The puddling of clay soils

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Summary

In the first section some basic ideas are discussed on the relation between soil micro-structure and soil-water. It is pointed out that the moisture content of a clay soil is the result of an equilibrium between the swelling pressure on one hand and the soil-suction plus Madelung attraction on the other hand. However, frictional forces, caused by organic matter bonds and by edge-surface attraction, tend to fix any given arrangement. When the primary particles are moved in relation to each other, the true equilibrium between swelling pressure and suction is obtained, which in most practical cases means that moisture is taken up.

Thereafter, the influence of mechanical treatments on soil micro-structure at increasing moisture contents is explained in a qualitative way. With increasing moisture content, the cohesion within the aggregates falls off rapidly, but the friction between the aggregates tends to increase. Depending on the force applied the maximum friction will develop at moisture contents above or below the moisture equivalent. As this frictional force also determines the drawbarpull, its effect on the force exercised on the aggregates is cumulative. Near the moisture equivalent the intra-aggregate cohesion is weak and therefore an infinite number of shear planes may develop (plasticity), resulting in a situation as mentioned at the end of the first section. At moisture contents near saturation point the friction falls off again and with it the degree of puddling caused per unit of mechanical action.

In the third section the properties of puddled soils are treated. The air filled pore volume is largely reduced, the permeability lowered, the suction raised, the resistance to raindrops lowered and the deformability increased. The regeneration of puddled soils is only possible by drying, either through evapotranspiration or by freezing. As puddling will very often occur during harvesting operations (sugarbeet) freezing will be the most important process: it has the special advantage of dividing the soil into aggregates of favourable dimension.

Introduction

In normally aggregated soils distinct units or aggregates can be discerned and isolated even when the soil is saturated with water. These aggregates behave like solids, perhaps as very soft ones. To the contrary, puddled soils form a rather uniform body marked by plastic features and often by much higher moisture contents than in case of well-aggregated and saturated soils. It is known that the soil has to be worked to some extend to convert it from the aggregated into the puddled state, and that this conversion only takes place when a certain amount of water is present.

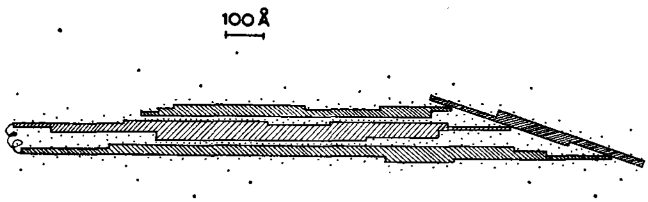
In order to understand the basic differences between an aggregated and a puddled soil and how these differences are brought about, we shall first have to consider the microstructure of clay soils and then the forces regulating the moisture uptake by the clay aggregates and the process of swelling.

The swelling process

a. The micro-structure of soil

Normally the clay crystals are rather closely packed, since the apparent density of clods in dry clay soils amounts to 1.8, which value gives a pore-space of $^1/_3$ assuming a particle density of 2.7. As the crystals are laminated this implies a parallel arrangement, because the pore-space is easily accounted for by the lack of fitting of the irregularly shaped platelets in one plane. Although a parallel arrangement will prevail over short distances, over a longer distance all sorts of directions will occur and occasionally a plate lying across a stack of day crystals may be present. The packing being very close, most of the moisture uptake must cause an expansion or swelling of the aggregate. FIGURE 1, illustrating a swollen clay, shows that the original arrangement can still be distinguished.

FIG. 1. Cross section through a clay-polyplate (domain) saturated with divalent ions, floating in water



Legend: Cross hatched area = clay crystals; points = adsorbed cations; corkscrew l.h.s. = organic bond.
Swelling pressure prevails in regions where distance between crystals is larger than 14 Å; Madelung attraction prevails where distance is smaller than 14 Å. Edge to surface attraction prevails at r.h.s. where this type of contact is possible.

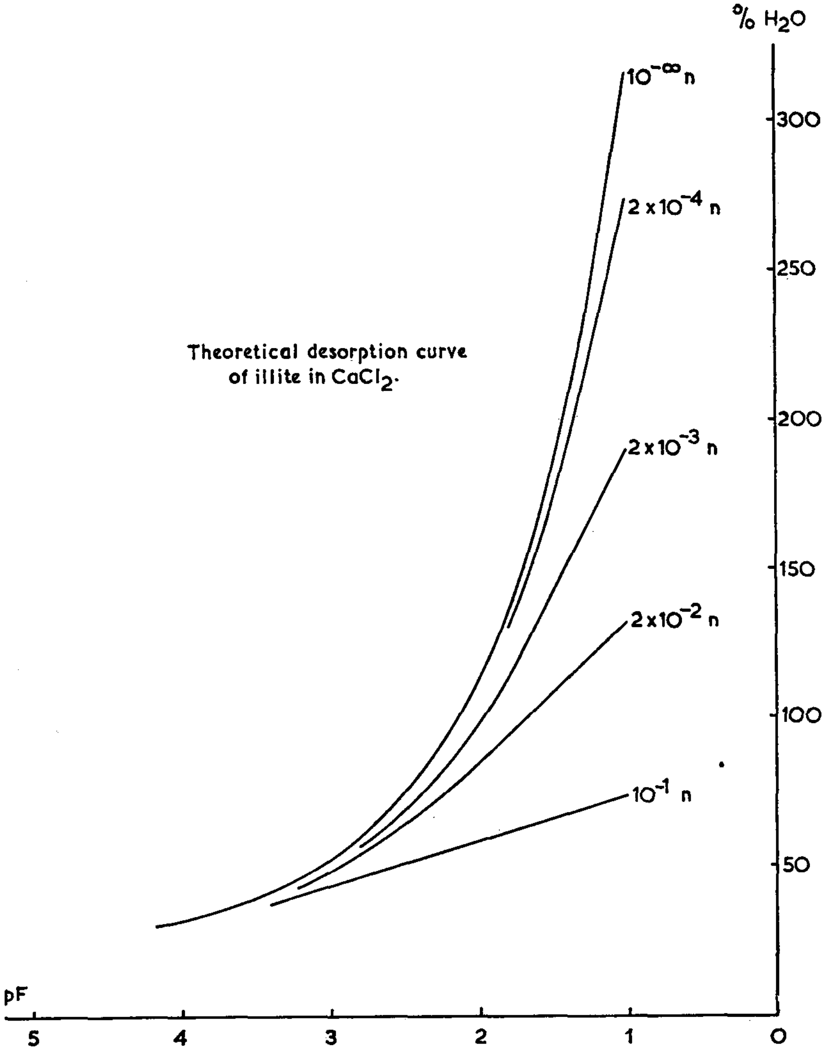
b. Hydration of ions

The strongest force binding the water is supplied by the hydration-energy of the cations and the clay surfaces. In the case of Ca-montmorillonite this force operates between pF 6.5 (relative humidity of 10 per cent) and pF 4.5 (95 % r.h.) and thus remains outside the range of plant growth but partly covers the moisture ranges of soil tillage. According to data of MOONEY, KEENAN and WOOD (1953) only a few layers of water (up to four) are adsorbed within the clay crystals of Ca-montmorillonite.

c. Osmotic swelling

Where the hydration energy ceases to operate, the osmotic swelling takes over. This attraction of water is caused by the difference between the concentration of ions at the plane midway between two clay plates and that of the soil solution. This force has been calculated by SCHOFIELD (1946) and BOLT (1956) in dependence on the concentration and composition of the soil solution and has in some special cases also been confirmed experimentally. As the difference between the midway concentration and the soil solution decreases with increasing concentration of the latter, the swelling force also decreases. This is illustrated by FIGURE 2 showing the theoretical relation between soil moisture and soil suction for Ca-illite at various salt concentrations. We see that the swelling is strongly reduced at high salt concentrations,

FIG. 2. Theoretical desorption curve of illite in $CaCl_2$
Surface area 120 m^2/g. Incompressible pore space 33.3 %



Legend: n = normality of $CaCl_2$ solution.

but at zero suction it should even then be infinite because the concentration half-way between two charged plates is always higher than that of the soil solution. Thus the theoretical curves do not resemble the pF curves of well-aggregated clay soils, which show only little water adsorption at suctions below pF 2. Obviously some other forces opposing the swelling are also active.

d. Madelung forces

The first force to be mentioned is the Madelung attraction, calculated by MACEWAN

(1954), which is active when the clay platelets fit perfectly as for instance inside a montmorillonite crystal. This attraction is due to the preponderance of the interaction between the electrical fields of the individual ions and the negative sites of the clay crystal, over the general electrical field of the double layer arrangement. This force diminishes sharply when the distance between the plates exceeds the one between the ions (10—14 Å). It is the main force which causes the binding of individual clay crystals into stacks or clusters, called "polyplates" by the author (1961) and "domains" by QUIRK (1960). The dimensions of the polyplates are not well defined as they vary with the force applied to separate the clay plates. The result of the Madelung forces is that in Ca-saturated clays the surface where the swelling may proceed unhampered is very much reduced and therefore also the amount of water absorbed at a certain suction. This osmotic swelling will be restricted to surfaces between the polyplates. Here, however, it still should proceed indefinitely at zero suction, according to the above mentioned theory.

e. Other binding forces

Besides the Madelung forces there exist localized binding forces such as the edge to plate attraction and the bonds of organic matter. The former is caused by the attraction between the positively charged edges (broken alumina bonds) and the negative sites on the planar surfaces of the clay crystal. The magnitude of the edge to plate bond has been calculated by VAN OLPHEN (1956, 1962) and by RAUSSEL COLOM (1958). These bonds are broken after a sufficient amount of energy is applied when working the soil, but they will be formed again at other locations once the system has come to rest. As the number of negative sites is infinite an also infinite number of positions is possible for these forces.

Therefore the edge to plate attraction tends to fix any given arrangement and its effect is one of friction. The rigidity of the system will increase with the number of bonds per polyplate and the edge to plate attraction becomes more important when the degree of parallel orientation becomes lower. In some soils iron and aluminium oxides may enhance the edge to plate attraction.

The effect of the organic matter is similar, but may differ slightly, firstly because the organic bonds are elastic and secondly, because the strength of a bond formed again after destruction may be lower than the original one, QUIRK and PANABOKKE (1962).

Summary

The swelling process may be summarized as follows: At zero suction the osmotic swelling tends to expand the soil aggregates indefinitely, but it is counteracted by the frictional forces, due to edge to plate attraction and organic matter bonds. As the swelling is usually very small below pF 2, the effect of the frictional forces is similar to the application of an external load of 100 g/cm^2. Therefore NORRISH (1962) called it an "internal"load, describing by this term all the attractive forces which prevent indefinite swelling.

The influence of shear

We will now devert our attention from the static system to the dynamic one where the polyplates are moved in relation to each another as occurs in practice during shear. While this movement takes place the frictional forces can not act as internal load. The edge to plate attraction ceases to function because the clay polyplates become orientated in the same direction during the movement. The organic bonds are broken by the movement and can not develop again so long as the movement continues. Also the Madelung attraction may cease to work at some places where the close contact area is relatively small. In this case a large shear force may induce a tangential movement of the clay plates. This movement of the plates must be followed by the adsorbed cations because of electro neutrality.

Thus instead of remaining in a fixed position between two negative charges, which is the first requisite of the Madelung attraction, the cations are dragged from these positions. On their way other cations are passed moving in the opposite direction. As the interaction of the cations is a repulsive one, of the same order of magnitude as the attraction in equilibrium position, the Madelung attraction is neutralized and the osmotic swelling may proceed during tangential movement.

As the various types of frictional and attractive forces are inactivated during shear it should be expected that the observed moisture suction would approach the value corresponding to the osmotic pressure as calculated from the existing theory. It will be identical with or very close to the "Unique relation" between suction and moisture content as described by CRONEY and COLEMAN (1954) and GREACEN (1961). Therefore, when in a dense moist aggregate the clay polyplates are moved relatively to each other, either the suction will increase or if the suction is maintained more water will be taken up.

Contrary to the above it should be expected that when a wider packing is present in a soil than the one corresponding to the theoretical distance either the tension will decrease during shear or, should the same tension be maintained, water is sucked from the sheared soil. This will be the case with drying clay slurries and subhydric clay deposits in the desorption cycle particularly if they are strongly flocculated.

The foregoing is illustrated by FIGURE 3, which is similar to FIGURE 5 of CRONEY and COLEMAN's paper (loc. cit.).

Curve A shows the drying and wetting cycle of the dense aggregate. Curve A shows the eventual effect of capillary pores on the desorption curve. Curve B shows the desorption curve of the soil slurry. Its general shape corresponds well to the curves

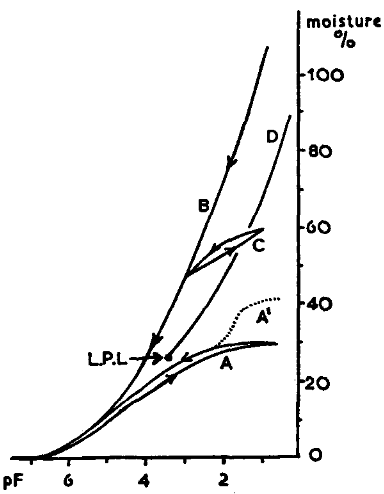


FIG. 3. Suction-moisture content relation for a very heavy clay soil (CRONEY and COLEMAN, 1954)

Legend: Curve A = desorption and adsorption curve for the soil after drying; Curve A' = influence of capillary pores; Curve B = curve of the slurry; Curve C = reversal of the desorption process; Curve D = desorption curve of disturbed sample; L.P.L. = lower plastic limit.

as calculated from the theory of osmotic swelling. The fact that curve B is not the result of the osmotic swelling forces only, is shown by curve C. The latter demonstrates that when the desorption of the slurry is stopped and the suction lowered, less water is adsorbed by the slurry than would correspond to the amount removed by an equal increase of suction during desorption.

This means that frictional forces to some extent prevent desorption and backswelling. If the osmotic swelling alone would be operative, the moisture-suction curve B would be completely reversible. Curve D is obtained when the sample is stirred or kneaded prior to the determination of the suction. When comparing curve D with curve B one observes that the suction is lowered by stirring, but in regard to curve A the suction is raised strongly. Below 30 % moisture curve D was obtained either by kneading the dense soil or the desorbed slurry; at the same moisture content an identical point was obtained on curve D. In this way it was proved experimentally that by moving the clay polyplates relatively to each other a "unique" suction moisture relation is obtained which probably is nothing but the one derived from the theory of osmotic swelling.

If water is held in capillary pores at relatively low suctions, these pores will be destroyed during kneading, and the water contained there will be redistributed through the system as double-layer-water between the polyplates.

In conclusion we may define the act of puddling as the creation of an infinite number of shear planes within the soil clods, and the perfectly puddled state as one where, as a result of shearing, the distance between the clay polyplates is more or less uniform and the suction corresponds to the theoretical swelling equilibrium.

Soil puddling in agricultural practice

We will now consider the conditions under which puddling may occur in agricultural practice and will start with soils having a high internal load as reflected by a pronounced difference between curves A and D of FIG. 3. This means a restricted swelling in the aggregated state and a high moisture content after puddling.

The first condition for the development of an infinite number of shear planes (e.g. one every 50 Å instead of one every few cms) is that the cohesion within the soil units be low. The cohesion drops with increasing moisture content and obtains its minimum value near the saturation point which is due to the ensuing larger distances between the clay-polyplates and the internal stresses caused by swelling. This connection has been investigated by numerous authors e.g. by HAINES (1925).

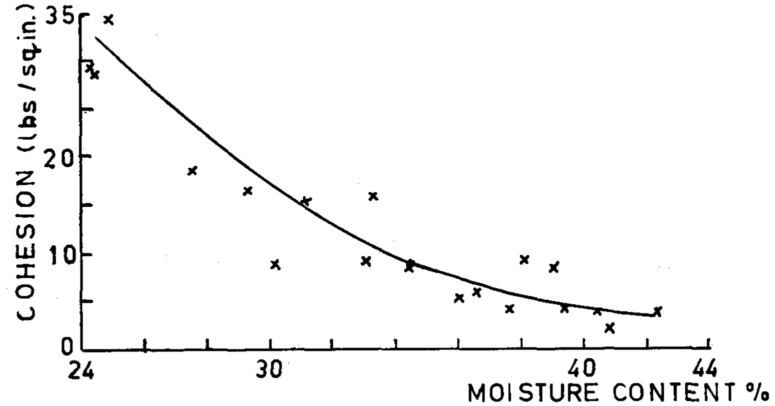
FIGURE 4 shows the relationship between bulk shear strength and moisture content as determined by FOUNTAINE (1956) and published here with the permission of the National Institute of Agricultural Engineering, Silsoe. The curve for clod shear strength would be even steeper.

The second condition is that a fair amount of energy should be transferred to the clods. This amount is often the limiting factor because many tillage implements are designed in such a way that the soil units broken or sheared from the massive crust by the cutting part of the implement evade the compressing and shearing forces.

Transfer of sufficient energy to the clods is only possible when the clods do not move easily along each other and along the implement.

Continuous shear planes develop only when the shear strength between the clods is equal to the one inside them. Now the cohesion between the clods, in this paper

FIG. 4. Relation between cohesion and moisture content of a clay soil. (FOUNTAINE, 1956)



also called soil-soil-adhesion, and the adhesion between the clods and the implement surface, are mainly caused by waterfilms adhering to both surfaces. When studying the mechanism of soil adhesion FOUNTAINE (1954) found that it depends on the soil water suction at the interfaces soil-metal or soil-soil and on the relative area of contact. At high suctions the number of water bridges is too small to cause sufficient adhesion; on the other hand if the soil is saturated the suction is too low. Thus a maximum of adhesion is found at intermediate suctions where it lies near a point either called the moisture equivalent, or field capacity or lento-capillary point.

Therefore it is to be expected that the maximum puddling action will take place at suctions very close to this water content, because then a maximum of energy is transferred to the clods while the internal cohesion inside them is considerably lower than in an air dry clod.

For a full understanding of the process of puddling, both the changes of soil structure and soil-moisture tension during the movement of the soil must be taken into account.

If the soil is compressed at field capacity and forced to slide over a metal surface or a soil interface, the points of contact will be changed into zones of contact. This flattening of the points of contact under a pressure higher than the yield pressure at these points was investigated by DAY and HOLMGREN (1952). The increased area of contact will enhance the shear strength at the interfaces, and resist the movement of the soil. This again will raise the pressure of the implement on the soil, and in this way increase the shear strength according to Coulomb's law. The final result will be that the drawbar pull is increased if the same speed is maintained. In this way the amount of energy transferred to the soil clods may be large at a moisture content where the cohesion is low. As the movement takes place on the interfaces, the puddling will start there, followed by a locally increased suction and adhesion, because the flow of the water is too slow to adjust the suction. This increase in suction for London clay may be estimated by comparing the suctions of curve A and D (FIG. 3) at the same moisture content. When the shear strength at the interfaces exceeds the one inside the clods, new shear planes must necessarily develop, and the soil will be puddled completely if the action is continued long enough. The puddling will start at the rough interlocking soil-soil interfaces where the friction will be higher than at the soil-metal interface.

If the increased suction at the soil-metal interface causes the soil to stick better to the metal than to the rest of the soil non scouring will occur. In accordance with this view on the origin of non scouring this problem is solved in practice by lowering the suction at the interface. Water is either directly injected behind the share or supplied by electro osmosis (CROWTHER and HAINES, 1924).

Mr. E. DALLEINE asked me some questions as to the place where non scouring may occur and also about the influence of the form of the mouldboard on it. The first question might probably be answered as follows.

Aggregates must be submitted to some mechanical treatment before a part of them is converted into a plastic mass which is necessary for the occurrence of non scouring. Therefore non scouring will not take place at the point of the implement but at some distance from it. A second factor of importance is that the normal load tends to compress clay soils and to squeeze water out of them. Thus normal load counterbalances the increased suction and consequently the soil may scour better where the normal pressure is high, but it will tend to stick where the normal pressure is lowered and the suction therefore raised. The requisite for non scouring viz. a good contact soil-metal may be achieved in various ways. When we compare ploughs with differently curved mouldboards and working at the same depth and the same speed we see the following difference. If the curvature is very small the elasticity of the soil may be large enough to make shearing unnecessary and only little shearing of the soil beam will take place. Therefore the contact will be good. If the curvature is steeper the beam will be sheared into large clods and the contact area will be smaller than in the former case; if the curvature is still steeper the clods will be smaller and the contact area will be larger partly because the normal load is increased by a higher curvature. (Equal mass of soil lifted and twisted in shorter time). The influence of the moisture content on soil properties and on different phenomena concerned with tillage is illustrated by FIGURE 5.

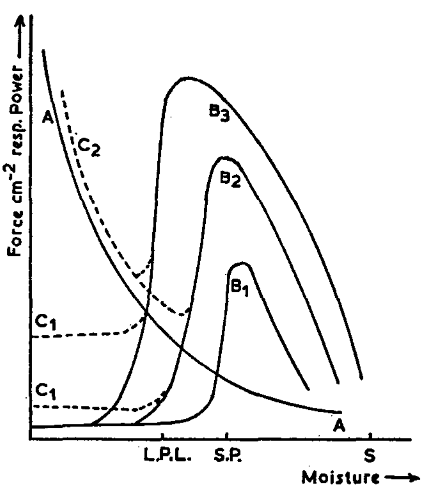


FIG. 5.
Relations between moisture content and soil properties of importance for tillage operations

Legend:

A = cohesion within the aggregates; B = cohesion between the aggregates (soil-soil adhesion), B_1 before working, B_2 after small compressive and shearing force, B_3 after large compressive and shearing force; C_1 = transfer of energy (Power per unit action) to small soil units, for small and large forces resp.; C_2 transfer of energy to very large soil units; L.P.L. = lower plastic limit; S.P. = sticky point; S = saturation.

It is a known fact that the type of implement affects the degree of puddling and in general one may assume that the longer and more intensive the kneading action, the worse the puddling will be (plough versus rotary tillage or spade). The range over which puddling may occur will be the wider, the more the evasive movements of the clods are prevented (wheel and roll versus plough). During the passage of roll and wheel the direction of the normal load changes continuously from forward to downward and with the traction wheel also backward (GLIEMEROTH, 1953).
Therefore the direction of the shear planes will also be changing continuously. In this way the weakest plane in the clods is automatically found. This also explains the severe puddling caused by these implements at high moisture contents and their effectiveness in reducing the size of clods at lower moisture contents.
When comparing soils with the same yield value as to their susceptibility for puddling by working at the critical suction (moisture equivalent) one may anticipate that the soil with the largest difference between curve A en D (FIG. 3) will be puddled most easily because its increase in suction and adhesion is the largest.
Puddling is certainly not limited to clay soils. Even sandy soils with only a small percentage of silt and clay may become puddled if worked at too high moisture content, especially if they are low in humus.
An example was communicated by Ir. J. R. WILLET (Ned. Heide Mij.), who had observed that slightly loamy sand soils became impervious after subsoiling at too high moisture contents, but regained their permeability after a drying cycle. The colloidal material in these soils is present in an aggregated form either as a coating on the sand granules or as small aggregates between them. If such a soil is worked when moist or saturated the sand granules during cultivation will roll over each other because usually under these conditions the cohesion is very low. The rolling sand grains act as a ball mill and by this grinding action the colloidal material is puddled very efficiently and suspended in the soil water. The viscosity of the thin mud being higher than that of water the permeability will be correspondingly decreased. Only reaggregation by drying can improve this situation.
Addition of salts might provoke flocculation and decrease the permeability still more.
We now revert our attention to soils which have never been totally dry, such as

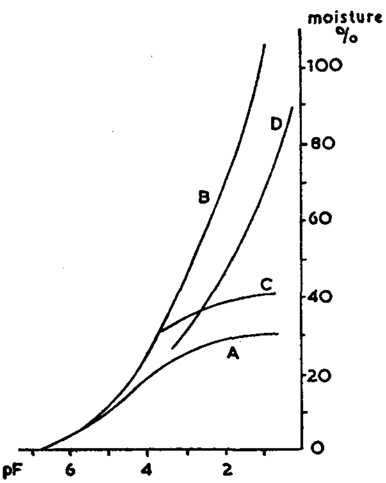


FIG. 6. Suction-moisture relation for a very heavy clay deposit, drying not yet completed

Legend: Curve A = desorption curve of completely dried soil; Curve B = desorption curve of the slurry; Curve C = desorption curve of deposit dried to pF 3.7; Curve D = desorption curve of disturbed sample.

subhydric clay deposits in not yet completely reclaimed polders. These soils will have a desorption curve of a shape resembling a combination of curve C and B (FIG. 3). The greater the degree of dehydration the more the desorption curve will resemble curve A. In a soil with a desorption curve C (see FIG. 6), the increase in suction by puddling will be small. When worked at higher suctions, (left of curve D), the initial tension will even decrease at the shear planes until it will reach the value on curve D corresponding to the given moisture content. Therefore the adhesion at the interfaces soil-soil and soil-implement will be less than the cohesion, with the result that no new shear planes will develop and neither puddling or non scouring will occur. The drawbar pull will be low. This is a possible explanation of the increased draught requirements with progressive "ripening" (irreversible dehydration) observed in the Zuiderzee polders (communicated to the author by Dr. J. J. JONKER). During the puddling operation the moisture content will not be changed appreciably, unless low tension water is available to be sucked up during this puddling. The change into liquid mud is only possible during rainfall or when excess moisture has accumulated during a period of frost. It occurs frequently on unsurfaced roads and on fields used as such during harvesting.

Properties of puddled soils

The properties of puddled soils have been studied extensively by a team from the Arizona University, MCGEORGE (1937), MCGEORGE and BREAZEALE (1938), BUEHRER and ROSE (1943).

Its main characteristics are: a destroyed system of macro pores and hence a minimum percentage of air filled pores and a low permeability, an increased moisture suction, a low resistance to raindrops. In the original system areas of low cohesion alternate with those of high cohesion. The former determine the cohesion of the bulk of the soil, the latter that of the single clod. If this heterogeneous system is transformed into a homogeneous one with uniform inter-polyplate distances, the bulk cohesion increases and the clod cohesion decreases until they reach the same level. The transition of a solid mass into a plastic one is shown by the undistinct yield

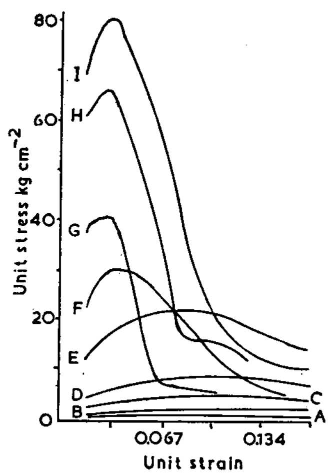


FIG. 7. Stress-strain diagram of puddled Preston red clay (CHRISTENSEN, 1930)

Legend: Curve A = 36 % moisture; Curve B = 31 %; Curve C = 26.2 %; Curve D = 21.4 %; Curve E = 16.5 %; Curve F = 11.6 %; Curve G = 6.8 %; Curve H = 1.9 %; Curve I = 0 %.

point as illustrated by FIG. 7 where the curve of the compression stress is determined on a gradually drying puddled clay soil (CHRISTENSEN, 1929).
A puddled soil is not only a very unfavourable medium for the roots of most plants, but puddling also creates conditions activating undesired microbiological processes such as denitrification and sulfate reduction.
In practice it may be difficult to determine whether a soil has been compacted or puddled. In so far as the air-filled pore space and permeability are concerned they may be identical in both cases, but the increase of the moisture suction and the loss of rigidity are less in compacted soils because here only a fraction of the soil suffers an internal rearrangement.

Regeneration of puddled soils

As the soil becomes puddled by mechanical action, one can not expect that its condition might be improved by any mechanical means before the moisture content has fallen below the lower limit of plasticity. Fundamentally one must consider the puddling as a breaking of the contact between stacks of primary clay particles or polyplates, while water is brought in between them.
Therefore, the only remedy lies in reastablishment of this contact by extraction of water. A close contact will then be assured by the capillary forces compressing the soil during the drying process.
In the field, extraction of water occurs either by evapotranspiration or by freezing. During the winter evaporation is a slow process and it has the disadvantage that comparatively large hard blocks are formed, which desintegrate only after repeated wetting and drying cycles.
Freezing not only draws water from the mass of soil but concentrates it in the ice wedges dividing the soil into small and sharpedged blocks. Through thawing and drying, the contact area between these blocks becomes small and they may easily be loosened by some tillage instrument.
The size of aggregates will depend on the original moisture content of the puddled soil and the rate of cooling. The higher the moisture content and the rate of cooling, the more ice lenses will be formed and the smaller will be the aggregates. For a qualitative explanation of the frost action see KOENIGS (1961, IV 2.2.5.), here it should be added that the principal factor for the growth of the ice lenses is the lower vapour pressure of ice compared to that of under-cooled water of the same temperature.
It is the opinion of the author that for the regeneration of puddled soils in the Netherlands freezing is of more importance than drying.

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