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"COLLEGE ON SOIL PHYSICS"

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"Soil Sealing and Crusting"

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1. IDENTIFICATION OF THE PROBLEM AT A WORLDWIDE SCALE

At the International Symposium on the Assessment of Soil Surface Sealing and Crusting, that took place in Gent in 1985, it has been recognized that, although a lot of knowledge has been gathered the lasr fifty years, dealing with nature and formation of seals and crusts, simulation, strentgh measurement, the problem of sealing and crusting is still a major one in todays agriculture at a worldwide scale. One of the reasons behind the complexity of sealing and crusting is the many factors involved in the phenomenon.

In his introductory at he Symposium, Dr. SOMBROEK W.G. (1986), Secretary-General of the International Society of Soil Science, describes the problem at a worldwide scale.

1.1. Sealing and crusting of the temperate zones soils with humid climate.

"Sealing" has always been a problem on a number of temperate zone soils with humid climate. in the Low Countries of north-western Europe it is kown as "verslemping" and it ocuurs both on some of the alluvial and polder-clay soils, and on the low uplands that are covered with loess of fine coversands. Farmers have learned how to handle it, taking advantage of the remedial effect of froston autumn-tilled sealed soils, and the application of chemical and biologicalamendments. In recent years the problem has tre-emerged, especially on the undulating uplands, because of lower application of organic matter in the soil, the stronger degree of mechanization, and the introduction of late-spring sowing new crops like sileage maize.

1.2. Sealing and crusting in the Arid and Semi-Arid Subtropics.

In the arid and semi-arid subtropics, crusting is well known in irrigation projects, when they deal with sodic soils, Planosols or Vertisols, the latter when of the mazic type (Australia).

1.3. Sealing and crusting in the Humid Tropics.

In the humid tropics soil sealing or surface compaction was never considered much of a problem; the inherently stable aggregate structure of the predominant soils overthere would prevent such a process to take place. However, recently it was established that there are quite a few soils of other nature that do have a compaction problem; especially those of low iron-content, higher silt content and/or higher-activity clay minerals: examples are the soils of Yurimaguas experiment station in the Amazon part of Peru, and those of IITA in Ibadan, Nigeria. even heavy textured xanthic Ferralsols (Oxisols), once they are cleared from their original vegetation, may show the feature, especially when occuring in a climate with some dry months (Paragominas area in the eastern Amazon region of Brazil).

1.4. Sealing and crusting in the Subhumid to Semi-arid Tropics.

It is the subhumid to semi-arid tropics, however, that the problem of sealing, or hard setting, or capping, would seem to be the most serious. Especially the Sudan-Sahelian zone of west africa is concerned, but also large parts of Eastern and Southern Africa, India, Thailand, the U.S.A, etc. In many situations the overhead climatic conditions conditions would allow the growing of annual crop in most years. A three month rainfall of 700-1000 mm is sufficient for crops like millet, sorghum, cowpeas and groundnuts to provide economic yields. It then depends on whether this rainwater can fully penetrate and be stored in the soil for dryland agriculture to be successfull.

Moisture storage per-se is usually not a bottleneck, unless the soils happen to be very sandy (Arenosols) or very shallow (Lithosols, Cambisols, lithic phase). Many of the soils in the semi-arid tropical areas have effective depths of 100 cm or so, with a subsoil structure and a clay minerals assemblage that guarantees an effective soil moisture storage capacity of at least 100 mm. A critical factor is however the degree to which the surface condition allows the rainwater to penetrate, right from the start of the rainy season.

Many soils of the semi-arid savannahs have a sandy topsoil. A strong textural differentiation between topsoil and subsoil can occur as a result of the pedogenetic illuviation process - formation of an "argillic"-B horizon - acting autochtone parent materials (sedimentary or crystalline basement rocks). Such sandy topsoils may, or may not, be prone to a form of crusting calling sealing, i.e. formation of a thin layer (1-5 mm) at the surface of the soil that is very dense and hard when dry, without any porosity and sometimes even water repellant with algae growth.

In general practically all soils in regions with seasonal rain fall and absence of a cold (frost) season, have tendency to surface compaction. Occasional dry-season showers, sunbaking and cattle trampling cause a hard surface layer. What counts is the degree to which the topsoil material re-compacts, re-seals after being tilled. The "liability to re-sealing after tillage operations " is therefore the right name fot the soil property concerned.

2. TYPES OF SEALS/ CRUSTS.

Several names are used for the phenomenon. There is an obvious need to precisely define each of them, if indeed they concern different features, related to different active forces, and occuring in relation to different climatic regimes and soil types.

A seal is usually thin (1-5 mm) and does not crack. A crust does crack, peels-off and is moderately thick (0.5-2.0 cm); Hard-setting seems to concern quite thick surface layers of 20-30 cm.

Different type of seals/crusts can be formed as the result of different active forces:

(i) structural crusts, those formed by physical forces through water drop impact, trampling, tractor traffic and flooding.

(ii) slaking, those formed by chemical dispersion of aggregates, mainly as the result of exchangeable sodium accumulation.

(iii) depositional crusts, those formed by translocation of fine soil particles and their deposition at a certain distance from their original location, through irrigation water.

3. SEALING AND CRUSTING MECHANISMS.

MC INTYRE (1958a & b) has described a sequence of events leading to crust formation under field conditions. The steps are as follows:

(I) breakdown of wet soil aggregates by slaking or raindrop impact,

(II) movement of fine particles into the upper few centimeters of soil and deposition in pores,

(III) compaction of soil surface to form a thin film on the surface which restricts entry of water and movement of fine particles in the soil pores, and

(IV) when the rain ceases, deposition of suspended material and orientation of clay particles sufficient to decrease the permeability still further.

MC INTYRE (1958a& b) found the crust to consist of two distinct parts:

(I) an upper skin of 0.1 mm thick attributed to compaction by raindrop impact, and

(II) a "washed in" region of 2 mm thick with decreased porosity attributed tio the accumulation of particles. The "washed in" layer was formed only on soils that were easily dispersed.

MORIN et al. cited by AGASSI et al. (1981) suggested that the sealing efficiency of the crust is achieved by suction forces which arrange the clay particles into a continuous dense skin. The suction forces at the soil crust interface are created as a result of the large differences in hydraulic conductivity between the crust and the underlying soil.

CHEN et al (1980) distinguished by SEM-analysis three stages during the structural crust formation:

(I) the initial stage, at which the soil exhibited uniform distribution of particles;

(II) a middle-term stage, at which coarse particles, stripped of the fine ones, constituted the surface layer of the soil; and

(III) a final stage, at which the coarse particles were washed away and a thin seal skin, about 0.1 mm thick, is formed at the soil surface.

The depositional crust, which was formed mainly by translocation of fine particles is also characterized by the presence, at the surface of the soil, of a thin skin about 0.1 mm thick.

AGASSI et al. (1981) and KAZMAN et al. (1983) suggested that crust formation is due to two mechanisms:

(I) a physical dispersion of soil aggregates caused by the impact action of the raindrops, and

(II) a chemical dispersion which depends on the soil exchangeable sodium percentage and the electrolyte concentration of the applied water.

GOYAL et al. (1980) and ONOFIOK and SINGER (1984) summarized the steps for crust formation into the following:

(I) breakdown of soil aggregates by raindrop impact, slaking or rupture by air entrapped in the previously dry soil particles;

(II) washing of fine particles into pores, clogging them preventing further movement of particles;

(III) deposition of soil particles on the surface from suspension. During deposition, particles are arranged either randomly or with a preferred orientation, depending upon their shapes, platy particles assume a preferred parallel orientation while spherical particles are randomly arranged; and

(IV) compaction of the soil surface due to rearrangement of particles on deposition to form a thin film on the surface which restricts further entry of water and movement of fine particles in the soil pores.

However, the intensity of each process, as influenced by the physical, chemical, and mineralogical properties of the soil.

Drying is the final process responsible for hardening of the soil crust.

HILLEL (1960) showed three factors to be responsible for the densification of particles in the crust drying:

(I) tendency of platy particles in a state of semi-suspension to settle with their long axis horizontally;

(II) possible attraction between adjoining particles as their spheres begin to overlap; and

(III) the retreating menisci of increasing of contact between adjoining particles.

The orientation of particles during crust formation would be expected to contribute to the rigidity of the crusts.

4. FACTORS INFLUENCING SEALING AND CRUST FORMATION.

Factors affecting crusting can be grouped into (i) external factors that are related to climatic conditions, and (ii) internal factors that are related to soil properties.

Only the influence of internal factors will be discussed.

4.1. Mechanical properties and type of clay.

Despite a great volume of published literature, it is still unclear which soil fraction, silt or clay influence most crust development.

GORBUNOV and BEKAVERITCH (1951) found that clay content was significant while LEMOS and LUTZ (1957) and HEINONEN (1965) did not. LEMOS and LUTZ (1957) and COOPER (1968) concluded that silt content was directly related to crust strength, as did TACKETH and PEARSON (1965) and GERARD (1965) using artificial mixtures. LEMOS and LUTZ (1957) observed as well that for some soils silt plus clay, or silt + clay + very fine sand were more closely related to crust strength.

LEMOS and LUTZ (1957) observed that for soils of the same mechanical composition, the montmorrillonite content was directly related to crust strength but HANKS (1960) identified kaolinite as the most significant clay mineral. ROBINSON and PAGE (1950) however found that aggregates of kaolinite, when wet in vacuum, showed no slaking at all. Aggregates of illite showed only a slight creacking while aggregates of montmorillonite showed a slow but complete desintegration. This observation suggests that for kaolinite and illite air within the aggregate in some way causes or is related to slaking. This supports YODER's (1936) hypothesis, which relates slaking to entrapped air.

The fact that montmorillonite slakes even when wet and in a vacuum indicates that for this type of clay there is some other factor causing slaking in addition to entrapped air. Since montmorillonite swells when placed in water, in contrast to the other two minerals, it can be inferred that swelling is also a cause of slaking (HENIN, 1948).

In recent years, less emphasis has been placed on the type of

clay as related to crusting, due to the fact that soils generally contain a mixture of clay minerals. Probably smectite clay is more effective in binding the soil particles and therefore causes harder crusts than kaolinitic clay. On the other hand high content of smectite will activate the swelling and shrinkage of crust and prevent complete sealing of soil surface. In arid regions the presence of fibrous clay minerals like palygorskite and sepiolite could affect the strength of crust. Hard and thick crusts were found in soils that contain high palygorskite content in some soils of Saudi Arabia.

So the two main causes of slaking are entrapped air and shear stresses due to swelling. The severety of slaking depends on the initial dryness of the crumbs (KOENIGS, 1961) and also on the orientation of the clay (BREWER and BLACKMORE, 1956). Further the size and shape of the clay crystals will affect both the total swelling and the amount of entrapped air.

DULEY (1939) observed that a dense layer was also formed on pure sand. RUSSELL (1934) indicated that soils containing 40 % or more of fine sand favor hard surfaces which are diffucult for young seedlings to break through. TACKETT and PEARSON (1965) reported that the addition of 5 percent of either silt or clay to the the sand tresulted in no measurable increase in crust strength, increasing the silt to 22.6 % caused a sharp rise in crust strength, and further 5 % increase in clay nearly doubled the strength again. BRYAN (1973) stated that sandy soils develop only weak and discontinuous crusts. Even in the absence of significant clay a coarse textures soil may develop some resistance to penetration, due to packing and interlocking of angular particles.

FERRY and OLSEN (1975) indicated the effect of particle size on the crust strength: clay › silt›› sand. They suggested that this trend is attributed to the relative irregularity of the larger particles and to the corresponding difference in total areas available for surface-to-surface attraction.

4.2. Organic matter.

The most consistent factor influencing crust resistance apart from montmorillonite is organic matter content.

ROBINSON and PAGE (1950) indicate that organic matter associated with the clay is largely responsible for aggregate stability. GIESEKING (1939) and (1941) have shown that the swelling properties of clay are reduced by absorption of organic complexes.

Measurement of the contact angle of water on clay surfaces showed that the destructive forces of entrapped air is reduced by absorbed organic matter. The decrease of the wettability of the clay surfaces results probably in a cementing bond that is less easily hydrated and therefore one which gives greater aggregate strength in water.

From these explanations it appears that organic matter promotes aggregate stability by:

(I) reduction of destructive forces of entrapped air,
(II) decrease in wettability, and
(III) strengthening the aggregate.

4.3. Cationic and electrolytic effects.

ROBINSON and PAGE (1950) shown that the hydrogen ion is much more effective in aggregate stabilization than calcium or sodium. However, it is shown that calcium exibit a more stable cementation in the absence of excess salts.

Crust formation increase as the rate of drying decreases and as the degree of colloidal dispersion increases. As water evaporates the soil surface often becomes charged with a relatively high concentration of sodic salts and consequently with a high exchangeable sodium percentage. With subsequent infiltration of rain or irrigation water, the salts are normally leached but the exchangeable sodium percentage (ESP) remains high. The resulting combination of high ESP and low salt concentration induces colloidal dispersion, which contributes to the formation of a dense crust (HILLEL,1960).

Another important factor affecting the formation of a surface seal is the chemical composition of the infiltrating solution. Indeed, it is known that a high sodium adsorption ratio (SAR), coupled with a low overall concentration of salts, induce dispersion and swelling of the clay present in the soil's surface layer. The effect of sodium in the added water is particularly pronounced energy of the applied water. Extreme clay dispersion and clogging can occur at SAR values as low as 10 if solution concentration is lower than 2 mole/m3. Particularly destructive to surface structure is the alternation of sodic irrigation water with rainfall.

When only the physical mechanisms operates, (no sodium in the exchangeable complex) the infiltration rate of the soil dropped to values around 9 mm/hr. In soil with low ESP (≈ 5) values watered with distilled water, chemical dsipersion also operated and the final infiltration rate dropped to values around 2 mm/hr. The intensity of chemical dispersion depended on both the soil ESP and electrolytic concentration in the applied water. In soils with low ESP (≈ 5), an increase in electrolyte concentration to 5 meq/l reduced the chemical dispersion sharply. Conversely, in soils with moderate to high ESP, a gradual change in infiltration rate occured as the electrical conductivity (EC) of the applied water was increased from 100 to 5600 µS/cm.

SHAINBERG et al. (1981) and GAL et al. (1984) found that clay dispersion occured at an ESP as low as 1 to 2.

5. EFFECTS OF SOIL SEALING AND CRUSTING ON SOIL PHYSICAL PROPERTIES.

The deleterious efffect of a seal or a crust on the agricultural properties of a soil are both direct, in that the crust inhibits plant growth, and indirect, in that desirable soil processes are adversely affected. The indirect affects, influencing soil processes, include the decrease of water intake rate, increase runoff and erosion hazards, restriction of air capacity and internal aeration and increase of mechanical strength as the soil crust dries out.

5.1. Mechanical strength.

Attempts have been made to characterize soil crusting, particularly with respect to its effect on seedling emergence, in terms of the resistance of the crust to the penetration of a probe (PARKER and TAYLOR, 1965) as well in terms of its strength as exhibited in the modulus of rupture test (RICHARDS, 1953).

5.1.1. Modulus of rupture.

RICHARDS (1953) and REEVE (1965) determined the modulus of rupture on prepared soil briquets approximately 1 x 3.5 x 7 cm formed replacing screened dry soil in brass molds, wetting for one hour and drying at 50°C. The force required to break a briquet when loaded as a horizontal beam is measured and the modulus of rupture, which is the maximum fiber stress is calculated.

RICHARDS (1953) found, using these technique, that an increase in modulus of rupture from 0.0108 to 0.0273 MPa resulted in a decrease in emergence of bean seedling from 100 top 0 percent. HANKS and THORP (1956, 1957) reported that crusts apparently limited emergence of wheat, grain, sorghum and soybeans, especially at the lower moisture contents. At constant moisture content seedling emergence decreased with increasing crust strength. although some seedlings emerged even where rhe crust strength was high as 0.1400 MPa. ALLISON (1956) also found that emergence of sweet corn was prevented only when the crust strength exceeded 0.1200 MPa.

It has been pointed out that the exchangeable sodium and texture are important in determining the crust strength of different soils. REEVE et al. (1954) found that exchangeable potassium had essentially no effects on the modulus of rupture of five soils studied, but the relationship of the exchangeable sodium to the modulus of rupture appeared to be positive and linear.

However, this method has been used by many investigators and sometimes with slight modifications (EVANS and BUOL, 1968; HANKS, 1960; LEMOS and LUTZ, 1957; FERRY and OLSEN, 1975; GERARD, 1965; TACKETT and PEARSON, 1965; EPSTEIN and GRANT, 1967; and HILLEL, 1960) ARNDT (1965a & b) reported the limitation of the use of such method for crust strength measurement.

Even RICHARDS (1953) did not offered any proof of a causal relationship between the modulus of rupture and seedling emergence data. After a detailed investigation, LEMOS and LUTZ (1957) expressed grave doubts about the application of laboratory results from Richard's technique to field practices. They virtually condemned the method without defining the basic faults or suggesting an alternative.

5.1.2. Penetrometer

Any device forced into the soil to measure its resistance to vertical penetration may be called a penetrometer (DAVIDSON, 1965). Different types for different purposes of penetrometer with procedure are described by DAVIDSON (1965). A hand-operated penetrometer with pointed cone was constructed and used by CRUSE et al. (1981) to determine a penetrometer resistance reported as cone index (C.I.). They reported that the motor-driven penetrometer caused localized compaction in the region surrounding the penetrometer cone and caused erroneous C.I. measurements. PAGE (1979) measured the strength of crust as the force required to drive a 2 mm diameter flat ended cylindrical silver steel penetrometer probe vertically downwards through the soil crust. GERARD (1980) measured the crust strength using a 60° con-shaped penetrometer fitted in the load bottom of a transducer. BILBRO and WANJURA (1982) determined the crust strength by slow forcing the blunt 3.97 mm diameter tip of a hand held penetrometer (a "push-pull" guage) into the crust until the resistance dropped. SHADFAN et al. (1986) measured the strength of crusted materials with a lat tip penetrometer attached to a single action hydraulic cylinder. To prevent the effect of roughness of the bottom surface of the different samples on their resistance to penetration pressure, the lower 1 cm of bulk samples was immersed in a high viscosity resin that does not penetrate soil pores and hardened at room temperature.

Only a few studies deal with the use of penetrometers in order to estimate crust strength in relation to shoot growth. TAYLOR et al. (1966) determined the relationship between crust strength and emergence of corn, onion, barley, wheat, switchgrass and rye seedlings by means of laboratory penetrometer. A slight decrease in emergence percentage was observed for crust strengths in the range of 0.6-9.0 MPa, with no emergence occuring above the 1.2-1.8 MPa range. Earlier experiments of PARKER and TAYLOR (1965) on emergence of sorghum seedlings, yields values of 0.3 MPa and 1.3-1.8 MPa, respectively.

CALLEBAUT et al. (1985) used a motor-driven needle-type penetrometer in order to determine the critical crust strength of salsify (Scorzonera hispanica) during a field experiment. A range of different crust strentgth were established by treating a sealed soil surface, which was created by natural rainfall, with different soil conditioners. They observed that the penetration resistance of the needle was negatively affected by the water content and positively by the density of the soil surface layer. Seedling

emergence of salsify was negatively correlated with the penetration resistance, the critical penetration resistance being 0.037 MPa.

Nevertheless, the comparison of the results from different investigators is difficult, even not possible, as different types of probes and different test procedures have been used.

LA et al. (1985) investigated deeply the effect of base area, cone angle, probe type as well as moisture content, aggregate-size and penetration speed on the penetration resistance under laboratory conditions.

Figure 1 shows the relationship between the penetration resistance versus <u>the moisture content</u> for different types of probes.

Figure 2 shows the effect of <u>the base area</u> of 60 deg. cones on the average penetration resistance of soils of different aggregate-size.

Figure 3 shows the effect of <u>cone angle</u> on the average penetration resistance for the cones of 30 deg., 60 deg. and 90 deg.

Figure 4 shows the effect of the <u>type of probe</u> on the average penetration resistance .

Figure 5 shows the effect of the <u>penetration speed</u>.

Table 1 shows the relationships between the penetration resistance of the 5 probes and the needle.

Obviously the critical crust strength which prevents emergence depends on crust thickness, soil wetness, plant species, seed placement (HILLEL, 1972; LA, 1985) as well as on the used probe and measuring conditions (LA, 1985).

5.1.3. Other devices.

ARNDT (1965 a,b) described a technique of using a crude balance which he burried in a chamber in the field to measure crust impedance. His measuring technique was laboritous ! His watering system to cause crust formation leave much to be desired. The limited data by Arndt's are, however, the first realistic data available.

BENNETT et al. (1964) used a device which consisted of 2 rollers set in ball bearings and mounted on a ooden frame. To make a measurement, a length of fly fishing line was tied to the end of the line protruding from the soil. The line was then placed over the two rollers and a small container tied to the opposite end. Sand was slowly added to the container until the line was pulled to the surface of the soil. The weight of sand used is reported as the crust breaking strength index. Similar design with some modification using water flow instead of sand to generate force was used by BROSSMAN et al. (1982).

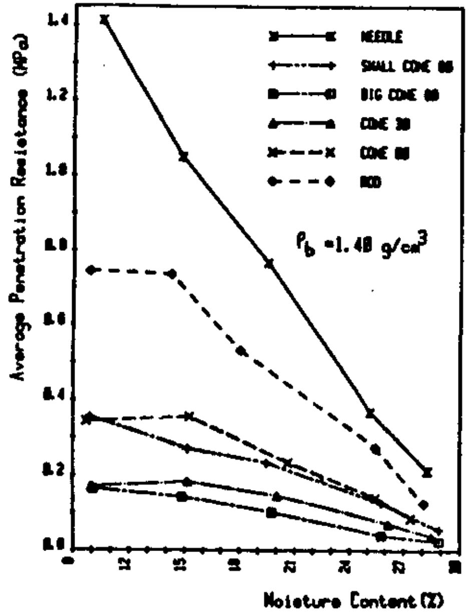

Figure 1 - Average penetration resistance vs. moisture content for different types of probe (fraction : < 2 mm, penetration speed : 15 mm/min)

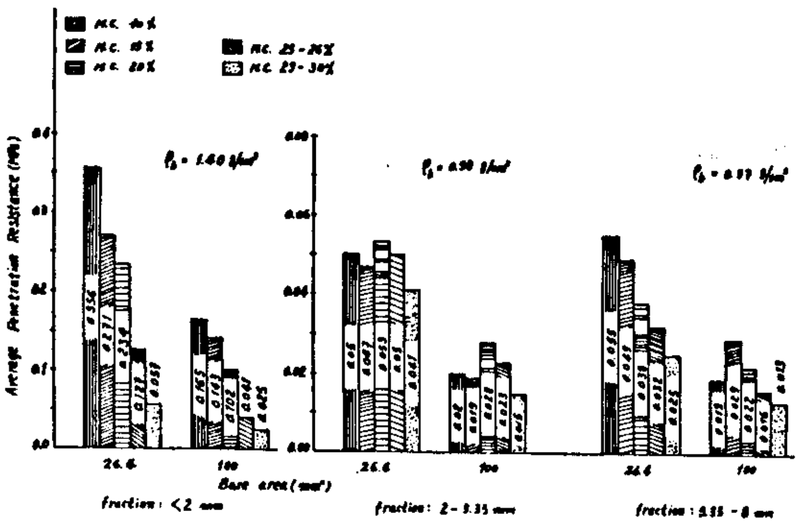

Figure 2 - Effect of the base area of 60 deg. cones on the average penetration resistance of soils of different aggregate sizes (penetration speed : 15 mm/min)

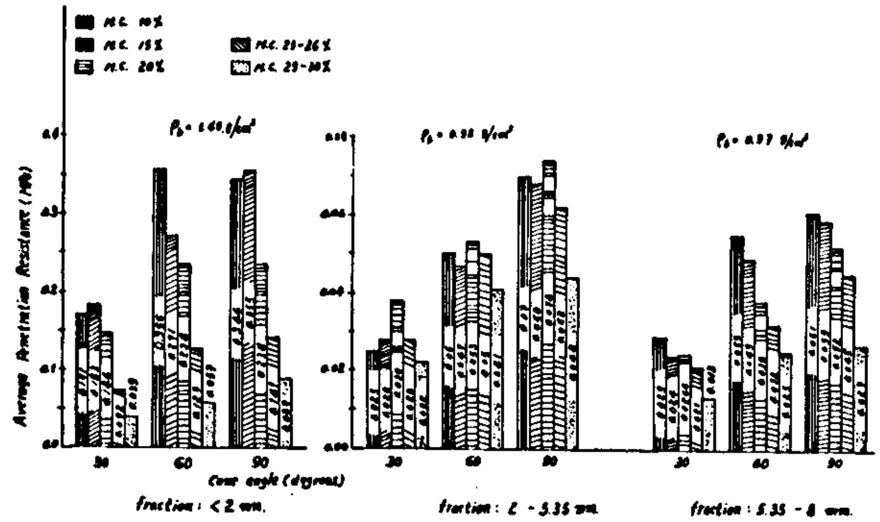

Figure 3 - Effect of the cone angle on the average penetration resistance for the cones of 30 deg. (28.3 mm^2), 60 deg. (26.4 mm^2) and 90 deg. (29.2 mm^2) (penetration speed : 15 mm/min)

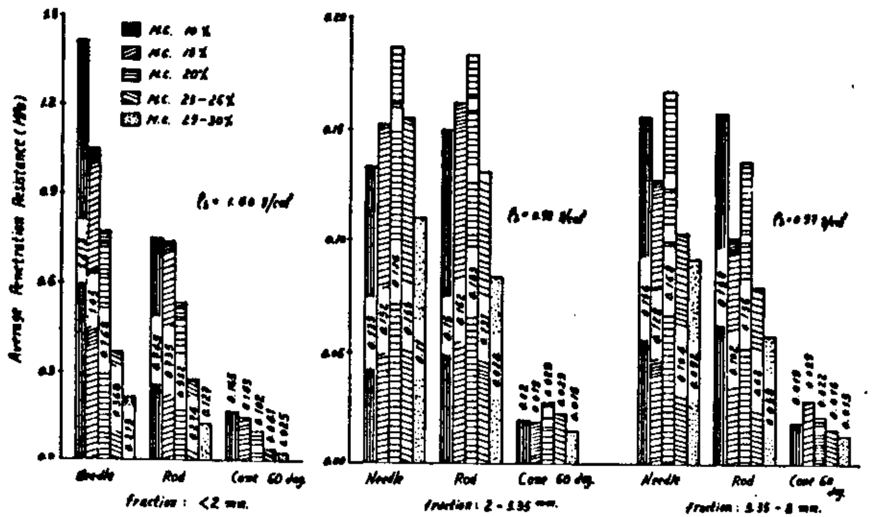

Figure 4 - Effect of the probe on the average penetration resistance for the needle (1.4 mm^2), rod (7.8 mm^2) and 60 deg. cone (100 mm^2) (penetration speed : 15 mm/min).

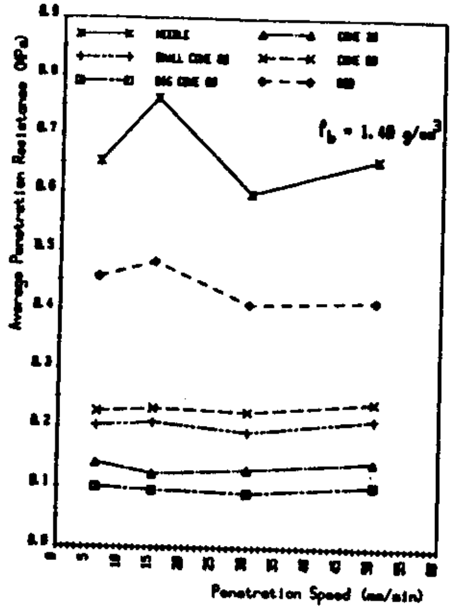

Figure 5 - Average penetration resistance versus penetration speed of probes for different types of probe (fraction < 2 mm, M.C. : 10-30 %)

TABLE 1 : Equation showing the relationship between the penetration resistance (MPa) of the 5 probes and the needle (penetration speed : 15 mm/min)

PROBES	EQUATION		FRACTION (mm)
Y - X $60°_S$ - Needle	$Y = 0.277X^{1.234}$	(r = 0.968)	< 2
	$Y = 0.703X^{1.483}$	(r = 0.903)	2 - 5.35
	$Y = 0.648X^{1.442}$	(r = 0.884)	5.35 - 8
$60°_B$ - Needle	$Y = 0.108X^{1.388}$	(r = 0.951)	< 2
	$Y = 1.07X^{2.247}$	(r = 0.928)	2 - 5.35
	$Y = 0.505X^{1.744}$	(r = 0.843)	5.35 - 8
30° - Needle	$Y = 0.151X^{1.246}$	(r = 0.944)	< 2
	$Y = 0.702X^{1.804}$	(r = 0.953)	2 - 5.35
	$Y = 0.339X^{1.442}$	(r = 0.859)	5.35 - 8
90° - Needle	$Y = 0.317X^{1.143}$	(r = 0.959)	< 2
	$Y = 0.814X^{1.383}$	(r = 0.907)	2 - 5.35
	$Y = 0.93X^{1.517}$	(r = 0.876)	5.35 - 8
Rod - Needle	$Y = 0.649^{X0.903}$	(r = 0.971)	< 2
	$Y = 0.979X^{1.015}$	(r = 0.897)	2 - 5.35
	$Y = 1.09X^{1.156}$	(r = 0.918)	5.35 - 8

HOLDER and BROWN (1974) used a simple instrument to evaluate the crust impedance. The measuring apparatus consisted of a probe, a 4000 g precision top-loading balance, and a hand operated screw jack on a small base with swirl wheels. The probe consisted of a steel ball bearing (3.24 mm diameter) welded to a brass rod of smaller diameter which was mounted on a flat box. The probe was placed on the pan of the balance which was on a wooden base bolted to the top platform of the scissors-type jack. The balance and probe were slowly and steadily raised by the jack and the mechanical impedance was recorded by noting the highest reading on the balance before the crust was broken.

5.2. Infiltration capacity.

The soil structural relationships of the immediate surface have a major effect on the infiltration capacity of the soil. The crust has a higher bulk density and lower porosity than the underlying soil and even though it may be quite thin (perhaps only a few miillimeter thick) its affect on the hydraulic properties can be important.

For example MC INTYRE (1958) found that a 1.5 mm surface seal decreased the permeability ofthe surface layer of a fine sandy loam from 10exp-3 cm/sec to about 5 x 10exp-7 cm/sec. SCHMIDT et al (1966) observed a very rapid decrease in infiltration during the first 15 minutes of rainfall, followed by a near constant infiltration rate of about 0.46 cm/hr after 30 minutes. This rapid decrease in infiltration rate was attributed to rapid surface sealing and crust development. These detachment and transportation processes are dependent to a large extent on rainfall impact energy and soil surface characteristics. FALAYI and BOUMA (1975) measured an infiltration rate into uncrustyed soil 0f 9.26 x 10exp-3 cm/sec. this was reduced in the presence of an 0.1 mm thick crust to 8.1 x 10exp-4 cm/sec.

The infiltrability as a function of time in a uniform soil, in a soil with a more permeable upper layer and in a soil covered by a surface crust is shown in figure 6.

5.3. Aeration.

Soil aeration is realated to the volume fraction, continuity and the stability of air-filled pores. The stability of the soil structure, especially the openess of the large pores at the top layer during wet periods is one of the most important factors determining soil aeration.

The emergence and root system can be paralysed if the aeration is blocked by a slaked and wet layer at tthe top. The effect is more pronunciated during a warm period when oxygen consumption is high. Diffusion of oxygen is not restricted significantly in the case of a dry crust.

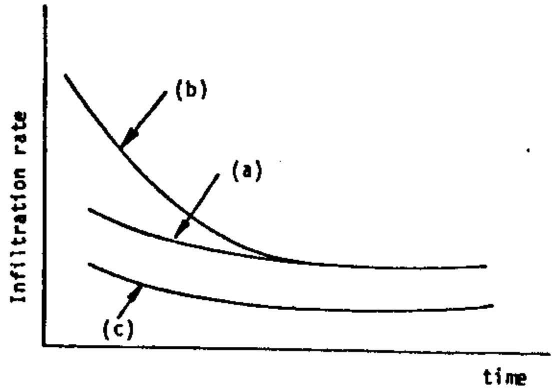

FIGURE 6 : Infiltrabilty as a function of time (a) an a uniform soil, (b) in a soil with a more permeable upper layer, and (c) in soil covered by a surface crust.

HANKS and THORP (1957) observed that oxygen was alimiting factor in the mergence of wheat seedlings whenever the oxygen diffusion rate (O.D.R.) was below 70 to 100 10exp-8 g/cm²min. This rate of diffusion corresponded to pore space of approximately 16 percent in silty clay loam and 25 percent in a fine sandy loam. As soil compaction was increased the oxygen diffusion rate decreased and at the same time the crust strength increased. Consequently it is difficult to say which of the two variables was responsible for the decreased seedling emergence. However there is no doubt that in some instances both oxygen diffusion rate and crust strength are important.

AHMAD and ROBBIN (1971) found a decrease in gaseous diffusion with a loam soil when a surface crust was present. Uncrusted wet soil allowed 23 percent diffusion compared with the dry uncrusted soil. Crusted wet soil allowed only 11 percent diffusion.

DOMBY and KOHNKE (1957) stated already that surface crusts restricted diffusion only at low moisture tensions. The wetter the soil the greater the influence of the crust on diffusion.

CALLEBAUT at al. (1981, 1982) investigate (1) the effect of soil sealing on oxygen diffusion and sugar beet emergence in a sandy loam and clay soil, (2) the application of a polyacrylamide, PAM, spray in order to protect the soil surface against the beating action of raindrops and (3) the use of calciumperoxide, CaO2, as an oxygen supplier. Favourable effects of stabilization with PAM and CaO2 fertilization on oxygen diffusion and emergence of sugar beets could be observed. Throughout the germinationthe O.D.R. remained above the critical level of 40 x 10exp-8 g/cm²min for PAM and CaO2 treated soil. Low O.D.R. values were recorded on the untreated slaked soil. On the sandy loam soil CaO2 besides being an oxygen supplier, stabilized the surface clods. On the

clay soil CaO2 did not improve the stability of the aggregates and surface sealing was observed after the simulated rainfall. However higher O.D.R. values and better emergences than in the untreated soil were recorded. It can be concluded that even in the presence of a mechanical barrier and high moisture contents the seeds can emerge if they have enough oxygen to break through.

6. SOME POSITIVE EFFECTS OF SOIL SEALING AND CRUSTING.

The effects of sealing and crusting are mostly but not all, negative. Some are however positive:

- protection against wind erosion.
- more economic distribution of irrigation water (longer lengths-of-run of furrows possible).
- water harvesting (traditional in parts of Hausa land in West Africa, in the Neguev, North Yemen, etc.).

7. SOIL SEALING AND CRUSTING MANAGEMENT.

Various practices and soil treatments have been used to prevent or reduce sealing and crusting.

CARNES (1934) indicated that calcium-treated soils had a greater modulus of rupture than the soil without treatment. PEELE (1936) found that the force required to penetrate the soil increased as the amount calciumcarbonate added increased.

On land covered by vegetation a large proportion of the raindrops are intercepted by plants and lose most of their kinetic energy before reaching the soil surface. This reduces crust formation as was shown by DULEY (1939).

Crusting of soils can also be controlled by surface mulches, which protect the soil from the impact of raindrops.

For soils in the humid regions the simple flocculation effects might be considered as the worst possible condition which can be improved by organic matter addition.

In arid regions the reclamation of dispersed soils by the use of soil amendments such as gypsum, which establish the flocculated condition, should be considered only as a prelimary step to the achievement of desirable soil structure and should be followed by a program of organic matter build up and maintenance.

Soil conditioners have been successfully used for preventing soil crusting on alkali soils. HEDRICK and MOWRY (1952) studied the effect of several complex polyelectrolytes on prevention of soil crusting. ALLISON (1952) obtained fulle stands of corn in saline-alkaline soil conditions by using synthetic polyelectrolytes. Stands on the non-treated soil varied from 0 to 40 percent with little or no yield because of heavy crust formation. Beneficial effects of soil conditioners have been found by SHERWOOD and ENGIBOUS (1953) and CALLEBAUT et al. (1981,1982).

Table 2 summarizes some of the suggested solutions.

Table 2. Suggested solutions to crusting

Applied Materials	Effect on Crust	Authors
Vinyl Acetate-Maleic Acid (VAMA) and hydrolyzed polyacrylonitrite (HPAN)	Stable aggregate reduced crusting, VAMA more effective than HPAN espec. for alkali soils	Allison and Moore (1956a & b) Allison (1956), Jamison (1954), Sherwood and Engibous (1953), Martin (1953)
Rosinate X, Rosinate T, Rosinate WVR, polyacrylonitrite, phenolic-aldehyde and silicate (N)	Found not active in decreasing modulus of rupture	Jamison (1954)
Formula No. 2793960 of Mansanto Chemical Company	Stabilized soil crumbs and reduced crust formation	Kirkham (1961)
4-Tert-Butylpyrocatechol	Induced fracturing in soil surfae	Hemwall and Scott (1962)
Calcium chloride, Kirlium, black plastic film, water emulsion asphalt, calcium sulfate, soil fracturing agent (S-1593, Dow Chemical) and planted in furrow	Reduced crust strength, increased seedling emergence of cotton as follows: plastic > S-1593 > asphalt > vinyl resin > furrow > calcium sulfate > krilium > calcium chloride	Bennett et al. (1964)
Black granular coke mulch	Formed friable soil crust	Qashu and Evans (1967)
Hexadecanol	Reduced modulus of rupture	Myhrman and Evans (1969)
Polyacrylamide	Increased oxygen diffusion rate and sugar beet germination	Callebaut et al. (1981)
Phosphoric acid	Decreased soil crusting, inreased emergence of seedlings	Delbert D. Hemphill (1982), Anderson (1976), Robbins et al. (1972), Thien (1976), Lutz et al.(1965)
Monocalcium phosphate	Less effective in reducing crust phosphoric acid	Lutz et al. (1965)
Concentrated sulphuric acid	Decreased crusting	Johnson and Law (1967)
Phosphogypsum	Prevented the formation of "washed in" layer in crust	Gal et al. (1984)

Applied Materials	Effect on Crust	Authors
Hydrolyzed starch polyacrylonitrite graft copolymer "super sluper"	Decreased crust strength and infiltration and increased water retention	Hemyari and Nofzinger (1981), Kaniuka (1975), Miller (1979)
Poly vinyl alcohol (PVA)	Prevented crust formation and enhanced aggregate stability	Page (1979) Oades (1976)
Polyelectrolytes (CRD-186, and CRD 189)	Reduced crusting and increased aggregation	Allison (1952), Hedrick and Mowry (1952)
Sewage sludge and big slurry	Decreased crusting, improved soil fertility	Pagliai et al. (1983)
Addition of Fe^{III} polycation	Decreased crust formation and improved physical properties	Shanmuganathan and Oades (1982)
Synthetic iron oxide	Decreased crust strength	Golden and Dixon (1985)
Tillage-gypsum	Decreased crust strength and runoff	Fenkel and Hadas (1981)
Calcium carbonate	Increased soil penetration resistance	Peele (1937), Carnes (1934)
Vermiculite and activated carbon granules	Reduced crusting	Willaim and Romanowski (1972)
Irrigation with saline water ($EC = 5.0\ dSm^{-1}$)	Increased infiltration rate	Hardy et al. (1983), Agassi et al. (1981)
The use of rotary hoe	Destroyed soil crust, increased emergence of cotton	Bilbro and Wanjura (1982)
Mechanical crust breaking	Prevented stand losses in tomatoes	Ells (1965)
Compaction below the seeds	Improved footing of seedlings	Carnes (1934)
Vegetation covers	Decreased impact of rainfall	Duley (1939)
Select varieties capable of rapidly exerting large emergence forces	Decreased effect of crusting on seedling	Parihar cited by Goyal et al. (1982), Gerard (1980)

8. LITERATURE

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