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Soil physical properties related to soil structure

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Abstract

The aim of this paper is to clarify the effect of soil aggregation on soil physical and chemical properties of structured soils both on a bulk soil scale, for single aggregates, as well as for homogenized material. Aggregate formation and aggregate strength depend on swelling and shrinkage processes and on biological activity and kinds of organic exudates as well as on the intensity, number and time of swelling and drying events. Such aggregates are, most of all, more dense than the aggregated bulk soil. The intra-aggregate pore distribution consists not only of finer pores but these are also more tortuous. Thus, water fluxes in aggregated soils are mostly multidimensional and the corresponding water fluxes in the intra-aggregate pore system are much smaller. Furthermore, ion transport by mass flow as well as by diffusion are delayed, whereby the length of the flow path in such tortuous finer pores further retards chemical exchange processes. The chemical composition of the percolating soil solution differs even more from that of the corresponding homogenized material the stronger and denser the aggregates are.

The rearrangement of particles by aggregate formation also induces an increased apparent thermal diffusivity as compared with the homogenized material. The aggregate formation also affects the aeration and the gaseous composition of the intra-aggregate pore space. Depending on the kind and intensity of aggregation, the intra-aggregate pores can be completely anoxic, while the inter-aggregate pores are already completely aerated. The higher the amount of dissolved organic carbon in the percolating soil solution, the more pronounced is the difference between the gaseous composition in the inter- and in the intra-aggregate pore system.

From the mechanical point of view, the strength of single aggregates, determined as the angle of internal friction and cohesion, depends on the number of contact points or the forces, which can be transmitted at each single contact point. The more structured soils are, the higher the proportion of the effective stress on total stress is, but even in single aggregates positive pore water pressure values can be revealed. Dynamic forces e.g. due to wheeling and/or slip processes can affect the pore system as well as the composition of the soil by: (1) a rearrangement of single aggregates in the existing inter-aggregate pore system

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resulting in an increased bulk density and a less aerated and less rootable soil volume, (2) a complete homogenization, i.e. aggregate deterioration due to shearing. Thus, the smaller texture dependent soil strength coincides with a more intensive soil compaction due to loading. (3) Aggregate deterioration due to shearing results in a complete homogenization, if excess soil water is available owing to kneading as soon as the octahedral shear stresses and the mean normal stresses exceed the stress state defined by the Mohr–Coulomb failure line. Consequently, normal shrinkage processes start again.

Thus, the rearrangement of particles and the formation of well defined single aggregates even at the same bulk density of the bulk soil both affect, to a great extent, various ecological parameters. Environmental aspects can also be correlated, or at least explained with the processes in soils, as a major compartment of terrestrial ecosystems, if the physical and chemical properties of the structure elements and their composition in the bulk soil are understood.

Keywords: Aggregate formation; Soil structure; Hydraulic process; Chemical property; Soil aeration; Mechanical effect

1. Introduction

As long as 100 years ago, Wollny (1898) described the positive effect of soil structure on root growth, water availability, gas transport in soils as well as the positive effects of soil structure on soil strength. He mentioned that the mechanisms involved in the interaction between soil structure and plant growth and yield need to be investigated. Since then, the positive effects of a favourable soil structure and negative effects of e.g. soil compaction on crop growth and/or yield have been repeatedly described (e.g. Blank, 1932–1939; Dexter, 1988; Håkansson et al., 1988; Kay, 1990). Although it was often speculated why crops respond favourably to good soil structure, reasonable experiments to convince both farmers and scientists are up to now rather rare, even if not only texture dependent parameters and bulk density data but mainly structure dependent data were included. Emmerson et al. (1978) pointed out interactions between soil structure, water status of structured soils, as well as soil aeration and root growth expressed as rootability and/or compressibility of arable land. How far soil structure may affect root growth as well as ion transport e.g. intro- and extro-directed iron and manganese movement as a function of pore systems, water saturation and redox reactions, can also be derived from data published by Blume (1968). Thus, Dexter (1988) defined soil structure as "the spatial heterogeneity of the different components or properties of soil" at various scales. Bouma (1990) amongst others has repeatedly pointed out that not only the determination of the amount and diameter of pores but also the function and the distribution of solid phase and pores as well as their connection define the ecologically important soil properties. This is especially true with respect to the accessibility of the particle surfaces to water, ions and gases.

Thus in the following, the present state of knowledge on aggregate and structure processes and properties is summarized as far as the literature available allows and fitted in the broader picture of ISTRO's interests. However, those papers which only deal with bulk density dependent changes in physical and chemical

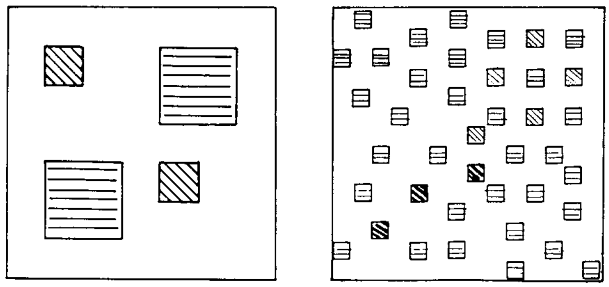


Fig. 1. Arrangements of particles in an area at constant mass per volume expressed for various stages of aggregation and its effect on the remaining pore space (schematic diagram). In the left picture, the same mass per volume is shown as in the right one, but the mineral particles are differently arranged. By adding the third dimension the soil volume can be described.

properties will not be included because of a too weak correlation to soil structure dependent properties. This is true because the bulk density value only relates properties of a certain soil mass per volume but does not consider the arrangement of the particles in such a volume (Fig. 1). These are mainly the interest for ecological and thus environmental discussions.

2. Aggregate formation processes

In soils containing more than 15% clay (particle size <2 μm), the mineral particles (sand, silt and clay) tend to form structured units known as aggregates. This process usually occurs when soils dry and swell but also occurs because of biological activities (Hillel, 1980; McKenzie, 1988; Anderson, 1991; Wolters, 1991). Aggregates may vary greatly in size from crumbs (diameter <2 mm), to polyhedres or subangular blocks (0.005–0.02 m), even to prisms and columns with a diameter larger than 0.1 m. During the first period of shrinkage of moulded soil, mineral particles will be tied together by capillary forces resulting in an increase in the number of contact points and in a higher aggregate bulk density as well as higher penetration resistance (Horn et al., 1989; Becher 1992). Aggregates are either sharp-edged and formed as rectangular volumes or they are defined by non-rectangular shear plains (Hartge and Horn, 1977; Hartge and Rathe, 1983; Babel et al., 1994). Consequently, the inter-aggregate pore system in structured soils also differs with respect to pore diameter, continuity and number if compared with the bulk soil. In aggregates of the first generation, the number of contact points depends on the range of applied pore water pressure and on the distribution of particle size as well as on the mobility of the particles (i.e. state of dispersion, flocculation and cementation).

Thus, soil shrinkage including crack formation first increases the bulk density of aggregates by forming only a few very wide inter-aggregate cracks. Because of particle rearrangement during consecutive swelling and drying and depending on the degree of soil wetness, aggregate bulk density may decline again but the aggregate strength increases at the same moment (Fig. 2). Furthermore, the more intensively soils are dried and the more often they are swollen, the smaller the aggregate diameter becomes. Also the intra-aggregate pores become coarser and the hydraulic conductivity–pore water pressure function can be classified as macroscopic homogeneous (Horn, 1994b). Depending on the chemical composition of the water menisci at the transition of the liquid to the gaseous phase, a further increase in aggregate strength can be postulated owing to increased viscosity and surface tension forces.

As it is well known for seedbeds, structure properties are always in a dynamic equilibrium both with respect to pore water pressure dependent changes of normal and residual shrinkage behaviour of clods and with respect to freezing and thawing i.e. soil curing (Schababerle, 1989). Furthermore, pore water menisci forces induce an outer clay skin and an accumulation of silt and sand inside the aggregates. The diameter of aggregates and their strength are furthermore affected even by single particles, which increased the total area of water menisci and reduced the diameter of the newly formed pores at the same time (Zhang, 1991). Aggregation was also enhanced by biological and chemical processes such as flocculation and cementation by organo-minerallic bondings (Dexter et al., 1988; Haynes and Swift, 1990; Helal, 1991). In the latter processes, polysaccharides and organic acids have to be considered as well (Hempfling et al., 1990). Aggregate stabilization by extracellular metabolic products of colonies of bacteria and by root exudates has been demonstrated. The effects may be reactions at the contact points of mineral particles (Martin, 1977; Cheshire, 1979; Goss and Reid, 1979; Tippkötter, 1988). Hydrophobization may also result in an increase in aggregate strength because of the theoretical strength decline as a result of greater

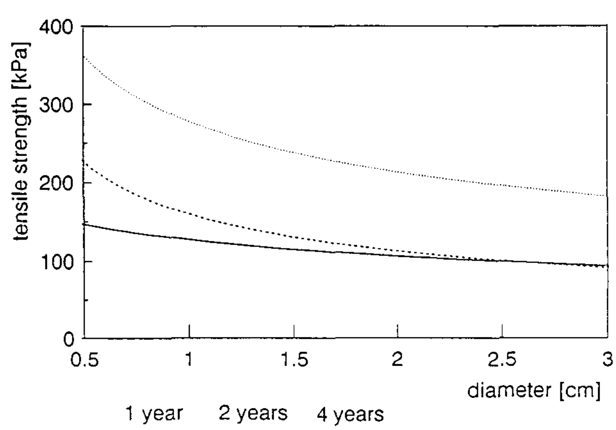


Fig. 2. Changes in aggregate tensile strength with time as a function of the aggregate diameter. The aggregates were only formed by wetting and drying cycles out of completely homogenized loess under well defined hydrological conditions (lysimeter experiment, Avdat, Israel).

pore water pressure during infiltration being prohibited (Sullivan, 1990). This is also in accordance with Taylor and Jaffé (1990) who pointed out that the water permeability in single aggregates was intensely reduced when various types of bacteria grew at the aggregate surface skin.

Thus, soil structure formation by shrinkage and swelling resulted in the well known heterogenization of the pore size distribution in the bulk soil (macroscale) owing to the formation of coarser inter-aggregate pores and finer intra-aggregate pores (microscale). Because of the higher bulk density value or the increased shear strength per contact point, aggregates always exhibit a higher mechanical strength than the bulk soil (Horn et al., 1987; Semmel et al., 1990). Moreover, the stronger outer skin of aggregates may have minor areas of increased weakness (Becher, 1992). The latter can be taken as an indicator of further microaggregate cracking (plains of weakness), or as an index of partial rooting, the existence of earthworm channels and of variations in grain size distribution.

Thus, aggregate strength will depend on: (a) capillary forces, (b) intensity of shrinkage (normal/residual), (c) number of swelling and shrinkage cycles, (d) mineral particle mobility i.e. rearrangement of particles in order to reach the status of lowest free energy, (e) bonding energy between particles in/or between aggregates or in the bulk soil, (f) biological activity and (g) chemical composition of the soil solution and of the organic components.

3. Hydraulic properties and processes

3.1. Water retention curve

Aggregation, as a result of swelling and shrinking, is dominated by hydrological and hydraulic properties of soils. By increasing the number of drying cycles, the total porosity first decreases and may later increase again (Horn and Dexter, 1989). The volume of fine pores (i.e. the volumetric water content at pF$>$4.2) is enhanced by decreasing drying intensity. In addition, the amount of plant available water (i.e. water content at a pF range from 1.8 to 4.2) decreases as the intensity of soil aggregation increases (Fig. 3). Only at a more negative pore water pressure the air entry value is exceeded, depending on how wet the soil had been kept (Horn et al., 1989). The latter effect is derived by the corresponding steep slope of the pF/water content curve at pF $-\infty$ to 1.8.

3.2. Hydraulic conductivity

Given a laminar flow, no Bingham flux behaviour and a homogeneous pore system, the water flux q ($m^3\ m^{-2}\ s^{-1}$) in soils can be quantified by Darcy's law assuming one dimensional fluxes. Values of the hydraulic conductivity range between 10^{-4} m s^{-1} and 10^{-9} m s^{-1} depending on water potential, texture and structure. Under saturated conditions, hydraulic conductivities range between 10^{-4} and 10^{-5} m s^{-1} in a sandy soil and between 10^{-6} and 10^{-9} m s^{-1} in a clay soil. Since the hydraulic conductivity is also affected by structure and texture it

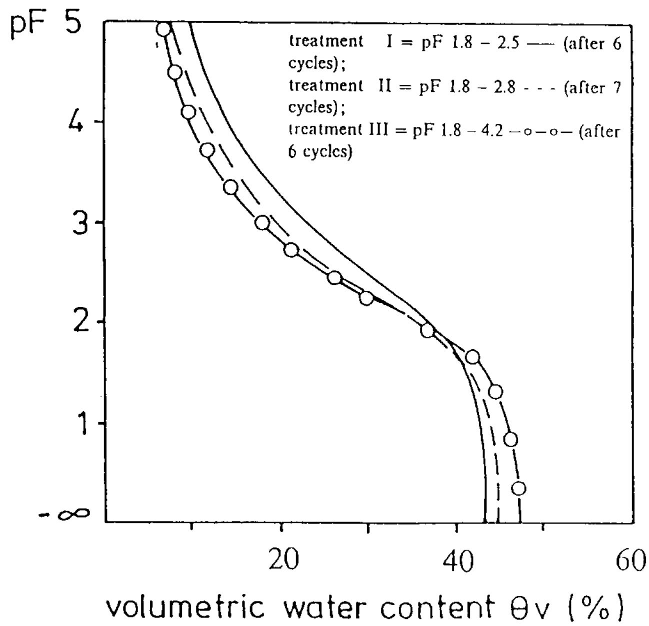


Fig. 3. Effect of drying intensity on changes in the water retention curve. (The volume of fine pores is more enhanced when the drying intensity had been small.)

will be higher, if the soil is highly porous, fractured or aggregated, than if it is tightly compacted and dense. The hydraulic conductivity value (k) not only depends on the pore volume but also on the continuity of conducting pores. In structured soils with very large cracks, the k value for the bulk soil increases, while flow velocity is strongly reduced inside the single aggregates (Horn, 1990). Depending on the aggregate density and pore continuity, the k value may decrease by 4 orders of magnitude in single aggregates as compared with the bulk soil, unless the same kind of aggregate contains more sand than silt and clay in which case there is no difference compared with the bulk soil. The effects of structure on hydraulic conductivity persist under unsaturated conditions. Also in this case, the kind of structure changes directly affects the intensity of variation of the hydraulic conductivity (Fig. 4). At less negative values of pore water pressure, the unsaturated hydraulic conductivity in single aggregates decreases with the compaction of the structural elements (prisms less than polyhedres or subangular blocks) compared with fluxes in bulk soil. Only in weak aggregates, differences and ranges are smaller (Gunzelmann et al., 1987). After exceeding the cross over suction values at very negative pore water pressure values (Hillel, 1980), higher values of hydraulic conductivity are obtained in aggregates compared with bulk soil if related to different sample area. This heterogenization of the flow paths in aggregates compared with the bulk soil is further enhanced, since the outer skin of aggregates contains more clay than the centre, and the latter has more coarse pores than the outer part (Horn, 1987). Consequently, water and/or air flow in

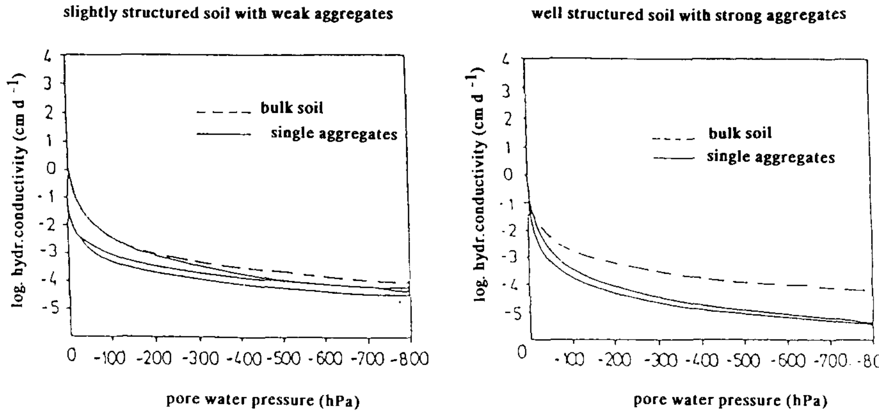


Fig. 4. Hydraulic conductivity (cm d^{-1}) as a function of pore water pressure (hPa) in a slightly structured soil with weak aggregates and in a well-structured soil with strong aggregates.

or out of single aggregates is further delayed what can also be derived from the variation in tortuosity of the pore system at different positions in the aggregate (Glinski and Stepniewski, 1985; Glasby et al., 1991)

3.3. Hydraulic, gradient and water flux density

Generally, the values of the hydraulic gradient (m m^{-1}) vary only by half an order of magnitude, depending on pore water pressure, grain and pore size distribution (Hartge and Horn, 1977). If the soil-plant interaction is also taken into account, values of hydraulic gradients of up to 9000 can be calculated, if water content differences are expressed as pF at a given time and assuming a constant water retention curve (Bohne, 1988). Those differences in hydraulic gradients should be greater in aggregated dense soils and in soils with conservation tillage systems at least at the beginning of the treatment changes and may also result in a reduced plant water uptake efficiency. Thus, in order to improve the rhizosphere properties, differences in root length density can be detected, which again can be correlated with hydraulic properties (Vetterlein and Marschner, 1993).

The greater the differences between the hydraulic properties of the bulk soil and of the single structure elements are, the more pronounced is the fluid flow in inter-aggregate pores and the smaller the possibility of an equilibrated pore water pressure profile . Pore continuity in macropores and a more tortuous pore system in single aggregates induce preferential flow especially near water saturation (Beven and Germann, 1982). Youngs and Leeds-Harrison (1990) described the various types of transport processes in structured soils. They pointed out that a pore water pressure gradient causes water to flow preferentially in the macropores with little flow within the aggregates when both the macropores (i.e. inter-aggregate) and micropores inside the aggregates are saturated. However, when macropores full of water surround unsaturated aggregates, solutes will be transported by diffusion into or out of the aggregates depending on the concentration gradient. If the macropores are empty the pores inside the aggregates become isolated so that redistribution of water and solutes occurs only within the aggregates with very little transport of water and solute between them. Booltink and Bouma (1991), Edwards et al. (1993), Dunn and Phillips (1991), Ghodrati and Jury (1990) and Tolchel'nikov et al. (1991) described the preferential flow in structured soils and showed that the hydraulic properties determined for the bulk soil do not coincide with or explain terms like pore continuity and/or pore accessibility with respect to water flux. How to determine macropore and intra-aggregate fluxes is discussed e.g. by Gunzelmann (1990), Gunzelmann et al. (1987), Plagge (1991), Grant et al. (1991), Singh et al. (1991), Jardine et al. (1990), Andreini and Steenhuis (1990) and Kung (1990a,b). Textbooks like those of Dullien (1979), Jury et al. (1991) and Nielsen and Kutilek (1993) deal with the effect of soil aggregation in structured soils on changes in the hydraulic properties. An open question, up to now, deals with the simultaneous determination of fluid water, water vapour and heat transport in bulk soils and single aggregates (Philip and De Vries, 1957; Yang and White, 1990). The effect of structure on these parameters is seldom discussed. Bach (1992) described soil water movement in response to temperature gradients.

4. Chemical properties and processes

Brusseau and Rao (1990) reviewed the effect of soil structure on solute transport and pointed out that the transport in aggregated soils is often characterized by non-ideal phenomena. These phenomena will be usually ascribed to the presence of immobile domains within the porous medium, which again influence the dynamics of physical processes.

4.1. Ion transport

The ion transport rate J (mmol m^{-2} day^{-1}) in soils includes the mass flow and diffusion for both the liquid and solid phases and it also considers the sink and source term in order to define and to quantify chemical exchange processes, ion precipitation, inclusive redox reactions and biological decay processes (Beese, 1982). In general, assuming a Taylor solute flow pattern in pores, the water flow near the particle surface is retarded if compared with that in the pore centre because the soil solution becomes more viscous with decreasing distance to particle surfaces. Consequently, the finer the pores are, the more deprived is the ion diffusion in the liquid phase. With increasing tortuosity (impedance factor f) of the pore system, the ion concentration gradient is further reduced. Thus, this parameter depends on both the volume and the geometry of the water pathway. In unsaturated soils with a high clay content, the f factor is further affected by reduced thickness of the water films coating particles, the increasing density of exchangeable cations adsorbed to clay surfaces, the corresponding exclusion of anions and an increase in viscosity of the liquid on diffusion.

4.2. Structure effect on ion exchange and transport

The inter- and intra-aggregate pore system affects both the accessiblity of exchange places and ion adsorption as well as desorption. Convective ion transport (e.g. of calcium and magnesium) is much smaller in single aggregates (polyhedres, texture: clayey loam) compared with bulk soil and especially compared with the homogenized material for a constant amount of water (Horn et al., 1989). Ion diffusion out of single aggregates is reduced compared with the bulk soil at a given time because: (1) the bulk density of single aggregates is greater than that of the bulk soil, (2) the ratio of directly accessible reaction sites represented by the sample outer surface to the sample mass increases with decreasing aggregate diameter, assuming a spherical aggregate shape, (3) flow length increases with aggregate size and (4) the average pore size and the pore continuity in single aggregates is much smaller owing to a higher clay content at the outer skin.

In general, the soil solution percolated through undisturbed soil samples always contains more cation acids as if it was in contact with homogenized material, as long as soils are structured. The more pronounced the macroporosity, the greater the differences. The less structured and/or the less saturated the soils, the smaller those differences are. However, even in less aggregated soils under unsaturated conditions, results could never be obtained that were comparable to those of the equilibrium soil solution (Hantschel et al., 1988; Kaupenjohann, 1991).

This principle chemical disequilibrium was also verified by Hantschel and Pfirrmann (1990) under in situ conditions. They found that the base saturation of equilibrium soil solution of forest soils was significantly higher compared with the aggregated soil samples for all investigated undisturbed soils that released essentially aluminum and protons during percolation. Taubner (1993) showed, in percolation experiments with acids, that the soil solution of single aggregates contains less protons and more basic cations than the corresponding solution in the inter-aggregate pores of the bulk soil. Those differences are more pronounced the more structured soils are, and the higher the clay content is. Such imbalances are also true for the chemical composition of the exchange sites at the different positions in the aggregate compared with those of the bulk soil. In general, aluminum and protons are enriched at the outer skin of aggregates, while in the centre the base saturation is increased.

How far ion diffusion is affected by the accessibility of the particle surfaces inside the aggregates, as well as by the concentration gradient between the chemical composition of the soil bathing solution or e.g. percolating rainwater and the ion concentration of the soil itself has been described by Horn and Taubner

(1989). In their experiments to determine cumulative potassium release rates out of single aggregates (polyhedres; texture: loamy clay) of structured bulk soil and of homogenized soil material (<2 mm) under saturated conditions, the release rates per mass unit of soil were the highest for the homogenized material (Fig. 5). In aggregates, however, release of potassium from internal reaction sites was retarded. The larger the aggregates, the smaller the release rates were at a given bathing solution. Bhadoria et al. (1991a,b) further quantified the impedance factor *f* for chloride diffusion in soils as affected by bulk density and water content. An increase in bulk density from 1.38 to 1.76 Mg m^{-3} at a constant gravimetric moisture content of 7% decreased *f* by a factor of 3, while at a water content greater than 10%, *f* increased linearily with increasing bulk density.

Palma et al. (1984), Schulin et al. (1986), Hildebrand (1988), Gisi et al. (1990), Augustin (1992), Chen and Wagenet (1992), and Buchter et al. (1992) defined the consequences of such chemical disequilibrium for ecosystem modelling approaches, whereby especially Augustin (1992) also considered the microbiological differentiation at the various positions inside the aggregate for complexation and exchange processes. The chemical composition of the accessible exchange places gives an explanation for the frequently measured drastic decline of the pH value in the ground water because of macropore fluxes (Kaupenjohann and Fischer, 1989).

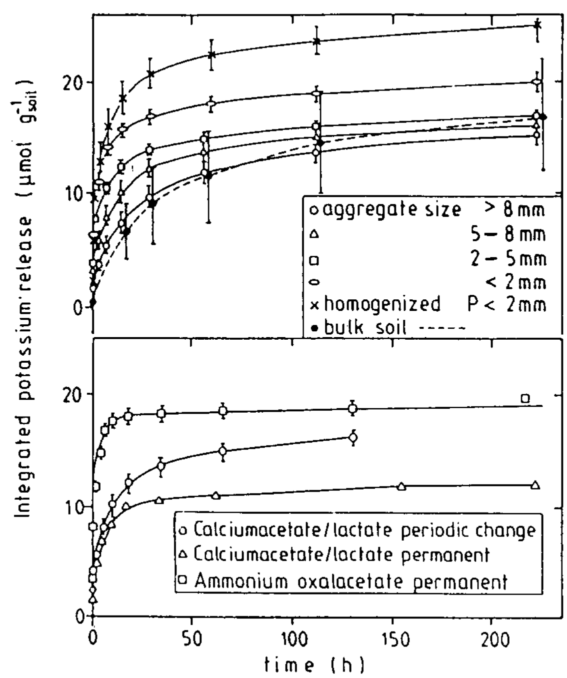


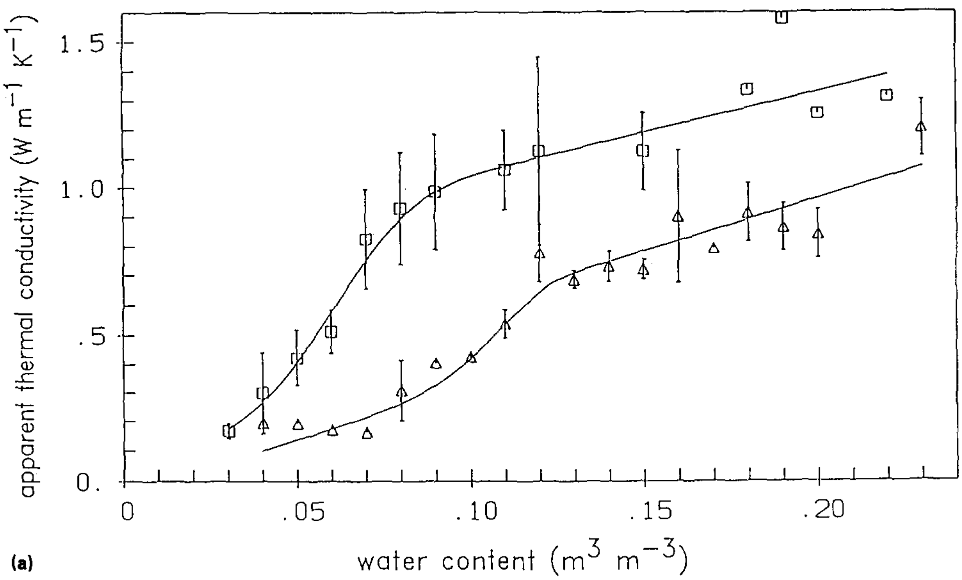
Fig. 5. K release of different soil aggregates and bulk soil into different bathing solutions as a function of time.

5. Thermal properties

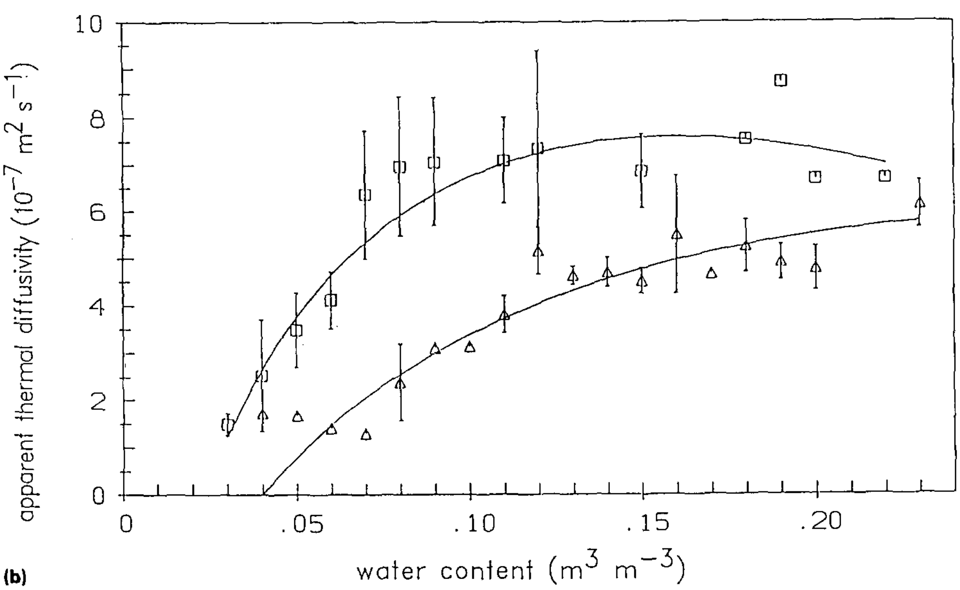
Owing to changes in the number of particles per aggregate volume and because of variations in the particle arrangement, the number of particle contact points and the degree of water saturation at a given pore water pressure both change the thermal properties of structured soils. Johnson and Lowery (1985) calculated the thermal diffusivity values for soils with different structures and found a 15–20% increase in thermal diffusivity in no-till sites as compared with continuously ploughed soil layers. Hay et al. (1978) found that, in no-tilled soil, the thermal diffusivity was significantly higher than in the seedbed. Wierenga et al. (1982) also pointed out the positive effect of soil structure on thermal properties. In order to quantify the effect of aggregate formation on thermal properties, Kaune et al. (1993) determined those changes in lysimeters with homogenized and hydraulically well controlled restructured loess by measuring temperature gradients. The results were modelled by a Fourier series and were fitted assuming a one-dimensional non-stationary heat transport in soils (Horton et al., 1983). Aggregation by swelling and shrinkage increased the thermal conductivity as well as the water content dependent heat conductivity (Fig. 6(a), (b)). Heat flow depended not only on the continuity of contact points (conductance), but also on the continuity of water filled pores. This is especially true for the finer intra-aggregate pores in which the ionic strength is comparably higher than in the macropores. Consequently these soil volumes support fluid water and ion fluxes up to a deeper soil temperature although the water in coarser pores is already frozen (Hartge and Horn, 1991; Nassar and Horton, 1992a,b) The combined heat and water transport was also described by Ouyang and Boersma (1992) who included the inter-relationship to gas flow and consumption. However, the effects of temperature on the surface tension of water at the various positions in structured soils, as well as the temperature dependency of hydraulic properties and the effect on gas inclusion and/or degasing, are still open and unsolved questions.

6. Soil aeration

In general, soil aeration is governed by two processes, namely (a) transport of oxygen from the atmosphere into the soil (atmospheric air contains, by volume, 20.5% O_2 and soil air 0%–20%), and (b) consumption of oxygen by biological respiration or by chemical reactions. Enhancement of gas transport in the soil occurs both as a mass flow along a pressure gradient and as diffusional flow with a concentration gradient in air-filled pores. As for water, gas transport phenomena in soils also include the problem of pore size distribution, pore continuity and water saturation (Scheffer and Schachtschabel, 1992). Currie (1965) described gas transport in aggregated soils and dealt with the problem of a bimodal pore system on gas exchange processes in soils. He pointed out that soils with a highly developed natural aggregation should have distinct zones of aggregated or crumb pores, separated by a more continuous system of inter-aggregate pores.



(a)



(b)

Fig. 6. Apparent thermal conductivity (a) and apparent thermal diffusivity (b) in disturbed (△) and in structured (□) loess as a function of water content ($m^3\ m^{-3}$).

Gas transport in soil profiles will occur preferentially through this inter-aggregate pore system formed by macropores (Flühler et al., 1976; Kirkham, 1986; Rolston, 1986a,b; Paul and Werner, 1986; Hodgson and MacLeod, 1989a,b; Gupta et al., 1989). Additionally, oxygen diffusion to sinks (respiration by soil micro-organisms) in the intra-aggregate pores is induced by the concentration gradient and would require further O_2 fluxes (Alef and Kleiner, 1986; Augustin, 1992). Provided that the oxygen demand within soil aggregates is high and O_2 diffusion limited because of (a) partial or complete water saturation within the aggregates, and (b) low pore continuity, anaerobic zones should exist inside single aggregates even if the inter-aggregate pore space contains sufficient oxygen.

6.1. Effect of texture on gas transport

Effects of soil texture on gas transport and on the composition of soil air in artificial (textured) aggregates reveal a strong correlation with the pore size distribution and with the air entry value. The coarser the pores and the less tortuous they are, the greater is the oxygen concentration at a given pore water pressure. However, as soon as only a small discontinuity in the pore system exists, the O_2 concentration is intensely reduced. Thus the higher the clay content, the smaller is the O_2 concentration at a given water content and bulk density. In fine-textured artificial aggregates of constant diameter of an A horizon (soil type: Udert derived from "Amaltheenton") e.g. oxygen diffusion was severely restricted at a given pore water pressure of -4 kPa, while an increase in sand resulted in an oxygen content increase even at a higher pore water pressure (Zausig et al., 1993).

6.2. The effect of soil structure on aeration

Soil structure always includes the creation of secondary coarser pores and the formation of finer intra-aggregate pores. This results in a heterogenization of the pore system and of the texture within the aggregates which strongly affects transport phenomena. The more aggregated soils are at a distinct texture, the smaller is the O_2 concentration up to more negative pore water pressure values. Aggregates with higher amounts of coarser pores and a more sandy structure are aerated at already less negative pore water pressure values. Greenwood and Goodman (1967), Smith (1980), Sextone et al. (1985), and Stepniewski et al. (1991) stated that O_2 gradients inside single aggregates appeared to be steeper in rolled or disturbed aggregates because of a more pronounced pore tortuosity. Alef and Kleiner (1986) pointed out that microbes were mainly concentrated at the aggregate surface which could result in a further O_2 consumption, if organic carbon is available. Several authors described an accumulation of organic substances at the surface of soil aggregates owing to: (a) the flux of dissolved organic carbon in the coarse pores, (b) a dominating root growth and following decay processes in that area and (c) the excretion of organic material by animals (Allison, 1968; Hattori, 1988; Christensen et al., 1990; Augustin and Beese, 1991; Augustin, 1992). Thus, spatial heterogeneity in soils also occurs as a consequence of the inhomogeneous distribution of microbial populations and of organic substances.

In particular, aggregates of the subsoil horizons fulfill these conditions. They are predominantly coated with dissolved organic carbon at the outer skin (pore walls) which is then translocated down to deeper layers by rain water infiltrating the macropore system. Because the amount of microbes is smaller in deeper soil horizons as compared with the seedbed and because they are mainly concentrated at the surface (Hattori, 1988) the O_2 concentration inside the aggregates declines only to a smaller extent even if watered to -2 kPa pore water pressure. Biogenic aggregate formation in the A horizons leads to intensive mixing of organic material with mineral soil particles. Thus in surface horizons microorganisms are equally distributed over the entire volume of loose and porous aggregates. Aerobic microbial activity would cause oxygen depletion all over the aggregates. Anoxic aggregate centres would be developed, where facultative anaerobe microorganisms become dominant (Horn et al., 1994b).

Significant amounts of decomposible organic substances may induce severe decreases in redox potential values in a short time after a saturation with water. Thus, in humic A horizons the redox potential values drop rapidly during wetting, while in subsurface horizons with low contents of organic substances only slow redox potential changes with low intensity occur. For example, if artificial aggregates were prepared from soil material of a Bg horizon (0.3% organic carbon) almost every change of the oxygen partial pressure could be measured during one week of saturation at a temperature of 20°C. However, adding peat soil extract or sucrose solution (10%) during aggregate production caused the redox potential to decrease within only 2 days and created an anoxic zone with a thickness of as large as 16mm (Zausig and Horn, 1991). The intensity and speed of redox potential changes do not only depend on the content of organic matter but also on the buffering capacity. Clayey soils show less intensive changes of redox potential than silty soils. The most severe decrease of redox potential occured in aggregates with sandy texture. One of the first substances that will be used as an electron acceptor by anaerobic microorganisms is nitrate-N. Already 12 h after saturating aggregates, made from N- and C-enriched soil material equilibrated to -0.5 kPa soil water pressure, denitrification was observed even in aggregates of 2mm diameter (Fig. 7).

Larger aggregates had greater anoxic volumes and thus the amount of denitrified N increased. Also the type of microorganisms differed between the inner and outer part of the aggregates. In the outer skin aerobes did exist, while in the centre denitrifiers dominated (Horn et al., 1994b). Although there are only very few data in the literature concerning N_2O gas release independent of the tillage system (see Logan et al., 1987), a more general first assumption about the possible N_2O release from soils should be made based on the composition of the pore system and on the kind of aggregates. Assuming an average water content, very fine aggregates in the tilth of conventionally ploughed soils encourage more N_2O release just after the seedbed preparation. This can be explained by a high amount of organic substances and nitrogen, the short distance to the atmosphere, which prevents a further reduction to N_2, a more tortuous inter-aggregate pore system and only a few but often smeared intra-aggregate fine pores. Later on, soil settlement and additional reaggregation by swelling and shrinkage and by microorganisms create more dense aggregates which are especially susceptible to N_2O production. Furthermore in the ploughpan as well as in the deeper mechanically

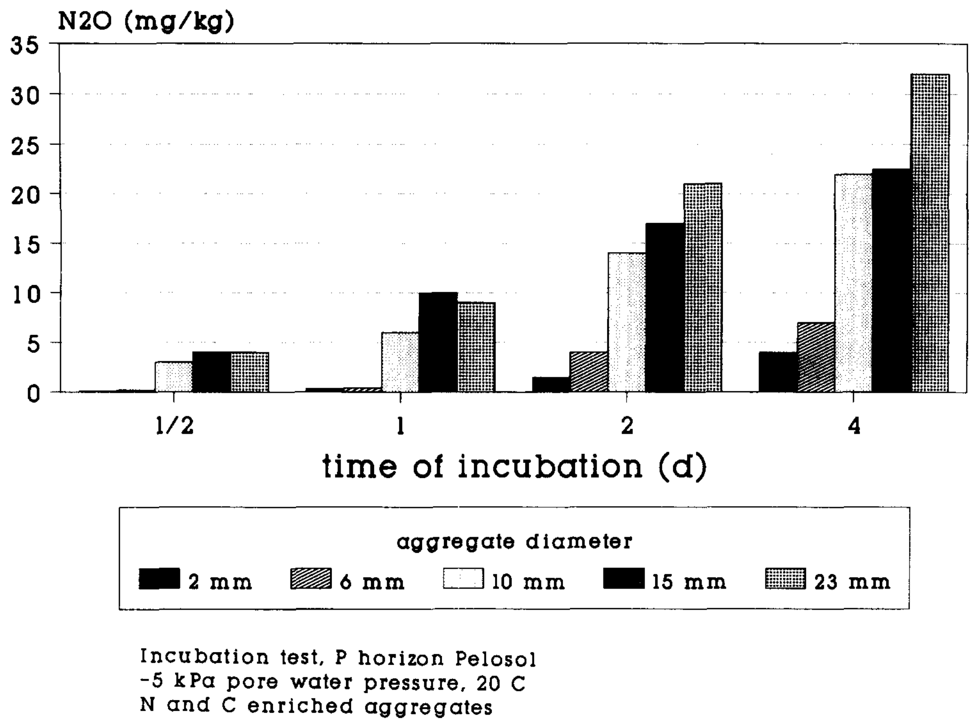


Fig. 7. Denitrification rate in single aggregates as a function of time of incubation, aggregate diameter for N and C enriched artificial aggregates.

stressed soil horizons, a more pronounced N_2O production could also occur which, however, in the case of very small Eh values could be even transformed to N_2 which would not be harmful. In soils with long term reduced or no-till systems, the theoretically higher N_2O production in the more dense aggregates during a transition time of several years should have been diminished later again owing to the better oxygen supply to the intra-aggregate pore system after the more pronounced rearrangement of the soil particles. The latter effect results in smaller aggregate bulk density values too.

7. Mechanical properties and processes

7.1. Effect of aggregate strength on bulk soil strength and on stress distribution

It is well known that if soils are loaded, only the air-filled and water-filled soil volumes are affected, both with respect to a total volume reduction and/or to changes in the pore size distribution and water saturation. The extent of soil deformation at a given stress depends on soil strength, particle mobility and rearrangement (determined as the grain to pore size ratio) as well as on the mobility of gas and water in the inter- and intra-aggregate pores. The mechanical strength of structured soils with comparable internal parameters like grain size distribution, type and amount of clay minerals and of cations, organic substances and bulk density, mainly depends on the following parameters: aggregation, actual and maximum pre-drying (Hartge, 1986), the composition and arrangement of the pore system. Furthermore, external factors like type of loading, load intensity, time dependence and number of compaction events have to be considered too (Horn, 1981, 1988). Schafer et al. (1992) summarized the present state of knowledge of soil compaction also with respect to stress distribution in soils, whereby the research efforts over the last 30 years were examined on a broader scale.

A strength increase owing to aggregation has been verified for differently aggregated and textured soils (Horn, 1981; Burger et al., 1988; Lebert, 1989). With increasing aggregation as well as/or in combination with increasing dryness, the transition from the over-consolidation load range to the virgin compression line (i.e. pre-compression stress) only occurs at a higher load. Consequently, less aggregated, i.e. coherent, soil horizons are more compressible than those with a prismatic or polyhedral structure. Besides, with increasing clay content ($>40\% < 2$ μm) the same structural elements become weaker. For homogenized soil material the pre-compression stress value corresponds to the value of the pore water pressure as effective stress. Furthermore, elastic soil deformation occurs in the over-consolidation load range, while exceeding the precompression stress value results in plastic, i.e. irreversible, soil deformation (Hartge and Horn, 1984). Thus, if soils are repeatedly loaded and unloaded with the same load, not only a destruction of existing soil structure may occur, but the proportion of elastic to plastic deformation can increase, whereupon horizontal cracks are also created at the transition of the over-compacted soil, i.e. elastic, to the weaker soil material at deeper depth. Horizontal cracks dominate in the completely consolidated or even over-consolidated topsoil (anisotropic pore system) which is more susceptible to soil compaction by vertical stresses than vertical cracks. No-tilled soils are always much stronger than conventionally ploughed soils owing to a better rearrangement of particles and a better stress equilibrated pore system. It could also be proved that the ancient plough pan in an originally ploughed luvisol still exists after more than 2 decades despite of an intensive increase in earthworm numbers and activity (Horn, 1986). Thus, neither optimum root penetration nor gas and water exchange or sorption processes can be expected in such horizons in the long run. Intra-aggregate pore size distribution, orientation and pore continuity also affect total settlement and water release (Baumgartl and Horn, 1989), as can be derived by Rankine Prandtl failure lines (Terzaghi and Jelinek, 1954).

During short-term loading clay soils with low hydraulic conductivity can be stronger than sandy or well-structured soils having the same bulk density and load and pore water pressure. In the latter ones the settling process is dominated by the initial, i.e. 'timeless', settlement and the very long-lasting secondary settlement owing to soil creep. In clay soils, the pre-compression stress value can be even doubled if a compression is applied only for a very short time (e.g. less than a second) compared with longer lasting compression (e.g. 1 day), while those differences are smaller in strongly aggregated loamy, clayey or sandy soils (Baumgartl, 1991). However, in general, timeless settlement in soils theoretically can not occur because each movement of gas and water requires time. The reduction in pore space caused by loading of wet soils results in an equivalent drainage of excess soil water, which depends on the hydraulic conductivity and hydraulic gradient, as well as on the inter- and intra-aggregate pore continuity. If, for example, a homogenized and unsaturated clay or loam is compressed, the neutral stress, i.e. the positive pore water pressure, is equivalent to the difference between the total stress and the matric potential, i.e. effective stress at the beginning of soil loading. In aggregated soils, the inter- and intra-aggregate shear forces also have to be defined as effective stresses (Horn, 1981).

7.2. Shear tests of bulk soils and of single aggregates

Comparison of the shear resistance of homogenized or of undisturbed bulk soil samples and of single aggregates

Under applied stresses, soil deformation will occur at the weakest points in the soil matrix and further increase in stress will result in the formation of failure zones. Therefore, the strength of the failure zone equals the energy required to create a new unit of surface area or to propagate a crack (Skidmore and Powers, 1982). It has been called the apparent surface energy (Hadas, 1987, 1990). Con-

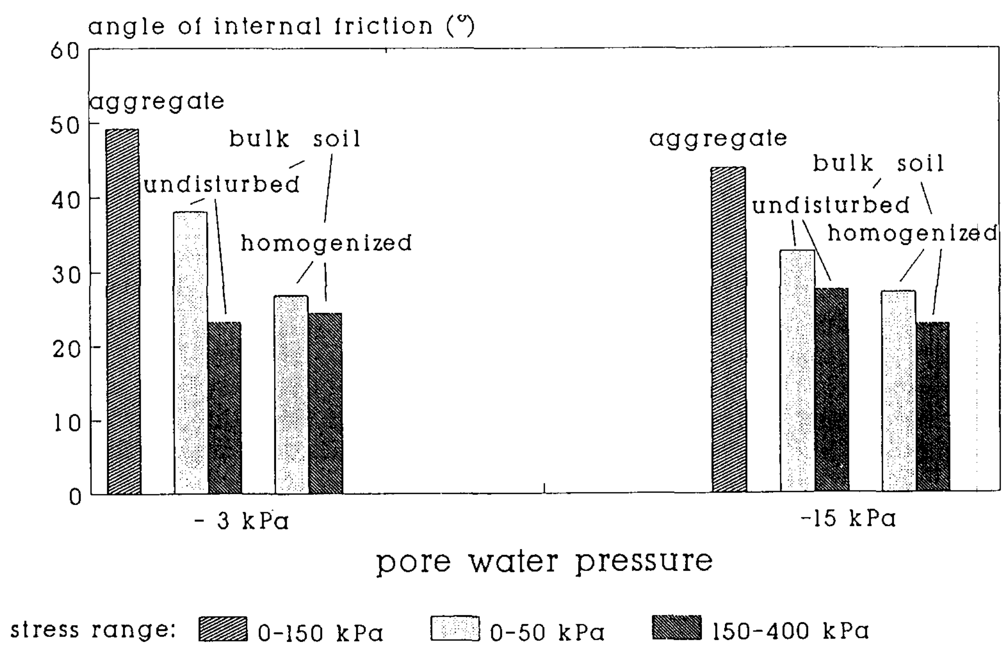


Fig. 8. Angle of internal friction for single aggregates, undisturbed and homogenized soil samples (Bt, Hapludalf) as a function of vertical stresses applied during shearing.

sequently, the stability of the soil is related to the distribution of strength in the failure zones. Soil structure will remain completely stable if the applied stress is smaller than the strength of the failure zone, i.e. if the degree of bonding between the points of contact exceeds the external stresses applied. The angle of internal friction for single aggregates is greater than for the bulk soil at low stress (Fig. 8). Furthermore at a load range of 0–50 kPa, the angle of internal friction of the undisturbed bulk soil is higher compared with that of the homogenized material, whereby the latter is affected mainly by textural friction properties at a given water content and bulk density. At a normal stress range of 150–400 kPa and at a pore water pressure of -3 kPa, the undisturbed and the homogenized bulk soil show nearly the same value for the angle of internal friction because aggregates are destroyed. Thus, the shape of the Mohr–Coulomb failure line can be always subdivided into a steeper straight line at low stresses and a further flatter one which resembles a Mohr–Coulomb envelope more because of: (1) the imcompressibility of water and (2) the limitation of water flux by hydraulic conductivity, even at a higher hydraulic gradient and at a given shear speed.

7.3. Effect of aggregation on changes in pore geometry and soil strength

Strength increase or decrease in unsaturated soils depends on changes in effective and neutral stresses and the strength/stress affected degree of water saturation, X. According to the effective stress equation for unsaturated soils, the total stress can be calculated as follows:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$

where σ' is the effective stress, σ is total normal stress, u_a is air pressure and u_w is the pore water pressure. The factor χ (chi factor) describes the normalized water content at a given pore water pressure value. χ varies between 1 for complete saturation (pF$=-\infty$) and 0 at pF 7, i.e. at complete dryness (Koolen and Kuipers, 1983; Horn, 1993).

Soil strength increases as long as the decrease in pore water pressure exceeds the decrease in the χ factor. Thus, each soil has a maximum strength at a certain pore water pressure that depends on the pore size distribution. In sandy soils, the highest strength value is obtained at less negative pore water pressure values than in silty or clayey soils, owing to the smaller fraction of finer pores. Negative pore water pressure values can be determined in single aggregates throughout a wider load range and less positive pore water pressure values occur at a given applied stress when these values are compared with those of an undisturbed or especially a homogenized soil sample. Maximum load dependent positive pore water pressure values exist for various aggregate types and grain size distributions. In aggregates developed out of clay material (P-horizon) the positive neutral stresses can be even the same, irrespective of the initial negative pore water pressure value. However, in sandy loamy prisms the maximum positive pore water pressure values are the smaller the more intensively the soils had been pre-dried at the same maximum stress. These differences can be explained by the hydraulic properties and the connection of the single intra-aggregate pores, which depend primarily on the grain sizes and their arrangements in the aggregates. The alteration of the pore water pressure value owing to loading is therefore smaller in less tortuous and more homogeneous intra-aggregate pore systems (Baumgartl, 1991).

The transition from stress induced increase to decrease of water menisci forces is always affected by the process of mechanical stress dependent pore size rearrangement, whereby the properties of the aggregate further define the slope of the pF/χ curve. This slope is generally steeper for aggregates than for bulk soil samples, especially at low pore water pressure. The higher the aggregate strength, the more pronounced is the load-dependent alteration of the pF/χ curve for the bulk soil and for single aggregates (Horn, 1989).

If, in addition, single aggregates or undisturbed unsaturated soils are loaded (and perhaps also sheared), at first the coarser pores are diminished in diameter resulting in an increasing amount of solid particles per unit volume and consequently in higher χ values. In contrast to the stress/strain theory of Kézdi (1969), the properties of the pore system are not constant but they are subjected to changes in accordance with the transition of effective to neutral stresses. A schematic diagram (Fig. 9) elucidates the possible types of behaviour.

When soils are compressed: (a) air-filled pores are diminished in diameter, the pore water pressure becomes more negative and the shear strength is increased if no extra water can refill the formerly air-filled pores; (b) the increase in the solid volume fraction on total results in higher strength values; (c) the shear strength declines partly because of the very small surface tension value for water at this

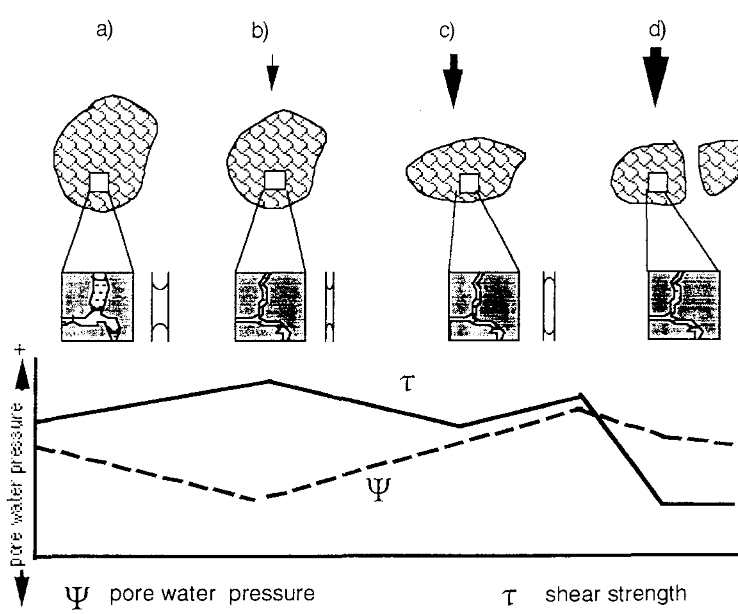


Fig. 9. Schematic diagram of stress induced changes in pore water pressure and in shear strength as a function of shear intensity.

higher degree of water saturation, and because the more pronounced soil softening during shearing and rearrangement of particles results in a complete water saturation and in addition creates convex water menisci; (d) the aggregate or the bulk soil is completely sheared, the strength further declines, and the pore water pressure becomes more negative again (Horn, 1981; Gupta and Larson, 1982; Bohne, 1983; Baumgartl, 1991; Horn et al., 1991). Furthermore, stress release can result in the formation of new pores and platy aggregates rectangular to the direction of the formerly applied stress. This might also cause intensive problems for the explanation of in situ water fluxes and may even be a very important factor for soil losses by water erosion because of those horizontal fluxes.

7.4. Dynamic aspects

Any load applied at the soil surface is transmitted in the soil in three dimensions via the solid, liquid and gaseous phases. The effect of soil aggregation on stress distribution as well as the consequences for ecological parameters have been described by Gupta and Allmaras (1989), Larson et al. (1989), Drescher et al. (1988) and Horn (1990). In homogenized soils, stresses are transmitted very deeply and the perpendicular stress propagation dominates during wheeling. The stress equipotential lines are more vertically oriented compared with those for well-structured soils. In the latter soils, applied stresses are more intensely atten-

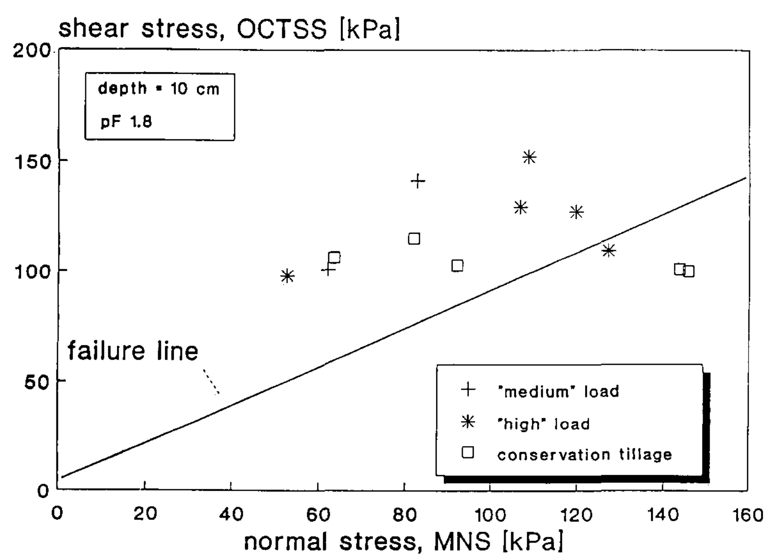


Fig. 10. Comparison of measured shear test parameters: angle of internal friction and cohesion defined by the Mohr–Coulomb (MC) failure line and in situ measurement data concerning the octahedral shear stress and mean normal stress at constant water content (luvisol derived from loess). As long as the data obtained from the in situ measurements are smaller than the strength range defined by the MC line, the soil remains stable. After exceeding the critical state, a further soil compaction must occur inclusive of a possible complete homgenization in the presence of excess soil water.

uated at a shallower soil depth, but they are transmitted more widely in the horizontal direction (Horn et al., 1994a). Stress measurements in soils principally require the application of stress-state transducer systems (SST) to later on calculate structure change processes (Nichols et al., 1987; Horn et al., 1992).

At a given pore water pressure, concentration factor values which describe the pattern of the stress equipotential line are smaller for well-aggregated soils and higher for those horizons with a very small pre-compression stress value. The larger the contact area of the tyre, the deeper the stresses will be transmitted at a given contact area pressure.

The transition between the various types of stress propagation directly depends on the relation between the actual shear stresses, created during loading at defined normal stresses, and soil strength. As long as the actual shear stresses at a given normal stress, i.e. mean principal stresses are smaller as compared with those defined by the Mohr–Coulomb failure line at a distinct pore water pressure, no further soil deformation will occur. If, however, the corresponding stress values exceed these critical data, the soil will be further deformed and weakened. In Fig. 10, shear and mean normal stress data are compared with those of the corresponding Mohr–Coulomb failure line. Both the mean normal stress data as well as the values for the octahedral shear stresses in soils during wheeling under in situ conditions are obtained by stress state transducer measurements, while the corresponding shear stress data resulted from shear box tests at the same pore water pressure and at a comparable shear speed. It can be seen that stresses applied by tractors or other kinds of agricultural machinery on top of a distinct soil

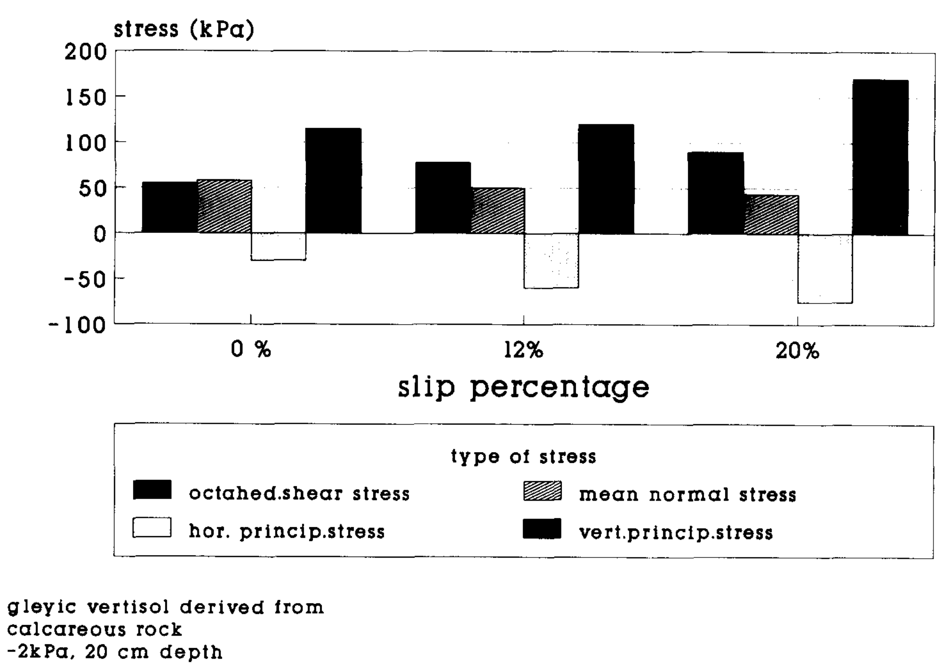


Fig. 11. Effect of slip percentage on octahedral shear stress, mean normal stress and the vertical σ_1 as well as horizontal σ_3 principal stresses.

horizon or during ploughing may exceed the internal soil strength and induce a further soil deformation. This may be expressed as soil compaction by a mere rearrangement of structure elements in a given volume or as soil homogenization even at constant bulk density including a complete homogenization of the aggregates and/or the soil structure. This effect of aggregate deterioration or of soil homogenization by kneading can be induced by positive and negative slip processes too (Fig. 11). This is true because, with increasing slip percentage, the octahedral shear stresses increase whereas the mean normal stresses decline and induce shear failure processes. The thereby induced weakening of the soil by aggregate deterioration can be finally derived from the principal vertical stress increase while the σ_3 value decreases (Horn et al. 1992; Horn, 1994a). A more complete review on soil compaction is given by Soane and Ouwerkerk (1994).

8. Conclusions

Soil structure is defined as the arrangement of single mineral particles and organic substances to greater units known as aggregates and the corresponding inter-aggregate pore system. In dependence of the external as well as internal forces and strength of the already existing structure unit, several more general but detailed accounts are available in the international literature, which have also been dealt with in the present paper. The presented results found in the literature verify the idea that processes of aggregation do affect the availability of water for plant uptake and the accessibility of water-filled pores for roots, which is reduced owing to the formation of finer pores where water is available only at more negative pore water pressures. If the processes of aggregate formation under mechanical and biological conditions are combined with the corresponding effects on hydraulic, aeration and thermal properties, it can be in general concluded that there is never a constancy at the beginning of soil structure formation but it is only reached after a longer period, i.e. at the smallest free entropy (Table 1).

With regards to chemical properties and processes, soil structure formation always includes the stages of a reduced accessibility to exchange places for soil solutions, a retarded exchange process and a stronger chemical disequilibrium. Only at the stage of smallest entropy, i.e. at an increased accessibility, do structured soils become macroscopically homogeneous. The smaller the pore water pressure, i.e. the more reduced the flux rate, the better and more complete the exchange process. The more intensive the water saturation, the more extended are anaerobic soil volumes in aggregates even for longer periods per year as well as in combined altered physico-chemical behaviour.

With regards to mechanical properties and processes, it can be concluded that, in arable as well as in forest soils, aggregate formation always results in increased soil strength. The more intensively soils are aggregated, the more negative is the pore water pressure at the same water content in the bulk soil. A smaller applied stress is attenuated by the strength of these soils. Single aggregates are always stronger than the bulk soil or the homogenized material, which is also verified by

Table 1
Processes of aggregation and changes in functions

Stage	Process	Aggregate type	Consequences	Hydraulic effects	Aeration effects	Thermal effects
I. Mechanical effects						
Early	Rectangular cracks	Singular coherent prism column	–Increasing number of contact points –Increasing aggregate bulk density –Formation of inter- and intra-aggregate pores	–Decreased intra-aggregate pore volume and saturated hydraulic conductivity –Increased macropore flux	–Reduced intra-aggregate aeration –Increased differentiation of aerobic and anaerobic zones	–Increased specific heat capacity –Increased thermal conductivity
Increased number of drying cycles or drying intensity	–Crack formation by shear forces –Oblique shear planes	Polyhedre	–Rearrangement of particles inside aggregates –Clay skins –Accumulation of coarser particles in aggregate centre –Increased intra-aggregate tortuosity	–Decreased hydraulic conductivity as compared with bulk soil –Smaller decline of the k/ψ curve of aggregates	–Differentiation of gaseous composition –Steeper decline of pO_2 at a given water potential	–Theoretical increase of conductivity in outer skin
Final	Reaching smallest free entropy	Natural aggregate density sphere	–Reduced aggregate bulk density –Increased aggregate strength	–Increased plant available water –Steeper slope of k/ψ curve	–Improved aeration	–Reduced thermal conductivity
II. Biological effects						
	Biological activity	Crumb	–Homogenization by mixing processes – a reduced bulk density –Increased strength	–Increased saturated hydraulic conductivity –Steeper slope of the k/ψ curve	–Increased aeration –Increased oxygen consumption –Decreased redox potential	–Reduced thermal conductivity

the smaller increase of the pore water pressure value during loading and by the higher aggregate bulk density. The shear strength parameters (angle of internal friction and cohesion) are always higher for single aggregates compared with the bulk soil for a given applied stress. As soon as the applied stresses exceed the internal soil strength, the aggregate or the bulk aggregated soil will become homogenized and structure will become destroyed. Thus, the pattern of the Mohr–Coulomb failure line resembles that of the homogenized material after exceeding this stress value.

The strength increase with decreasing pore water pressure depends on the pattern of the pF/χ curve for single aggregates as well as for the bulk soil. As soon as the decrease in χ with decreasing pore water pressure exceeds the increase in effective stress because of this drying, the net effect becomes negative. Thus, each single aggregate as well as each aggregated soil horizon has to be characterized by its specific maximum strength. Especially in nearly water saturated soils, the pore water pressure dependent increase in soil strength can coincide with a stress affected decrease of the hydraulic conductivity. The smaller the hydraulic conductivity, the higher the pore tortuosity, and the higher the shear speed are, the larger the neutral stress is and the smaller the effective stress is.

Soil strength is strongly affected by spatial differences in pore water pressure. Hydraulic properties of single aggregates as well as the arrangement of these aggregates in the bulk soil are therefore most important if soil strength and the corresponding stress distribution shall be predicted. Stress attenuation and stress distribution (intensity and spatial direction), because of loading under running wheels, can vary to a great extent independently of soil and machinery parameters. Soil compressibility and compactability by means of volumetric stress–strain properties can often be predicted, if the mechanical strength properties for the bulk and/or the homogenized soil as well as the single aggregates and their arrangement in the bulk soil samples are known. If merely the corresponding parameters for the bulk soil were available, the differences between the measured and calculated soil stresses at the various positions, e.g. under a running tractor wheel, would be larger.

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