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BARD

United States - Israel Binational Agricultural Research and Development Fund

FINAL REPORT

PROJECT No. I-77-80

The Chemistry of Soil Crust Management

I. Shainberg, J. Morin, J.D. Oster

1984

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APPENDIX IV.

Date: December, 1983.

BARD
P.O.B. 6,
Bet Dagan, ISRAEL.

BARD No. of Proposal: 1-77-80

Title of Proposed Research:

THE CHEMISTRY OF SOIL CRUST MANAGEMENT

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Project starting date: October 1, 1980.

Type of Report: Final

Signature:

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1) Soil chemistry

630.72 : 631.41

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c. - Abstract

Crust formation at the soil surface is a common feature of many soils particularly in the arid and semi-arid regions. Crust formation is due to two complementary mechanisms: i) a mechanical breakdown of soil aggregates caused by the beating action of the rain drops and ii) a chemical dispersion which depends on the soil ESP and the electrolyte concentration of the applied water. In soils exposed to rain, 3-5 percent of exchangeable Na are enough to cause crust formation and low infiltration rate. Presence of electrolytes in the percolating water prevent crust formation. Soil surface is especially susceptible to exchangeable Na because of the mechanical impact of the raindrops, the low concentration of electrolytes in the rain and the relative freedom for particle movement at the soil surface.

The crust may consist of two distinct parts: i) an upper skin seal attributed to compaction by raindrop impact and ii) a "washed in zone" of decreased porosity attributed to accumulation of clay particles. When the soil ESP is <1-2, or when the electrolyte concentration in the applied water is high, chemical dispersion of the clay particles and the formation of the "washed in zone" is prevented. Under these conditions, the crust consists of a compacted seal skin only with relatively high infiltration rate. Conversely, when the ESP of the soil exceeds 4-5, clay movement and the formation of a "washed in" layer is the dominant mechanism and the IR drops to 1-2 mm/h.

d. Report

1. INTRODUCTION

The formation of crust at the soil surface, especially due to the action of rain drops but also as a result of sprinkler irrigation (Aarstad and Miller, 1973), is a common feature of many soils, particularly in the arid and semi-arid regions. Surface crusts are thin (<2-3 mm) and are characterized by greater density, finer pores and lower saturated conductivity than the underlying soil. Soil crusts have a prominent effect on many soil phenomena, e.g. the reduction of infiltration and increase in runoff (Cary and Evans, 1974; Hillel, 1980; Hillel and Gardner, 1969, 1970; Morin et al., 1981; Parr and Bertrand, 1960), slowing of the soil-atmosphere gas exchange (Domby and Kohnke, 1956), and interference with seed germination (Frelich et al., 1973; Hanks and Thorpe, 1957; Sale and Harrison, 1964; Taylor, 1962).

It is customary to distinguish between two types of crusts by their mechanisms of formation: those formed as a result of water drop impact (structural crusts), and those formed by translocation of fine soil particles and their deposition at a certain distance from their original location (depositional crusts). The formation of structural crust is the subject of this review.

The properties of structural crusts and their manner of formation have been studied for many years (see, for example, the reviews by Cary and Evans, 1974; Hillel, 1980; Parr and Bertrand, 1960), and attempts have been made to apply the knowledge gained to rational control of crusting. This application has been difficult because of the problems of isolating factors of crust formation and evaluating their relative contribution (Cary and Evans, 1974).

Crust formation in soils exposed to the beating action of falling drops is due to two mechanisms: (i) Breakdown of the soil aggregates caused by the impact action of the raindrops over the soil surface. The destruction of the aggregates reduces the average size of the pores of the surface layer. Also, raindrops' impact causes compaction of the uppermost layer of the soil. These factors produce the thin skin seal at the soil surface (Epstein and Grant, 1973; Farres, 1978; McIntyre, 1958; Morin et al., 1981). (ii) A physico-chemical dispersion of the soil clays which can then migrate into the soil with the infiltrating water, and clog the pores immediately beneath the surface (the "washed in" zone) (McIntyre, 1958; Agassi, et al., 1981; Kazman et al., 1983). The first mechanism is mechanical in nature and the relations between crust formation, runoff and erosion on the one hand, and the energy and momentum of the raindrops on the other hand, have been described in many reviews (e.g. Parr and Bertrand, 1960; Wischmeier and Smith, 1978). Aggregate disintegration and clay dispersion due to chemical forces predominate in the second mechanism, and the effect on crust formation of the adsorbed cations and the electrolyte concentration in the applied water, was not studied systematically until recently. Soil surfaces are particularly susceptible to the chemistry (electrolyte concentration and cationic composition) of the applied water, because of the mechanical action of the falling drops and the relative freedom for particle movement at the soil surface (Oster and Schroer, 1979).

These chemical aspects of crust formation and their interaction with the mechanical aspects, are discussed in this review. The interactions are evaluated by two experimental methods: (i) the effect of

1 soil sodicity and electrolyte concentration on the hydraulic pro-
2 perties of the crust as determined by the infiltration rate, and (ii)
3 the effect of soil sodicity and electrolyte concentration on the
4 structure of the crust as determined by scanning electron microscope
5 (SEM) observations.

2. CRUST PROPERTIES AS DETERMINED BY THE INFILTRATION RATE (IR)

2.1 Definitions and Experiments

The infiltration rate (IR) is defined as the volume flux of water flowing into the profile per unit surface area of soil, and this flux has the dimension of velocity. In general, the soil infiltration capacity is initially high, particularly when the soil is initially dry, but tends to decrease monotonically until it asymptotically approaches a constant rate--the final infiltration rate (FIR) or steady-state infiltration rate. If the water delivery rate to the surface is lower than the soil infiltration capacity, water infiltrates as fast as it is delivered and the supply rate determines the infiltration rate. When the delivery rate exceeds the soil infiltration capacity, it is the latter which determines the actual infiltration rate, and the process becomes surface-controlled.

The rate of water infiltration into a fallow soil is affected by the hydraulic properties of the soil profile and by the hydraulic conductivity of the soil surface. When crust of very low hydraulic conductivity is formed at the soil surface, the reduced permeability of the crust determines the IR of the soil (Baver et al., 1972; Hillel and Gardner, 1970; Hillel, 1980, Morin and Benyamini, 1977).

Numerous formulations have been proposed in repeated attempts to express the infiltration rate as a function of time or of the total quantity of water infiltrated into the soil (Baver, et al., 1972; Hillel, 1980; Parr and Bertrand, 1960). The equation most pertinent to crusted soils is that of Horton (see Baver et al., 1972; Hillel, 1980, Morin and Benyamini, 1977).

$$i = i_c + (i_o - i_c)e^{-kt} \quad (1)$$

where i is the infiltration rate, i_c is the asymptotic final infiltration rate (FIR) reached when the time (t) (and the cumulative volume of water that infiltrated) becomes large, i_o is the initial infiltration capacity of the soil, and k is a constant which determines how quickly it will decrease from i_o to i_c .

A tool for studying the effect of soil sodicity and irrigation water salinity on the infiltration rate and crust formation in soils is the rain simulator, such as that developed by Morin et al. (1967). Soil samples are packed in 30 x 50 cm trays, which are placed in the simulator at a predetermined slope, and subjected to simulated rain. The intensity of the rain and the impact energy of the drops can be controlled; the chemistry of the water can be changed according to experimental plan. When rain water is to be simulated, water of electrical conductivity of 0.01 dS/m is applied. Irrigation water of any desired quality can also be placed in the rain simulator. The volume of the runoff water and that of the percolating water is measured and the infiltration rate is calculated.

2.2 Effect of soil sodicity on the IR of soils

The effect of exchangeable sodium percentage (ESP) on the IR and crust formation of four soils varying in texture, clay mineralogy and CaCO_3 content was studied by Kazman et al. (1983) using distilled water in a rain simulator. The IR of two soils, a non-calcareous sandy loam and a calcareous silty loam, are presented in Figs. 1 and 2. The final IR of the sandy loam with ESP 1.0 was maintained at 7.8 mm/h, whereas the final IR of the soil with ESP values of 2.2,

4.6 and 11.6 dropped to 2.3, 0.7 and 0.6 mm/h, respectively. An ESP value of 2.2 was enough to cause a drop of 70% in the final IR. Similar effects of ESP were observed on the silty loam soil. The amount of rain required to approach the final infiltration rate was also affected by ESP (Figs. 1 and 2). As the ESP of the soil increased, the depth of rain required to reach the FIR decreased.

The U.S. Salinity Laboratory Staff (1954), studying many soil samples from western USA, suggested an ESP value of 15 as the critical level above which soil structure could be deleteriously affected. This value was supported by the studies of McNeal and co-workers (1966, 1968) of the hydraulic conductivity of a number of soils. It is evident that the IR is much more sensitive than the hydraulic conductivity to the ESP of the soil. The higher susceptibility of the soil surface to low levels of ESP is explained by three factors (Kazman et al., 1983; Oster and Schroer, 1979): (1) the mechanical impact of the raindrops, which enhances dispersion; (2) the absence of the soil matrix (sand particles), which slows clay dispersion and clay movement; and (3) the low electrolyte concentration in the applied distilled water.

The rain drop impact energy was the same in all the experiments described in Figs. 1 and 2; thus, the differences in IR curves for the various soil samples were due to the potential for soil dispersion caused by sodicity. It should be noted that in soils with very low ESP (<1.0), the mechanical dispersion mechanism predominates, and the FIR of the soils dropped to values around 7-8 mm/h (Figs. 1 and 2). When the impact energy of the rain drops was prevented (by mulching) in soils with low ESP, the IR of the soil was higher than the rate of

1 rain application and the IR line was parallel to the x-axis at IR of
 2 and Morin and Benyamini, 1977).
 3 26 mm/h (Kazman et al., 1983/ Thus, the drop in IR in soils with
 4 ESP 1, which is due mainly to the mechanical action of the rain drop,
 5 is very significant. The further drop in FIR in the soils with higher
 6 ESP (>2.0) is due to chemical dispersion. The degree of the chemical
 7 dispersion depended on the ESP of the soil with increasing ESP resul-
 8 ting in increasing chemical dispersion. In soils with ESP >4.0, the
 9 FIR was maintained at values < 2 mm/h. This effect of ESP has a very
 10 important practical value. Most of the rainstorms have intensities
 11 between 2 and 8 mm h⁻¹. These storms will not produce runoff on soils
 12 with ESP below 1.0, but will produce runoff and erosion in soils with
 13 ESP >4.0.

14 The mechanical and chemical mechanisms are complementary. The
 15 kinetics of the chemical dispersion depends markedly on the intensity
 16 of mechanical stirring. Thus, the mechanical impact of the rain
 17 drops has two effects: (1) breakdown of the soil aggregates, followed
 18 by compaction of the surface and production of thin skin seals
 19 (McIntyre, 1958); and (2) stirring of the soil particles, which enhances
 20 their rate of chemical dispersion. Without the stirring process, the
 21 rate of chemical dispersion might be slow. In HC measurements the
 22 stirring process is kept at a minimal value and a higher percentage of
 23 exchangeable sodium is needed to cause dispersion (U.S. Salinity
 24 Laboratory Staff, 1954; McNeal et al., 1968; McNeal and Coleman, 1966).

25 2.3 Effect of electrolyte concentration on the IR of sodic soils

26 Chemical dispersion of the soil surface may be prevented by
 27 "raining" with solutions of various concentrations using the rain simu-
 28 lator. Agassi et al. (1981) studied the effect of electrolyte concen-

1 tration (and soil sodicity) on the infiltration rate of the two loamy
2 soils described previously; their results are presented in Figures 3
3 and 4. They found that the IR of these soils was affected by the
4 electrolyte concentration up to 50 meq/l. For example, the final IR
5 of sandy loam Netanya soil with ESP 13.6, increased from 1.2 to 2.2,
6 5.3 and 7.5 mm/h as the electrical conductivity of the applied water
7 increased from distilled water to 0.5, 2.3 and 5.6 dS/m, respectively
8 (Fig. 3). Similar results were obtained by Oster and Schroer (1979)
9 on Heimdal soil from North Dakota. They also found that the cation
10 concentration greatly affected infiltration rates even at low SAR
11 levels of 2 to 5. Their data showed that for SAR values between 2
12 and 4.6, the final infiltration rate increased from 2 to 28 mm/h as
13 the cation concentration of the applied water increased from 5 to 28
14 meq/l.

15 Returning to Figures 3 and 4, it is evident that the salt con-
16 centration had an effect on both the final infiltration rate and the
17 rate at which the IR of the soil dropped from the initial to the
18 final IR value. A similar effect was attributed to the soil sodicity
19 (Fig. 1 and 2). The higher the sodicity of the soil, the greater was
20 the rate at which the IR dropped to its final value, and the lower was
21 this final value. It is evident that crust formation is a kinetic
22 process which depends on the electrolyte concentration in the applied
23 water, the ESP of the soil and the disturbance caused by the applied
24 water at the soil surface. When solutions of high concentration are
25 applied, the impact energy of the drops is the main force causing
26 breakdown of the soil aggregates, and a compacted layer with low
27 permeability is produced at the soil surface. The rate at which this

1 compacted layer is formed is relatively slow, and the final IR values
 2 are maintained at 8-15 mm/h. When low salinity water is applied to
 3 the soil, even with low levels of exchangeable sodium, chemical dis-
 4 persion of the soil clays also occurs, the dispersed clay particle
 5 can be washed into the soil with the infiltrating water, and the pores
 6 immediately beneath the surface become clogged quite rapidly.

7 2.4 Chemical management of the crust

8 Chemical dispersion can be prevented by spreading phosphogypsum
 9 (PG) (or other readily available electrolyte source) at the surface of
 10 sodic soils (Agassi et al., 1982; Kazman et al., 1983; Keren and
 11 Shainberg, 1981). Phosphogypsum is a by-product of the phosphate
 12 fertilizer industry and is available in large quantities. Application
 13 of PG at 5 t/ha prior to the rain (Figs. 1 and 2) prevented the drop
 14 in the final IR and the formation of the crust. PG acted as a slow-
 15 releasing salt (Keren and Shainberg, 1981) supplying sufficient
 16 electrolytes to the rainwater and preventing clay dispersion. PG
 17 application increased the final IR of the sandy loam soil from 7.5 to
 18 12 mm h^{-1} for the sample with ESP 1.0, and from 0.6 to $\sim 10 \text{ mm h}^{-1}$ for
 19 soil sample with ESP 11.6 (Fig. 1). Similar observations were made
 20 for the silty loam (Fig. 2) and for other soils (Agassi et al., 1982;
 21 Kazman et al., 1983).

22 2.5 Effect of low-energy rain on the IR of sodic soils

23 A fog-type rain was simulated by Agassi et al. (1984). The fog
 24 drop's diameter was $<0.1 \text{ mm}$, with a maximum drop velocity of 0.1 m
 25 sec^{-1} . The kinetic energy of the fog was $<0.01 \text{ joules/mm.m}^2$. The
 26 fog-type rain simulates the conditions in the field when the soil is
 27

protected from the beating action of the rain drops by the plant canopy or mulching.

The infiltration rates (IR) of the silty loam at two ESP levels (6.5 and 21.0) as a function of the depth of the applied water, at low energy, is presented in Fig. 5. The IR of the silty loam with ESP 6.5 was maintained at the initial infiltration value when water of EC = 0.5 dS/m was applied. Only when distilled water was applied to the soil with ESP 6.5, was a gradual drop in the IR obtained (Fig. 5). In the silty loam with ESP 21, only the saline water maintained the initial IR value. When dilute solutions were applied a gradual drop in the IR was obtained (Fig. 5).

Comparing the IR curves in the low-energy experiments (Fig. 5) with those in the high-energy experiments (Fig. 2), the following differences are evident: The change in IR in the fog experiments is very gradual; the final IR in the high-energy rain is much lower than the corresponding value in the low-energy rain; and the soils exposed to high-energy rain are much more sensitive than the soils exposed to low energy rain to low levels of ESP and to electrolyte concentration in the applied water.

The effect of soil sodicity and electrolyte concentration on the final IR of the silty loam exposed to low-energy rain is given in Fig. 6. Also, in Fig. 6 the relative hydraulic conductivity of the silty loam as a function of the soil ESP and the electrolyte concentration is presented (based on data from Felhendler *et al.*, 1974). The similarity between the two properties in their response to both soil sodicity and water salinity is very pronounced, and they differ markedly from the response of the same soil to sodicity and salinity

1 when the soil was exposed to high-energy rain. When waters of low-
2 energy are applied, the mechanical breakdown of the soil aggregates at
3 the soil surface, and the mechanical stirring of the clay-water system
4 is prevented. Under these conditions the soil is much less sensitive
5 to low levels of exchangeable Na and higher concentrations of electro-
6 lytes are needed to prevent the adverse effect of sodium.

7 Based on these results it is recommended that, in order to
8 increase the IR of irrigation waters into soils with ESP values >3-5,
9 an irrigation method which does not involve the beating action of the
10 drops should be used. Likewise, an irrigation method that does not
11 involve the stirring of the soil surface is preferred. Thus, for
12 soils with the tendency to form a crust, trickle irrigation or sprink-
13 lers with low energy are preferred.

14 2.6 Effect of drying and water quality in consecutive 15 storms on crust stability

16 Morin et al. (1977) studied the effect of drying on the crust of
17 a sandy loam soil. The soil was first rained on with tap water and
18 the final infiltration rate was 8 mm/h^{-1} . The crusted soil was
19 exposed to drying periods of 23 hours, 6 and 11 days, and thereafter
20 was rained on again. The final IR at the end of the second storm was
21 the same as at the end of the first storm, and was independent of the
22 drying period. The initial IR was 50, 160 and 170 mm/h^{-1} for the above
23 drying periods, respectively. The explanation given by Morin et al.
24 was that the increase in the initial IR's in the second storm was due
25 to crack formation in the crust. The number and size of the cracks
26 increased with drying, and thus the initial IR also increased.

27 It is shown in Figures 3 and 4 that when saline water was

1 applied to soils with low sodicity, a final IR of 7-8 mm/h was main-
2 tained, whereas when distilled water was applied, crust was formed and
3 the infiltration rate dropped to 1-2 mm/h. Hardy et al. (1983) stu-
4 died the stability and the reversibility of the crust formed on the
5 sandy loam and the silty loam soils by studying the effect of sub-
6 sequent saline water (SW) irrigation on the stability of crusts
7 formed under distilled water (DW) rain. A drying period of 24 h
8 between the storms was maintained. Their results are presented in
9 Fig. 7.

10 Application of SW in the second storm to the already crusted
11 silty loam (Fig. 7) resulted in a small increase in final IR, from
12 1.8 to 2.5 mm/h, the final value being reached after the application
13 of 40 mm rain. A third storm, of DW, resulted in an infiltration
14 curve essentially identical to that obtained for a second consecutive
15 storm of DW. The crust that was formed in the first DW storm was
16 stable, and there was only a small increase in IR in the SW storm.
17 When a third DW storm was applied, the IR curve was that typical of
18 a second consecutive DW storm, and the intermittent SW storm had no
19 effect on the properties of the crust.

20 Application of SW in the second storm to the crusted sandy loam
21 caused a much larger increase in final IR, to 5.6 mm/h. Application
22 of a third storm, of DW, resulted in a much lower IR at any given rain
23 depth.

24 It is evident that the two soils responded very differently to
25 a storm sequence of alternating water quality. Whereas the crust in
26 sandy loam behaved in a reversible way and the final IR of consecutive
27 storms was almost independent of the previous storm, the silty loam

1 crust behaved in an irreversible way and the effect of the crust
2 formed in the first DW storm was maintained in the second SW storm.
3 This pronounced difference between the two soils was explained as
4 follows: rain drop impact causes¹¹ a breakdown of the soil structure¹¹
5 and the formation of small craters or pits at the soil surface. As
6 rain proceeds, soil erosion takes place and the surface becomes
7 progressively less pitted, until a smooth crust is formed. This
8 phenomenon is well documented (McIntyre, 1958; Farres, 1978). Pit-
9 ting was more pronounced in the sandy loam than in the silty loam.

10 The crust formed during the first storm maintained a continuous
11 crust structure during subsequent storms in the silty loam, while in
12 the sandy loam the crust was reworked by rain drop impact. Conse-
13 quently, in the sandy loam the crust formed during any particular
14 storm has little relationship to the crusts formed in previous storms,
15 whereas in the silty loam the crust - which is not destroyed by sub-
16 sequent storms - determines the IR curves of the consecutive storms.
17 The response of the crust of the two soils to the beating action of
18 the rain drops explains the IR curves in Figure 7. Since no major
19 rearrangement of the loessial crust occurs during the subsequent SW
20 storm, the "washed-in zone" remains complete and in situ. Floccula-
21 tion of the clay particles by the SW can occur, but not movement.
22 The possibilities for increased hydraulic conductivity in this limi-
23 ting zone are therefore small, and only a small increase in IR is
24 found. Rainfall impact on sandy loam soil causes the destruction of
25 the crust formed during the previous DW storm, while the SW causes
26 flocculation of the clay particles. The new crust will therefore be
27 mainly as a result of the physical action of the rain drops. Clay

1 movement and formation of the "washed-in zone" will be limited.

2 The underlying difference between the soils is one of texture
3 and the resulting cohesiveness of the crust. The impact of the rain
4 drops mechanically disrupts the crusted surface of the sandy loam,
5 since the coarse texture results in only a relatively small number
6 of contact points between soil particles and low cohesion forces
7 between the particles. Conversely, soils with a high silt content
8 have sufficient particle-to-particle contact points to form strong
9 bonds when the soil dries, therefore forming a strong crust (Cary and
10 Evans, 1974). The cohesion of the particles in the crusted silty
11 loam soil was sufficient to render it resistant to rain drop impact,
12 but cohesion between the particles of the sandy loam was insufficient
13 to prevent reworking by rainfall impact during each storm. Crust
14 formation therefore occurs with each storm in the sandy loam and the
15 IR obtained is a consequence of the EC of the applied water of that
16 storm only.

3. THE EFFECT OF ESP AND ELECTROLYTE CONCENTRATION ON THE STRUCTURE OF THE SOIL CRUST

The structure of the crust was investigated micromorphologically by McIntyre (1958), who found that it consisted of two distinct parts: (a) an upper skin seal attributable to compaction by rain drop impact; and (b) a "washed-in zone" of decreased porosity, attributed to the accumulation of small particles. McIntyre (1958) measured thickness of 0.1 mm and 2 mm for the skin seal and "washed-in zones," respectively. The "washed-in" layer was formed only in soils that were easily dispersed (McIntyre, 1958). The permeability of the soil bulk was ~ 800 times that of the "washed-in zone" and ~ 2000 times that of the skin seal. Low magnification micrographs (x15) taken by Duley (1939) substantiated McIntyre's results. Higher resolution micrographs of soil crusts taken with a petrographic microscope, at magnification of up to x100, were published by Evans and Buol (1968). These micrographs showed that, in some soils, particles in the layer immediately below the surface skin were oriented, whereas in others, orientation of silt and sand particles occurred in deeper layers of the crust. In other studies (Epstein and Grant, 1973; Chen *et al.*, 1980) only one of the two layers was found. Chen *et al.* (1980), studying scanning electron micrographs (SEM) of crust on loessial soil, found only a thin skin seal ~ 0.1 m in thickness at the uppermost layer of the soil. They did not find accumulation of fine particles in the 0.1 to 2.8 mm zone, as observed previously by McIntyre (1958) (the "washed-in zone").

Two mechanisms were proposed to explain the formation of surface crust by rain drop impact: (i) aggregate breakdown and compaction

19

1 by drops striking the soil surface and the formation of a thin skin
2 seal; and (ii) clay dispersion and movement of fine particles into a
3 region of decreased porosity ("washed-in zone"). Whereas the first
4 mechanism is mechanical in nature, clay dispersion due to chemical
5 forces predominates in the second mechanism. The relative importance
6 of these two mechanisms as expressed in the structure of the crust
7 was studied by Gal et al. (1984). Figure 8 shows the micrograph
8 (x100) of the upper 2 mm of the sandy loam soil sample with ESP 1,
9 after it was subjected to simulated rain with 75 mm of distilled water.
10 Sand grains covered with a skin of clay layer are seen throughout the
11 profile. The absence of clean sand grains or a layer of accumulated
12 clay indicates that no clay dispersion or clay movement took place in
13 this profile. There is only a thin (~ 0.1 mm) and compacted layer of
14 broken aggregates sealing the soil surface. This compacted layer with
15 low hydraulic conductivity was formed by the mechanical impact of the
16 rain drops and is responsible for the final IR of the sandy loam soil
17 with ESP 1.0 (~ 8 mm h⁻¹) (Fig. 1).

18 Figures 9a and 9b show SEM micrographs of the sandy loam soil
19 with ESP 11.6 which was rained on with distilled water. Figure 9a
20 (magnification x300) shows the soil profile including the soil surface,
21 whereas Fig. 9b (magnification x1000) shows only part of 9a. It is
22 evident from Fig. 9a that the surface layer (~ 0.25 mm) consists of
23 large sand grains. The medium level of ESP in the soil (ESP 11.6),
24 combined with the low electrolyte concentration of the applied water
25 (almost distilled) and the mechanical impact of the drops, caused
26 clay dispersion and stripping the clay skin of the sand grains. Some
27 of the clay removal is probably associated with erosion and horizontal

1 removal of the clay in the runoff water. However, some downward
2 movement of clay and silt also occurred and the clay particles accu-
3 mulated in the "washed-in" layer (~ 0.75 mm thick). This conclusion
4 is also based on the fact that the infiltration rate decreased
5 (Fig. 1) despite the existence of large sand grains accumulated at
6 the soil surface.

7 Figure 9b shows a section of Fig. 9a (see arrow) at a higher
8 magnification ($\times 1000$). Whereas in Fig. 9a the area around the arrow
9 has the appearance of a hole, it is evident from Fig. 9b that this
10 "hole" is actually clogged with clay particles.

11 The effect of applying PG (at 5 t/ha) on the surface of the
12 sandy loam soil with ESP 11.6 (prior to the rainstorm) is shown in
13 Fig. 10. The PG application prevented clay dispersion and clay move-
14 ment; no stripping of the clay skin from the sand grains occurred
15 and the final IR was maintained at 12 mm h^{-1} . The decrease in IR to
16 that final value was due mainly to aggregates' breakdown at the soil
17 surface as a result of the mechanical impact of rain drops.

18 Comparison of the SEM micrograph (Fig. 10) and IR of this soil
19 (ESP 11.6) with and without gypsum indicates also that clay accumu-
20 lation in the "washed-in zone" occurs in the sodic soil only when
21 gypsum is absent. The permeability of the crust, and the IR of the
22 soil, are determined by the "washed-in" layer below the sandy layer
23 which is formed under conditions which are favorable for clay disper-
24 sion (high sodicity, distilled water and mechanical impact of the
25 rain drops). No compacted layer ("skin seal") attributed to rain
26 drop impact is formed at the soil surface under conditions favorable
27 for clay dispersion and particle movement. Only naked sand grains

are left over the soil surface. The presence of naked white sand grains is typical for sodic soils exposed to rainstorms. These sand grains are held loosely at the surface and are eroded easily by the runoff water (Chen et al., 1980). When this happens, the "washed-in" layer is exposed at the soil surface. The presence of a compacted layer at the soil surface under conditions favorable for clay dispersion is a secondary process which follows the erosion of the sandy layer. Similar results were obtained with a soil containing 60% clay (Gal et al., 1984).

4. EFFECT OF SOIL SODICITY ON CRUST FORMATION (AND RAIN INFILTRATION) - FIELD STUDIES

Annual rainfall in semi-arid regions is low, uncertain and patchy. Paradoxical as it may sound, however, in spite of the deficiency in rainfall, large amounts of water are lost due to runoff. The amounts of runoff measured in the northern part of the Negev in Israel ranged from 30 to 50% in small (6 m^2) plots (Hillel, 1971).

The arable soils in the arid and semi-arid regions of Israel contain 2-6% exchangeable sodium in the upper layer. It was postulated that these ESP values are responsible for crust formation and the high runoff in many of the arid regions. This hypothesis was tested recently by Frenkel and Hadas (1981) and Keren *et al.* (1983) in field studies. Measurements of water runoff were conducted (Keren *et al.*, 1983) in standard Wischmeier plots (25 m long and 6 m wide) on bare soil with a slope of about 2-4%. Soils with ESP 4.6 predominate in the studied area (northwestern Negev in Israel), and soils with ESP 19.3 were obtained by commercial irrigation for 4 years with saline-sodic waters ($\text{EC}=5.5 \text{ dS m}^{-1}$ and $\text{SAR}=18$). The surface runoff and the beneficial effect of PG are presented in Table 1 (from Keren *et al.*, 1983). The pronounced effect of exchangeable sodium and of PG is evident. Even in a dry winter, with altogether only 182 mm of rain in seven storms, the total amount of runoff from the soils with ESP of 4.6 and 19 was 22.8 and 64.2 mm, respectively.* Spreading PG at 5 t/ha on the soil with ESP 4.6, reduced the yearly amount of runoff from 22.8 to 3.8 mm. Similar gypsum treatment to the soil with ESP 19.3 reduced runoff from 64.2 mm in the control to 18.7 mm. Considering the rain intensities, these results are in good agreement

*In a wet winter (1982/83) the recorded rainfall was 520 mm and the runoff in a 25 m-long plot of soil with ESP 4.6 was 30% (157 mm).

1 with the prediction based on the laboratory studied (Kazman et al.,
2 1983). The high amount of runoff from this calcareous loess soil with
3 ESP 4.6, and the beneficial effect of PG, confirmed the hypothesis
4 that even a low percentage of sodium is enough to cause aggregate
5 dispersion and crust formation. The mechanical impact of the rain
6 drops enhances the rate of crust formation and the amount of runoff.
7 However, since the rain intensity was the same in both the control
8 and the gypsum-treated soils, it is evident that chemical dispersion
9 (enhanced by sodicity and electrolyte concentration) plays a dominant
10 role in affecting the infiltration rate.
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5. SUMMARY

Crust formation at the soil surface is a common feature of many soils, particularly in the arid and semi-arid regions. Crust formation is due to two complementary mechanisms: (i) mechanical breakdown of soil aggregates caused by the beating action of the rain drops, followed by compaction of a thin layer at the soil surface; and (ii) chemical dispersion of the clay particles, which depends on the soil ESP and the electrolyte concentration of the applied water. In soils exposed to rain, 3-5% exchangeable Na is enough to cause clay dispersion, crust formation and a very low infiltration rate. The soil surface is especially susceptible to exchangeable Na because of the mechanical impact of the rain drops, the low concentration of electrolytes in the rainwater, and the relative freedom for particle movement at the soil surface.

The crust may consist of two distinct parts: (i) an upper skin seal attributed to compaction by rain drop impact, and (ii) a "washed-in zone" of decreased porosity attributed to accumulation of clay particles. When the soil ESP is <1 , or when the electrolyte concentration in the applied water is high, chemical dispersion of the clay particles and their downward movement and the formation of the "washed-in zone" are prevented. Under these conditions, the crust consists of a compacted skin seal only (attributed to the mechanical impact of the rain drops), and the infiltration rate of typical soils drops to 8-12 mm/h. Conversely, when the ESP of the soil $>4-5$, clay movement and the formation of a "washed-in" layer are the dominant mechanisms and the IR drops to $1-2 \text{ mm h}^{-1}$.

FIGURE LEGENDS

Figure 1. The effect of soil ESP (and phosphogypsum) on the infiltration rate of a sandy loam (Netanya) soil (Kazman et al., 1983).

Figure 2. The effect of soil ESP (and phosphogypsum) on the infiltration rate of a silty loam loess (Kazman et al., 1983).

Figure 3. Effect of electrolyte concentration in rain simulation experiments on the infiltration rate of a sandy loam soil (Agassi et al., 1981).

Figure 4. Effect of electrolyte concentration in rain simulation experiments on the infiltration rate of a silty loam loess (Agassi et al., 1981).

Figure 5. Effect of electrolyte concentration on the infiltration rate of a silty loam loess at two ESP levels (low-energy rain) (Agassi et al., 1984).

Figure 6. Effect of soil sodicity and electrolyte concentration on the final infiltration rate (a) and the hydraulic conductivity of a silty loam loess (b) ((a) from Agassi et al., 1984; and (b) from Felhendler et al., 1974).

Figure 7. Infiltration rates of a silty loam loess and a sandy loam soil (Netanya) subjected to three consecutive storms (of sequence: DW-SW-DW) (Hardy et al., 1983).

Figure 8. SEM micrograph of a sandy loam soil with low sodicity (ESP 1). Original magnification (O.M.) x100 (Gal et al., 1984).

1 Figure 9. SEM micrographs of the Netanya sandy loam soil with ESP
2 11.6 (Gal et al., 1984).

3 a. O.M. x300

4 b. O.M. x1000

5 Figure 10 SEM micrographs of the phosphogypsum-treated Netanya sandy
6 (Gal et al., 1984) loam soil. O.M. x300.

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TABLE 1

Surface runoff, during rainstorms, from loess soil at two levels of
ESP as affected by gypsum treatments

Storm No.	Amount of rainfall mm	Time between storms days	Surface runoff, % of rainfall				
			ESP 4.6		ESP 19.3		
			Control	Gypsum spread over *	Control	Gypsum mixed in *	Gypsum spread over *
1	16	--	0	0	23.1	2.6	0
2	20	40	6.5	0	13.3	3.0	0.7
3	19	20	1.3	0.5	27.3	10.5	3.8
4	59	6	21.5	3.8	41.0	21.2	17.2
5	44	9	13.4	2.1	45.0	22.5	12.4
6	12	1	12.5	2.5	40.0	25.0	12.5
7	12	15	10.1	2.5	31.7	13.8	6.7
Total (mm)	182		22.8	3.8	64.2	30.1	18.7
% of annual rainfall			12.5	2.1	35.3	16.5	10.3

* The rates of phosphogypsum application were 5 and 19 t/ha for the
soils with ESP 4.6 and 19.3, respectively.

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e. - Evaluation of research achievements

All of the objectives described in the original proposal were met.

f. - Description and results of cooperation

Cooperation between the principal investigators in Israel (I. Shainberg and J. Morin) was very productive and resulted in 4 papers together (see list of papers at the end of this report). The American investigator concentrated on maintaining objective No.1 (to study the colloid properties of Na/Ca clays - see ref. 11) whereas the Israeli investigators worked on maintaining the other objectives. The cooperation between the two teams of investigators was mostly in terms of consultation and discussion of the experimental results. The results of this study (use of phosphogypsum to increase the infiltration rate of soils) is now being applied in both countries in field experiments.

g. Benefit to agriculture

Management of the soil surface is essential to prevent runoff and erosion, to facilitate seedling emergence and to promote water harvesting. The beneficial results of this study were:

- 1) Understanding why the soils in semi-arid regions (in Israel and USA) have the tendency to form crust. The arable soils in the semi-arid and arid regions contain 2-6% exchangeable sodium in the upper layer. It was proven that these ESP values are responsible for crust formation.
- 2) The beneficial effect of phosphogypsum (and gypsum) on preventing crust formation and maintaining high infiltration rate when the soil is exposed to rain was demonstrated.

- 3) The effect of phosphogypsum in preventing runoff and erosion in field experiments was demonstrated.
- 4) The effect of spreading phosphogypsum in increasing the yield of dry land wheat was demonstrated.

k. - Published reprints and manuscripts

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