussie.

Hierbij dient als uitgangspunt een beschouwing van de grond als groeimilieu voor de plant, terwijl de moderne ontwikkeling in de landbouw het noodzakelijk maakt daarnaast ook de berijdbaarheid en stabiliteit van de grond te benadrukken. Getracht is op basis van deze orientatie een analyse te maken voor de beide Pedons, toegespitst op de bodemstruktuur, die als een directe resultante van de bodembehandeling moet worden beschouwd. De beschouwing resulteert in een compromis: de meest stabiele grond is niet geschikt voor de plantengroei, terwijl een zeer poreuze grond te gemakkelijk wordt verdicht.

Het drogen van het bodemmateriaal heeft gunstige effecten. Het capillair geleidingsvermogen is, na herbevochtiging, groter geworden, waardoor lagere vochtgehaltes sneller worden bereikt. Niet alleen hierdoor, maar ook door de ontstane microstructuur zelf, neemt de stabiliteit van het bodemmateriaal toe. Dit is waarneembaar in het veld door het bepalen van de consistentie.

Grotere holten moeten in de bodem aanwezig zijn om de wortelontwikkeling mogelijk te maken. Daartoe zijn wortel- en diergangen te prefereren boven pakkingsporiën tussen bodemfragmenten, gemaakt tijdens een grondbewerking. Bij de grondbewerking zijn namelijk twee aspecten te onderscheiden. In de eerste plaats: het effect van de bewerking zelf. Daarbij treedt in deze gevoelige gronden vrijwel altijd enige versmering op, die echter ook zeer ernstig kan zijn (Pedon B, 1966). De ongunstige gevolgen hiervan zijn in de modelproeven (hoofdstuk 4) duidelijk gebleken. Het oppervlakkig stagneren van water moet ook hieraan worden toegeschreven. In de tweede plaats is een laag bestaande uit fragmenten gescheiden door grote pakkingsporiën in deze gronden minder stabiel dan een meer compacte laag met alleen wortel en diergangen (modelproeven en Pedon G 1967). Voor dit bodemmateriaal is daarom laatstgenoemde structuur, voorkomend in de Ap_2 van pedon G, het beste compromis. Dit betekent in feite dat geen grondbewerking zou moeten worden uitgevoerd, tenzij dit om andere redenen bv. voor de onkruidbestrijding nodig wordt geacht. Wanneer het op de grond uitgeoefende krachtenspel groter is dan de aldus maximaal te realiseren stabiliteit, zal het bewerken van de grond nodig zijn, tenzij door technische maatregelen de krachten kunnen worden verlaagd. De gewenste diepte van bewerken zal kunnen worden afgeleid uit een afweging van deze twee factoren.

Naast dit statische structuurbeeld moeten ook de dynamische eigenschappen van het bodemmateriaal als functie van het vochtgehalte, worden beschouwd. Voor dit doel zijn de Atterbergse waarden gehanteerd. Een hoger organisch stofgehalte ontstaan door organische bemesting, leidt tot een grotere stabiliteit (fig. 58). De microstructuur zal slechts variabel kunnen zijn in een vrij beperkt traject (Fig. 18), variërend van het beeld van een volledig versmeerd tot het beeld van een versmeerd sterk ingedroogd en herbevochtigd materiaal.

Onder natuurlijke omstandigheden zal een toestand worden aangetroffen die ergens ligt in dit traject.

Een bodemgeschiktheidsbeoordeling zal gebaseerd moeten zijn op een samenwerken van vele deskundigen. Volgens het geschetste model kan de bodemstructuur, gezien in morfologische zin maar geconcretiseerd door fysische metingen,als onafhankelijk gegeven worden gehanteerd.

REFERENCES

Anderson, D.M. & R.R. Binnie 1961 Modal analysis of soil.Proc. Soil Sci. Soc. Am. 25: 499-503.

Andersson, S. & T. Håkansson 1966 Markfysikaliska Undersökningar I Odland jord. (English summary). Grundforbättring 3: 191-228.

Baganz, K. 1964 Spannungs- und Verdichtungsmessungen im Boden bei verschiedenen Fahrgeschwindigkeiten. Arch. Landtech. 4(1): 35-46.

Barley, K.P. 1963 Influence of soil strength on growth of roots. Soil Sci. 96: 175-180.

Baver, L.D. 1958 Soil Physics. 3rd Ed., John Wiley and Sons Inc., New York.

Boekel, P. 1963 Soil structure and plant growth. Neth. J. agric. Sci. 11 (Special Issue No. 2): 120-127.

Boekel, P. 1963 The effect of organic matter on the structure of clay soils. Neth. J. agric. Sci. 11(4): 250-263.

Boekel, P. 1965 Karakterisering van de slempigheid van zavelgronden door bepaling van de consistentie. Landbouwk. Tijdschr., 's-Grav. 77: 306-312.

De Boodt, M. 1961 Soil aggregate stability indices and crop yields. Soil Sci. 91: 138.

De Boodt, M. (Ed.) and others 1967 West European methods for soil structure determination. Issued at State Faculty of Agricultural Science Ghent, Belgium.

Brewer, R. 1964 Fabric and Mineral analysis of soils. John Wiley and Sons Inc., New York.

Butijn, J. & J. Wesseling 1959 Determination of the capillary conductivity of soils at low moisture tensions. Neth. J. agric. Sci. 71: 155-163.

Cernuda, C.F., R.M. Smith & J. Vicente Chandler 1954 Influence of initial soil moisture on resistance of macro-aggregates to slaking and to water-drop impact. Soil Sci. 77: 18-29.

Chayes, F. 1956 Petrographic modal analysis. John Wiley and Sons Inc., New York.

Croney, D. & J.D. Coleman 1954 Soil structure in relation to soil suction. J. Soil Sci. 5: 75-85.

Day, P.R. & G.G. Holmgren 1952 Microscopic changes in soil structure during compression. Proc. Soil Sci. Soc. Am. 16: 73-77.

Emerson, W.W. 1954 The determination of the stability of soil crumbs. J. Soil Sci. 5(2).

Fountaine, E.R. 1954 Investigations into the mechanism of soil adhesion. J. Soil Sci. 5: 251-263.

Gill, W.R. & G.E. van den Berg 1967 Soil Dynamics in Tillage and Traction. US Gov. Printing Office. Washington D.C., pp. 512.

Greacen, E.L. 1960 Water content and soil strength. J. Soil Sci. 11(2): 313-333.

Haans, J.C.F.M. 1954 De Bodemgesteldheid van de Haarlemmermeer. Verslagen van Landbouwkundige Onderzoekingen 60.7, pp.152.

Haines, W.B. 1925a Studies in the physical properties of soils. I. Mechanical properties concerned in cultivation. J.agric. Sci. 15: 178-201.

Haines, W.B. 1925b Studies in the physical properties of soils. II. A note on the cohesion developed by capillary forces in an ideal soil. J. agric. Sci. 15: 529-535.

Horton, J.H. & R.H. Hawkins 1965 Flow path of rain from the soil surface to the water table. Soil Sci. 100(6): 377-383.

Hutter, W. 1966 Action des compressions sur la structure des sols. Annales Agronomiques. Vol.17 no.1,37-52.

McIntyre, D.S. 1958a Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 85: 185-189.

McIntyre, D.S. 1958b Soil splash and the formation of surface crusts by raindrop impact. Soil Sci. 85: 261-266.

McIntyre, D.S. & G.B. Stirk 1954 A method for determination of apparent density of soil aggregates. Austr. J. agric. Res. 5: 291-296.

Jongerius, A. 1957 Morfologische onderzoekingen over de bodemstruktuur. Thesis Wageningen, pp. 93.

Jongerius, A. & G. Heintzberger 1963 The preparation of mammoth sized thin sections. Soil Survey Papers no. 1, Soil Survey Institute Wageningen.

Koenigs, F.F.R. 1963 The puddling of clay soils. Neth. J. agric. Sci. 11 Special Issue No. 2: 145-156.

Koenigs, F.F.R. 1964 Basic properties of soil constituents and their bearing on the mechanical properties of soils. International study group on soils. Lectures, Cambridge (Engl.) Section W III lect.3: 320-331.

Kubiena, W.L. (Ed.) 1967 Die mikromorphometrische Bodenanalyse. Ferd. Enke Verlag, Stuttgart.

Kuipers, H. 1959a Confined Compression tests on soil aggregate samples. Meded. Landb.Hoogesch. Opzoek Stns Gent 24(1): 349-357.

Kuipers, H. 1959b Some remarks on pore space and pressure on marine clay soils. Meded. Landb. Hoogesch. Opzoek Stns Gent 24(1): 392-397.

Kuipers, H. 1961a Preliminary remarks on porosity of soil aggregates in an air-dry state and at pF 2. Neth.J.agric. Sci. 9(3): 168-173.

Kuipers, H. 1961b Water content at pF 2 as a characteristic in soil cultivation research in the Netherlands. Neth.J.agric.Sci. 9: 27-35.

Kuipers, H. 1963 The objective of soil tillage. Neth.J. agric. Sci. 11 (Special Issue No.2): 91-96.

Kuipers, H. & C. van Ouwerkerk 1963 Total pore-space estimations in freshly ploughed soil. Neth. J. agric. Sci. 11(1): 45-53.

Kuipers, H. 1966 Die bearbeitung schwerer Böden in den Niederlanden. Tag.Ber. dt. Akad. Landw. Wiss. Leipzig 82 (1965).

Kuipers, H. 1968 Entgegengesetzte Effekte von Reifen und Bodenbearbeitungen. Bodenbearbeitungs-symposium-Varna.

Letey, J. & L.H.Stolzy 1964 I. Theory and Equipment for measuring ODR values. Hilgardia 35(20): 545-565.

Marshall, T.J. 1958 A relation between permeability and size distribution of pores. J. Soil. Sci. 9 (1): 1-8.

Mitchell, J.K. 1956 The fabric of natural clays and its relationship to engineering properties. Proc. Highway Res. Board 35, 693.

Oswalt, D.L., A.R.Bertrand & M.R.Teel 1959 Influence of nitrogen fertilisation and clipping on grass roots. Proc.Soil Sci. Soc. Am. 23: 228-230.

Plas, L. van der & A.C. Tobi | 1965 | A chart for judging the reliability of point counting results. Am.J.Sci. 263: 87-90.

Rickman, R.W., J.Letey & L.H.Stolzy | 1966 | Plant responses to oxygen supply and physical resistance in the root development. Proc. Soil Sci. Soc. Am. 30: 304-307.

Rosenberg, N.J. | 1964 | Response of plants to the physical effects of soil compaction. Adv. Agron. 16: 181-196.

Scheffer, F. & P. Schachtschabel | 1966 | Lehrbuch der Bodenkunde. Ferd. Enke Verlag. Stuttgart.

Sekera | 1951 | Gesunder und Kranker Boden. Paul Parey, Berlin.

Slager, S. | 1966 | Morphological studies of some cultivated soils. Thesis State Agricultural University, Agric. Res. Rep. 670.

Söhne, W. | 1958 | Fundamentals of pressure distribution and soil compaction under tractor tires. Agric. Engng, Lond. (May): 276-281.

Söhne, W. | 1955 | Die Verdichtbarkeit des Ackerbodens unter Berücksichtigung des Einflusses organischer Bestandteile. Z. Pfl. Ernähr. Düng. Bodenk.

Soil Survey Staff | 1962 | Soil Survey Manual USDA, Handbook 18, pp.503.

Stolzy, L.H., J. Letey, T.E. Szuskiewicz & D.R. Lunt | 1961 | Root growth and diffusion rates as functions of oxygen concentration. Proc. Soil Sci. Soc. Am. 25: 463-467.

Stolzy, L.H. & J. Letey | 1964 | III. Correlation of Plant Response to Soil Oxygen Diffusion Rates. Hilgardia 35 (20): 567-576.

Sunkel, R. | 1960 | Uber die Porosität von Bodenaggregaten. Z. Pfl. Ernähr. Düng. Bodenk. 89(134): 17-27.

Swanson, D.M. & J.B. Peterson | 1942 | The use of the micrometric and other methods for the evaluation of soil structure. Soil Sci. 53: 173-183.

Tacket, J.L. & R.W. Pearson | 1965 | Some characteristics of soil crusts formed by simulated rainfall. Soil. Sci. 99(6): 407-413.

Trouse, A.C. & L.D. Baver | 1962 | The effect of soil compaction on root development. Int. Soil Conf. N.Z. 258-263.

Vink, A.P.A. & E.J. van Zuilen | 1967 | De geschiktheid van de bodem van Nederland voor akker- en weidebouw. Toelichting bij de bodemgeschiktheidskaart 1:200.000, Stiboka, Wageningen, pp. 49.

Wiersum, L.K. 1957 The relationship of the size and rigidity of pores to their penetration by roots. Pl. Soil 9: 75-85.

Wiersum, L.K. 1962 Enkele beschouwingen betreffende de voorziening van de plant met stikstof en de opneming ervan. Landbouwk. Tijdschr. 74(14): 589-603.

Willet, J.R. 1962 Ongerijpte zandgronden en hun ontwatering. Tijdschrift der K.N.H.M. december.

APPENDIX I.

Description of Pedon B

Location: 477.77 N - 105.04 O; 4 m below sea level, about 8 m from tile drain. Described: 1-9-1966.

Map unit: Pgb on Soil Map Haarlemmermeer (Haans, 1954).

Parent material: level lake deposit in a 'polder', reclaimed in 1850.

Hydrology: watertable at 105 cm; the profile is well drained but mottling below the Ap indicates poor drainage before tile drains were laid 10 years ago (25 m apart).

Land use: wheat harvested two weeks before date of description leaving grass cover (green manure, applied for the first time).

Profile description:

Ap 0-30 cm sandy loam; moist dark gray to very dark gray (10 YR 3.5/1); apedal structure with dense angular fragments without very fine biopores and some interconnected fragments with locally irregularly rounded faces with few very fine biopores; firm; local concentrations of fine sand, sometimes stratified; few continuous very thin coatings along larger voids on fragments (10 YR 3/1); abrupt and smooth on;

C1g 30-43 cm sandy loam; moist; light brownish gray (2.5 Y 6/2); sponge structure with few very fine biopores; slightly firm; common medium distinct brown to dark brown (7.5 YR 4/4) iron mottles, chiefly along vertical root channels with a clear boundary; gradual and wavy on:

C2g 43-85 cm sandy loam; moist; 60% dark gray to light brown (10 YR 4/2) and 20% gray (5 Y 5/1); sponge structure with many very fine biopores; slightly plastic and sticky; common medium distinct brown to dark brown (7.5 YR 4/4) iron mottles at some distance along the larger vertical root channels. The inner part along channels is reduced; below 50 cm with many white shells; gradual and smooth on:

C3g >85 cm, perforated stratified sediments, with many white shells, varying in texture; sandy layers; non-sticky and non-plastic; clayey layers plastic and sticky; large prominent iron mottles at some distance along the larger vertical root channels

(2 per dm^2) with large reduced areas (up to 1 cm wide) around the channel itself. At 1.30 m a totally reduced blue layer is found, without roots.

Description of Pedon G.

Location: 483, 13N; 111.10 O; 4 m below sea level, about 8 m from tile drain. Described: 1-9-1968.

Map unit: Pgb on soil map Haarlemmermeer (Haans, 1952)

Parent material: as pedon B.

Hydrology: watertable at 100 cm, profile well drained but prominent mottling below Ap indicates poor drainage before tile drains were laid 20 years ago (they are 15 m apart).

Land use: after three-years with Lolium multiflorum wheat was sown which was harvested two weeks before the data of description; clover was growing as a green manure crop.

Profile description:

Ap_1 0-24 cm sandy loam; moist; very dark gray to very dark grayish brown (10 YR 3/1.5), when rubbed very dark grayish brown (10 YR 3/2); apedal structure; few dense fragments without very fine biopores, many rounded interconcected fragments with few very fine biopores; locally strong fine granular structure in pockets often concentrated around plant fragments; earthworms were present; about 4 large vertical wormholes >2 mm diameter per 20x20 cm^2; common local concentrations of fine sand particles, larger concentrations clearly stratified; few continuous very thin very dark grayish brown (10 YR 3/2) coatings on fragments along larger voids; friable, dense fragments: firm; clear and smooth on;

Ap_2 24-37 cm sandy loam; moist; very dark gray to very dark grayish brown (10 YR 3/1.5), when rubbed dark brown (10 YR 3/3); weak to moderate medium subangular blocky; common very fine biopores on ped faces; about 4 vertical worm tracks >2 mm diameter per 20x20 cm^2; firm; clear and smooth, locally broken on:

C_{1g} 37-64 cm sandy loam; moist; gray to olive gray (5 Y 5/1.5); sponge structure; common very fine biopores; upper 6 cm with weak medium platy structure; friable; many medium prominent vertically elongated and hardened reddish brown (5 YR 4/4) iron mottles along larger root channels; clear and broken on:

C_{2g} 64-86 cm sandy loam; wet; (5 Y 4/1); sponge structure with many very fine biopores; slightly plastic; slightly sticky; many medium vertical hardened brown to dark brown (7.5 YR 4/4) iron pipes around large root channels as in C_{1g}.

C_{3g} 86-95 cm stratified bands of sandy clayey material, partly disturbed; wet; (10 BG 4/); in disturbed parts: few very fine biopores; clayey bands very sticky and plastic; common dark yellowish brown (10 YR 4/4) iron pipes as in C_{1g}; gradual and wavy on:

C_{4g} >95 cm undisturbed stratification structures; texture and consistence as C_{3g}; (10 BG 4/1); no biopores; no iron mottles.

SOME PHYSICAL AND CHEMICAL DATA ON PEDONS B AND G.

	Particle size distribution										Analytical data			
	>420μ	300-420μ	210-300μ	150-210μ	105-150μ	75-105μ	50-75μ	16-50μ	2-16μ	<2μ	pH-H_2O	pH-$CaCl_2$	% org. matter	$CaCO_3$ %
Pedon B:														
Ap_1 0-20 cm	0.1	0.2	1.5	5.9	18.4	21.4	11.4	20.8	7.6	12.8	6.8	6.3	1.7	0.1
Ap_2 20-30 cm	0.2	0.2	1.6	6.3	19.0	22.2	10.1	21.4	6.1	12.9	6.8	6.4	1.4	0.1
C_{1g} 30-43 cm	0.1	0.7	5.1	15.7	25.8	19.6	8.1	12.6	3.1	9.2	7.7	7.0	0.6	1.2
C_{2g} 43-77 cm	0.1	0.9	4.3	12.7	23.1	23.2	9.8	14.0	2.6	9.3	7.9	7.3	0.4	9.0
Pedon G:														
Ap_1 0-8 cm	0.1	0.1	0.6	7.9	17.0	19.6	11.4	22.2	6.9	13.3	7.4	7.1	2.4	1.0
Ap_2 8-24 cm	0.3	0.1	0.7	7.8	18.2	19.3	12.3	22.0	6.3	13.0	7.3	7.0	2.2	0.8
Ap_3 24-37 cm	0.1	0.1	0.6	6.8	16.6	18.8	11.5	23.7	8.1	13.7	7.3	6.9	2.5	0.1
C_{1g} 37-64 cm	0.2	0.2	1.6	12.2	22.0	22.6	11.7	16.4	4.4	8.7	7.3	6.9	0.8	-
C_{2g} 64-86 cm	0.7	0.3	1.0	13.3	27.5	27.5	9.1	11.2	5.9	10.7	6.8	6.6	1.2	-

Some climatological data (de Bilt 1930-1960).

	J	F	M	A	M	J	J	A	S	O	N	D
Av. daily temp.(°C)	2.0	2.5	5.8	9.8	14.1	17.3	18.7	18.4	15.4	10.7	6.3	3.3
Av. daily max. temp. (°C)	4.3	5.3	9.5	13.4	17.8	20.9	22.1	21.9	19.2	14.1	8.9	5.4
Av. daily min. temp. (°C)	-0.8	-0.7	1.3	4.3	7.6	10.6	12.7	12.5	10.2	6.6	3.4	0.6
Av. precipitation (mm)	68.0	52.2	44.6	48.8	51.5	58.0	76.8	88.0	71.2	72.2	80.0	63.4
Evaporation free water surface (mm)	6	16	41	78	109	129	120	101	65	30	11	4
Largest daily precip. (mm)	12	6	12	27	30	52	31	25	32	7	25	30
Av. rel. humidity(%)	87	84	77	71	68	68	72	75	79	84	88	89

APPENDIX II.

Micromorphological description of pedon B (samples of August 1968)
(Terminology according to Brewer 1964)

Ap: plasmic fabric: skelsepic.
plasmic structure: brown gray plasma with common very fine (15 μm) light brown isotropic organic fragments and very fine opaque particles (normal light).
basic fabric: dominantly intertextic but also with granular and porphyroskelic parts in irregularly distributed patterns; granular fabric locally with some layers of varying sandy texture; very fine orthochannels and medium orthovughs.
pedological features: -few fragments (150-170 μm thick and up to some mm long) with recognizable soil fabric including silt and very fine sand particles, with a orientation pattern dominantly striated; containing common very fine light brown isotropic organic fragments and very fine opaque particles with irregular boundaries that penetrate partly into the surrounding s-matrix; the fragments do not border natural voids, they are locally surrounded by layers of clean skeleton grains: the fragments are pedorelicts, rests of plasma layers in the crust, that were mixed through the soil during ploughing.
-Few thin (100 μm) illuviation channel and fragment organo-argillans with a flecked, locally striated orientation pattern, with many very fine brown isotropic and opaque organic fragments; boundary sharp; also quasi organo-argillans are found.

C: plasmic fabric; silasepic or weak skelsepic
plasmic structure: gray plasma with a very high content of extremely fine carbonate particles
basic fabric: intertextic fabric dominant but also many granular parts in irregularly distributed patterns; with very fine orthochannels and many rounded carbonate grains that follow the mineral grain size distribution.
pedological features:-few fine (50 μm) illuviation channel argillans with moderate orientation, locally striated with irregular inner boundaries;
-common coarse (up to some mm) diffusion channel neo- and quasiferrans with diffuse boundaries;

- few coarse elongated fragments chiefly composed of extremely fine single carbonate crystals, some silt and very fine sandy skeleton grains; without organic particles.
  (These fragments are lithorelicts; remnants of bands in the original sedimentation pattern. Deeper in the C the amount increases).

Micromorphological description of pedon G (samples of August 1966)

Ap_1 plasmic fabric: skelsepic.

plasmic structure: brown gray, plasma with many very fine (15 µm) light brown isotropic organic fragments and very fine opaque particles (normal light); very fine diatoms.

basic fabric: dominant agglomeroplasmic tending to intertextic, also granular and porphyroskelic parts are found in irregular distributed patterns; the granular fabric often with thin sandy layers varying in texture over short distances; very fine orthochannels, medium orthovughs.

pedological features:-few medium (150-170 µm thick and up to some mm long) fragments with recognizable soil fabric, including few silt and sand grains; with a flecked and weakly striated orientation pattern, many very fine light brown isotropic organic fragments and very fine opaque particles; with irregular boundaries partly penetrating the s-matrix; not bordering any natural void (genesis as pedorelicts in the Ap of pedon B)

- Few fine (100 µm) dark brown illuviation channel and ped organo-argillans with a flecked, locally striated orientation pattern and a sharp boundary. Also quasi organo-argillans are found.

Ap_2 as Ap_1, but with few fine (30-60 µm) yellow illuviation channel argillans with a moderate orientation and a sharp boundary.

C plasmic fabric: locally silasepic or weakly skelsepic; basic fabric: intertextic s-matrix dominant, but also granular in irregular distribution patterns, with very fine orthochannels.

Pedological features: -common coarse (up to some mm) diffusion channel neo- and quasiferrans with a diffuse boundary;

- few fine (30 µm) illuviation channel argillans with a moderate orientation and irregular inner boundary;
- common coarse elongated or equant fragments with a masepic plasmic fabric; with some included fine skeleton grains with very few organic fragments
  (These fragments are lithorelicts; remnants of bands in the original sedimentation pattern).

Crusts on both pedons, developed during winter (Fig. 6 and 7)

The crust is composed of many thin layers, each with a very specific narrow granular composition. Thin silty layers alternate with thicker coarser grained ones. Also continuous layers are found (varying in thickness between 200 μ and 2 mm) dominantly composed of plasma with few included skeleton grains. The brown gray plasma has a flecked and locally striated orientation pattern. It contains many very fine lightbrown isotropic organic particles and opaque bodies, as well as diatoms. In the coarser textured bands common very fine (400 - 800 μ) vesicles are found.

Explanation of some micromorphological terms (according to Brewer 1964)

Plasma of a soil material is that part which is capable of being or has been moved, reorganized and/or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloïdal size and relatively soluble material which is not bound up in the skeleton grains (p. 12).

Skeleton grains of a soil material are individual grains which are relatively stable and not readily translocated, concentrated or reorganized by soil forming processes; they include mineral grains and resistant siliceous and organic bodies larger than colloïdal size (p. 12).

Soil structure: The physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves; fabric is the element of structure which deals with arrangement (p. 132).

A ped is an individual natural soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognizable as natural voids or by the occurrence of cutans (p. 138).

Pedological features: Recognizable units within the soil material which are distinguishable from the enclosing material for any reason such as origin, differences in concentration of some fraction of the plasma, or differences in arrangement of the constituents (p. 142).

S-matrix of a soil material is the material within the simplest (primary) peds, or composing apedal soil materials, in which the pedological features occur; it consists of the plasma skeleton grains and voids that do not occur in pedological features other than plasma separations (p. 147).

Plasmic fabric: The fabric of the plasma of the s-matrix, that is, the arrangement of the plasma grains and associated simple packing voids (p. 154).

One important type of plasmic fabric:

Skelsepic plasmic fabric: part of the plasma has a flecked orientation pattern, but plasma separations with striated orientation occur subcutanically to the surfaces of skeleton grains; the striated orientation of the plasma separations is dominantly parallel to the surfaces of the skeleton grain (plasma separations are embedded free grain neostrians).

Basic fabric: The fabric of the s-matrix, that is, the arrangement of simple grains (plasma and skeleton grains) and voids in primary peds or apedal soil material, excluding pedological features other than plasma separations (p. 154).

Some types of basic fabrics (p. 320):

Granular fabric: with simple packing voids between skeleton grains, but other kinds of associated voids can occur.

Porphyroskelic fabric: with a relatively high proportion of ultra-microscopic voids.

Agglomeroplasmic fabric: within the plasma a relatively high proportion of small interconnected vughs.

Intertextic fabric: plasma occurs as bridges between the skeleton grains, the void pattern forms an extreme development of interconnected vughs.

Cutan: A modification of the texture, structure or fabric at natural surfaces in soil material due to concentration of particular soil constituents or in situ modification of the plasma; cutans can be composed of any of the component substances of the soil material (p. 206).

Argillans: cutans, composed of clay minerals.

APPENDIX III.

Permeability (K) of saturated soil estimated in natural undisturbed field samples taken from 3 or 4 places in each soil layer, calculated in cm per day from K = 1440 Q / {At(P/L)}.

(Hydraulic Head = 2.5 cm)

August 1966

B	12-17 cm	22-27 cm	31-36 cm	51-56 cm
	18	150	18	54
	18	30	18	90
	420	15	33	18
		141	36	

G	1-6 cm	15-20 cm	26-31 cm(Ap_2)	38-43 cm	58-63 cm
	273	660	90	90	210
	36	720	60	105	195
	36	690	168	54	1020

December 1966

G	crust
	90
	90
	102
	226

March 1967

B	5-10 cm	12-17 cm	22-27 cm	35-40 cm	45-50 cm	60-65 cm	crust
	6	6	6	18	30	87	100
	0	0	24	10	30	18	150
	18	12	36	24	33	12	270
	3	4	3	74	69	12	

	5-10 cm	15-20 cm	26-31 cm(Ap_2)	33-38 cm	45-50 cm	60-65 cm
	1140	2100	60	18	2220	4380
	1530	360	15	49	1860	144
	420	360	60	43	1500	18
	90	780	300	870	18	2310

November 1967

B	5-10 cm	12-17 cm	22-27 cm
	210	75	24
	75	54	30
	30	126	21

G	type III	type IV
	6	360
	3	270
	0	480

December 1967

B	5-10 cm	12-17 cm	22-27 cm
	240	30	54
	72	432	44
	39	72	22
	402	96	24

G	5-10 cm	12-17 cm
	258	1050
	411	9
	600	3
	18	231