Surface crusting in two alluvial soils of northern Niger

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ABSTRACT


Surface crusting was studied in a sandy soil and a clay loam soil in northern Niger in a subdesert to desert environment. Light microscopy, electron microscopy, image analysis and soil physics were used to study and explain different crusting processes in experimental plots. Two 1-m² plots on each soil were subjected to rainfall simulation in the field under natural and tilled surface conditions.

This study demonstrates that kinetic energy of rainfall is the major crusting factor for the sandy soil. Waterlogging and subsequent slaking led to the formation of structural and depositional crusts in the tilled clay loam plot. In this case, a surface crust can be formed regardless of kinetic energy of the rainfall. This was substantiated through double-ring infiltrometer measurements. In both soils, infiltration was severely hindered by crusting. The relationships of crusting to water and wind erosion were more ambiguous. Four types of crusts could be defined from this study in terms of structure, genetic processes and properties. It could also be demonstrated that crust control practices should take into account the texture of the original soil materials.

INTRODUCTION

The presence of a crusted soil surface is a common feature of most soils in arid regions. The usefulness of micromorphology to characterize the structure of crusts and the various processes involved in crust formation has been demonstrated by several researchers (Tackett and Pearson, 1964; Evans and Buol, 1968; Bresson and Boiffin, 1991). Porosity in thin sections can be measured using light microscopy and image analysis (Jongerius et al., 1972; Bouma et al., 1977; Schoonderbeek et al., 1983). More recently, scanning electron microscopy (SEM) has also been used to examine undisturbed soil crust sections (Chen et al., 1980; Onofiok and Singer, 1984).

As surface crusting is a time-dependent phenomenon, the use of rainfall simulators may be very helpful in obtaining data on the effects of various rainfall patterns on the stages of crust formation (Epstein and Grant, 1967; Farres, 1978; Norton, 1987).
It must be noted that little attention has been paid to surface crusting in arid regions of Africa. Moreover, most works have focused on one specific aspect of the problem. This study was part of an effort to relate the structure of surface crusts, which occur in sandy and clay loam arid soils, to genetic processes and to the main impact of the crusts on infiltration rate and detachability.

**MATERIALS AND METHODS**

*Region and soils*

The field study was carried out in the vicinity of the city of Agadez, situated in northern Niger, on a fluvial plain which receives the erratic flow of a river collecting water over a 1360-km² watershed belonging to the Saharan mountains of Aïr. This plain covers an area of 95 km² and sustains a population of about 20,000 inhabitants, mostly concentrated in the city of Agadez, which is of paramount importance for Saharan communications. The annual average rainfall is 149 mm, as observed over an 18-year period, but large fluctuations occur (e.g. 39 mm in 1970; 4 mm in 1984).

The spatial soil differentiations substantiate the well-established sedimentary laws that govern such an alluvial system. Sandy soils occur in the upper part of the plain and more clayey soils 20 km further downstream. These natural sedimentation patterns provided an opportunity for the selection of two experimental sites: one with a sandy surface and the other with a clay loam surface. Some important characteristics of the top layers of these soils are listed in Table I. According to the FAO world soil map legend (1973), both soils are Dystric Fluvisols. Despite their low content of exchangeable sodium

<table>
<thead>
<tr>
<th>TABLE I</th>
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<td>Important physical and chemical properties of the top layers of the studied soils</td>
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<table>
<thead>
<tr>
<th></th>
<th>Sandy soil (0-10 cm)</th>
<th>Clay loamy soil (0-20 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2 μm (%)</td>
<td>5.0</td>
<td>34.0</td>
</tr>
<tr>
<td>2–20 μm (%)</td>
<td>2.3</td>
<td>21.5</td>
</tr>
<tr>
<td>20–50 μm (%)</td>
<td>3.9</td>
<td>15.1</td>
</tr>
<tr>
<td>50–200 μm (%)</td>
<td>36.7</td>
<td>19.4</td>
</tr>
<tr>
<td>200–2000 μm (%)</td>
<td>53.1</td>
<td>6.0</td>
</tr>
<tr>
<td>&gt;2000 μm (%)</td>
<td>4.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Exchangeable sodium (%)</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>pH (H₂O)</td>
<td>7.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Dominant clay</td>
<td>–</td>
<td>Montmorillonite</td>
</tr>
</tbody>
</table>
and the very coarse texture of the sandy soil, both soils are very vulnerable to severe surface crusting.

**Experimental set-up, field measurements and procedures**

To study the effect of rainfall on crust formation, two runoff plots were prepared at each site. Treatments included a reference treatment where surface remained under natural conditions, i.e. bare and untilled, and a standard cultivation where the 10-cm top layer was manually hoed and raked so that all the laminae were destroyed. These treatments were applied not only to the 1-m² plots but also to the 10-m² surrounding buffer rings. The slope of the soil surface was approximately 2% in each case.

An elaborate sprinkling infiltrometer, after the design of Asseline and Valentin (1978), was used to simulate rainfall with kinetic energies similar to natural rainfall (Table II). The experimental plan was established in reference to the climatic data of the study area. Thus, the total amount of rainfall simulated during the tests matched the mean annual rainfall of 150 mm. The patterns of the simulated storms did not exceed the limits yielded by the previously established intensity–duration curves. As the test period occurred during the dry season, the first storm was simulated under very dry surface conditions. Each run lasted 45 min and comprised four sub-runs with different application rates. Whereas the first run was continuous, short intervals were introduced between sub-runs for the two last runs (Table II). Thus a wider range of initial moisture conditions was achieved. The intervals before the second and the last runs were 15 and 22 h, respectively.

Rainfall intensity from the simulator was measured before each run by placing a 1-m² pan over the plot and then adjusting to the required rate by selecting a suitable angle of oscillation of the nozzle. Runoff was collected in a buried tank equipped with a very sensitive water-level recorder. The infiltration rate was determined as the difference between the controlled rainfall intensity and the recorded runoff rate. The final infiltration rate (FIR) could be fitted to a linear ascending function of rainfall intensity ($I$). The saturated hydraulic conductivity ($K_s$) of the soil surface was assumed to be very similar

<table>
<thead>
<tr>
<th>Experimental conditions for rainfall simulation (second run)</th>
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<tbody>
<tr>
<td>Sub-runs</td>
</tr>
<tr>
<td>Interval since previous run (h)</td>
</tr>
<tr>
<td>Duration (min)</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>Intensity (mm h⁻¹)</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>Kinetic energy (J mm⁻¹ m⁻²)</td>
</tr>
<tr>
<td>18.9</td>
</tr>
</tbody>
</table>
to the minimal rainfall intensity necessary for runoff to occur under very wet conditions. This threshold was experimentally determined for the third run as the point where the function \( FIR = f(L) \) intercepts the first bisectrix (Colli-net and Valentin, 1982).

The soil losses were measured by collecting sediment samples from the flume in 0.3-1 bottles at intervals depending on runoff rates. The runoff hydrographs were integrated with sediment concentration values to compute sediment discharge rates and total soil losses. In addition, the sediments were subjected to particle-size analysis.

To complement the assessment of the soil infiltration capacity, saturated hydraulic conductivity \((K_s)\) was measured in other plots under ponded conditions, using a double-ring infiltrometer as described by Poss (1978). Six replicates were performed for each treatment on soil to which no rain had been applied. The values of \(K_s\) were the medians of the data.

**Light microscopy, submicroscopy and image analysis**

As an attempt to characterize the stages of crust formation, undisturbed samples were taken from the buffer rings around the experimental plots: before the rainfall tests; during the preponding period; and once overland flow had occurred. This pattern of sampling was repeated for each run. After the rainfall tests, several samples were collected from the plots, at various points along the microslopes. As a result, microtoposequences as well as time sequences were sampled. The undisturbed specimens were taken from the upper 7 cm and carefully packed in cardboard containers for transport to Abidjan, where they were air-dried and impregnated under vacuum with a polyester resin (Stratyl 116), using styrene as a thinner. After 1 month of hardening, 85 thin sections measuring 3 cm \( \times \) 4.5 cm \( \times \) 30 \( \mu \)m were prepared following the method described by Hanrion (1976). These sections were studied in transmitted light with a polarizing microscope and described using Brewer’s (1964) nomenclature. Special attention was paid to arrangement, microstructure, degree of particle sorting and porosity.

To characterize more accurately the porosity of the various laminae within the crusts, an image analyser (Quantimet 720) was used at the Netherlands Soil Survey Institute, in Wageningen. Distribution of the size (seven classes) and shape (three classes) of pores with equivalent spherical diameters larger than 30 \( \mu \)m were determined in photomicrographs made with transmitted light using the method proposed by Ismail (1975). Each pore was classified into a shape class using the area/perimeter squared measurements (Jongerius and Bisdom, 1981; Norton, 1987). This technique was applied to three thin sections corresponding to the natural and tilled clay loam plots. The values thus obtained were the means of three replications.

In combination with these microscope techniques, a scanning electron mi-
croscope (SEM) was used to provide more detailed information on the microstructure from 10 unhardened specimens of crusts that had been collected from the four plots after the rainfall tests. On each specimen, a series of electron micrographs was taken at magnifications ranging from 35 to 3500. One hundred micrographs were thus studied.

RESULTS

Sandy soil

Natural plot

Before the rainfall experiments, the soil surface of the desert soil exhibited distinct stratification, with three well-sorted microlayers (Fig. 1), as seen in thin section. The uppermost of these is a pavement-like layer composed of small gravels and loose coarse sand grains; the middle one is predominantly built up of fine tightly packed sand grains with vesicular pores; and the lower microlayer is a plasmic seal of considerably reduced porosity, composed of a

Fig. 1. Idealized evolution of soil surface features in the sandy soil. (a) Natural plot before rainfall. (b) Natural plot after rainfall. (c) Tilled plot before rainfall. (d) Tilled plot after rainfall (see also Fig. 2). (1) Loose coarse materials; (2) fine tightly packed sand grains; (3) plasmic seal; (4) bulk soil; (5) loose materials; (6) clod; (7) compacted layer.
higher concentration of fine, mainly clay-sized particles. No striking alteration was found after the rainfall simulation tests.

During the first simulated storm, overland flow occurred after only 7.9 mm of applied rainfall (Table III), although the antecedent soil moisture was very low (0.8% by weight). This result demonstrates the dominant role of the surface seal in hampering infiltration into the sandy soil. In contrast, the saturated hydraulic conductivity \( K_s \) measured under ponded conditions was substantially greater than under rainfall (Table III). It must be pointed out that the seal was partly broken just as the double-ring infiltrometer was set up. Some macropores were created, hence enhancing infiltrability. An additional point is that this seal was not restored under the water layer of the double-ring infiltrometer.

Soil losses from this plot were very limited, especially for fine particles (Table IV). This result is due to the gravel and sandy pavement-like layer that protected the underlying soil from detachment.

**TABLE III**

Rainfall applied before overland flow (PR), infiltrability as measured under rainfall simulation \( K_s \) and with the double-ring infiltrometer \( K_{ds} \)

<table>
<thead>
<tr>
<th>Plot</th>
<th>PR (mm)</th>
<th>( K_s ) (mm h(^{-1}))</th>
<th>( K_{ds} ) (mm h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Q1</td>
<td>Q3—Q1</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>7.9</td>
<td>17.9</td>
<td>887</td>
</tr>
<tr>
<td>Tilled</td>
<td>25.1</td>
<td>19.6</td>
<td>1480</td>
</tr>
<tr>
<td>Clay loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>2.7</td>
<td>1.9</td>
<td>56</td>
</tr>
<tr>
<td>Tilled</td>
<td>25.0</td>
<td>6.9</td>
<td>52</td>
</tr>
</tbody>
</table>

Q1: first quartile; Q3—Q1: interquartile.

**TABLE IV**

Soil losses and median diameters \( D_{50} \) of sediments from the experimental plots

<table>
<thead>
<tr>
<th>Plot</th>
<th>Soil losses (kg m(^{-2}))</th>
<th>( D_{50} ) (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>9.3</td>
<td>475</td>
</tr>
<tr>
<td>Tilled</td>
<td>0.4</td>
<td>150</td>
</tr>
<tr>
<td>Clay loam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>1.3</td>
<td>53</td>
</tr>
<tr>
<td>Tilled</td>
<td>2.1</td>
<td>5</td>
</tr>
</tbody>
</table>
**Tilled plot**

The original three microlayers were utterly destroyed by tillage. Before the rainfall tests, 40% of the plot surface was covered with brittle aggregates of about 15 mm. In comparing the surface features of the natural and tilled plots after the rainstorms (Figs. 1 and 2), it must be emphasized that in both cases a very similar vertical differentiation was encountered. However, the vertical sorting of particles was much more pronounced in the case of the natural plot: the tilled layer (10 cm deep) was compacted to a depth of 20 mm, as indicated by thin-section observations, whereas the uppermost 3 mm were weakly differentiated into two microlayers: a 0–2 mm-thick layer with individual coarse particles and a 1-mm-thick compacted seal which enclosed fine sand grains and small vesicles (0.5-mm diameter). The upper part of this layer was compacted so that a very thin skin seal developed, as revealed by scanning electron micrographs (Fig. 2).

Based on field observations and microscopic analysis, one may reconstruct the processes leading to crust formation in this sandy soil. At the onset of the first storm, aggregates broke down and the surface was riddled with microcraters from waterdrop impact. The walls of these crater-like features were clearly sorted, with coarse particles on top of finer ones. This suggests that the disjunction between skeleton and plasma occurred at the very beginning of simulated rainfall. Under such circumstances, the entire range of particle sizes is mobile and subject to splash erosion. The detachment of larger grains by waterdrop impact proceeds rapidly and causes gaps which are filled subsequently by finer particles. Because of these mechanical sieving processes, the finer particles are carried with the percolating water and thus accumulate above the zone of reduced porosity which results from compaction by waterdrop impact. The finer particles are compacted in turn, therefore sealing the surface at a shallow depth.

Results from the field experiments indicate how, as the new crust formed on the tilled plot, the infiltration rate decreased sharply and was eventually exceeded by rainfall intensity. As a result, runoff occurred and the saturated hydraulic conductivity \( K_s \) decreased to a level similar to that of the reference plot (Table III). Conversely, the value of \( K_s \), assessed with the double-ring method, was a few orders of magnitude greater than that measured with rainfall as no crust was formed under ponded conditions.

Tillage only slightly increased the detachability of this sandy soil. Although soil losses still remained limited, the sediments from the tilled plot contained 3.3 times as many clay-sized particles as the bulk soil (Table IV). It may be concluded that tillage fosters an accelerated soil impoverishment of clay particles in this sandy soil.
Fig. 2. Scanning electron micrographs of the soil surface of the tilled sandy plot. (a) Vertical section; the plasmic seal (2) is topped with a compacted skin seal (1) with no macroporosity. (b) Vertical section, two ovoid vughs which might have been subjected to compaction after their development. (c) Horizontal section showing vesicles formed in the boundary of the sandy layer at top and the plasmic seal with cracks below. (d) Horizontal section at greater magnification (note that the particles building the vesicle-walls were horizontally and concentrically oriented).
Clay loam soil

Natural plot
The clay loam soil studied was capped with a compact layer, 2 mm thick, composed chiefly of fine particles which included 30% of fine skeleton grains and numerous vesicles (0.15–0.40 mm diameter). The fabric was isotic porphyroskelic because of the presence of silt. After rainfall, this structure was only partly altered and a sandy layer expanded all over the surface. Its thickness varied from 0.6 mm in the upper part of the plot to 0.3 mm near the flume. This coarse layer contained few vesicles (0.1-mm diameter). The thickness of the underlying plasmic seal concomitantly decreased to 0.4 mm. Such differentiation in the surface crust could result from the removal of fine particles by overland flow, leaving a sandy pavement-like layer over the remaining part of the seal. These observations were substantiated by measurements of infiltration capacity and soil losses. Hydraulic conductivity measured under rainfall and under ponded conditions was very low, hence intense overland flow occurred after only 2.7 mm of applied rainfall (Table III). Soil losses were three times greater and the median sediment diameter was much less than for the sandy natural plot (Table IV).

Tilled plot

Structural changes. In the case of the tilled plot, the structural alteration was much more complex than for the natural plot. Initially, hoeing brought up clods to the surface, with random packing and considerable inter-clod porosity (Fig. 3). Coarse clods (5–6 cm), medium-sized clods (2–3 cm) and small clods (0.5–2 cm) covered 25, 60 and 15% of the surface, respectively. Their fabric was isotic porphyroskelic and their porosity was restricted to a few planar voids (20%). In addition, these clods contained about 30% argillaceous micropeds (1–3 mm), which were very dark in thin section and almost completely deprived of macroporosity.

Two main stages in crust formation could be discriminated: before and after ponding (see Fig. 5 below).

(1) Before ponding. Field observations (Fig. 3) combined with microscopy indicated that initial crust formation resulted from splash erosion and waterlogging. At the start of the applied rainfall, the clods were subjected to splash erosion. The marks of the impact of raindrops could be observed easily in thin sections of the earlier time sequence. As a result, microaggregates were detached from the clods that broke up. The size of larger clods declined gradually and the smaller ones collapsed completely. Simultaneously, compaction because of the impact of raindrops led to the formation of a dense layer at the surface of the larger clods. Consequently, the breaking-up of clods, which oc-
Fig. 3. Time-sequence of photographs of the tilled clay loam plot. (a) Before rainfall (note the clods at the surface). (b) After 10 min of rainfall, swelling of clods was perceptible. (c) After 17 min of rainfall, the clogging of pores triggered ponding. (d) Two days after the last rainstorm (note the remnants of larger clods and cracks). Fig. 7 corresponds to the microtoposequence sampled between (1) the upper part of the plot and (2) a microdepression.
SURFACE CRUSTING IN PRE-SAHARAN ALLUVIAL SOILS

curred very rapidly at the beginning of the simulated storm, became less efficient over time, because an armouring seal developed.

Even more destructive was the effect of wetting (Fig. 4). As soon as the superficial part of the clods was affected by wetting, explosion of enclosed air within the clods triggered their slaking into smaller aggregates. Concurrently, swelling was observed because of the expansion of the clay lattices. These dispersed materials turned into slush, which sank along the walls of clods and filled the interstices (Fig. 5). The analysis of the time-sequence thin sections, sampled at 13- and 20-min intervals, in the course of the first rainstorm, assisted in depicting these processes (Fig. 5). The larger clods remained dry in their centres during the entire experiment, and thus were undisturbed: however, their superficial parts were subjected to wetting and subsequently washed.

![Diagram of soil surface features](image)

**Fig. 4.** Idealized evolution of soil surface features in the tilled clay loam soil. (1) Undisturbed clod materials, (2) plasmic seal, (3) structural crust, (4) depositional crust. (Note that the smaller clods and the wet parts of the larger clods are incorporated in the structural crust, whereas the dry parts of the larger clods remain unchanged.)
out. One characteristic of this dispersion stage is the banded distribution of clean skeleton grains at the surface of clods, parallel to the downward direction of the percolating flow. Such a feature clearly indicates the impoverishment in fine particles. Important changes also occurred among the materials which filled the interstices between the clods: at first, these materials were composed of loose coarse aggregates, composed of fine aggregates and individual particles, and later of densely packed individual particles (clean skeleton grains and water-resistant micropeds that embedded some vesicles). This rearrangement of soil particles resulted in the formation of a structural crust which affected the oversaturated zone. Whereas, just after tillage, between individual clods there was a continuum of interconnected large packing pores, this preponding stage is characterized by the areal and vertical development of a structural crust a few millimetres thick with virtually no macroporosity. This stage ends when the infiltration rate of this crust is exceeded by the intensity of applied rainfall and overland flow develops.

(2) After ponding. Once ponding and runoff had occurred, specific fea-
SURFACE CRUSTING IN PRE-SAHARAN ALLUVIAL SOILS

Fig. 5. Thin sections of a time-sequence from the tilled clay loam plot and diagrams of results of wetting. (a) After 13 min of rainfall (note the size decrease of the aggregates resulting from the breaking-up of clods). (b) After 20 min of rainfall (note the banded distribution of the clean skeleton grains in the washed-out zone. (1) Undisturbed clod materials, (2) structural crust built-up with aggregates from the breaking-up of clods, (2') structural crust composed of dispersed materials, (2'') structural crust comprising washed-out materials, (3) depositional crust.


tures could be observed (Fig. 4). A well-laminated crust, up to 10 mm thick, in which the particles were fairly well sorted, developed below the water layer, especially where the runoff velocity was locally reduced. Disjunction between skeleton and plasma, which already occurred at the end of the previous stage, was almost completed during the overland flow stage. Most of the laminae were composed of tightly packed and clean sand-sized quartz grains. Others were composed of water-resistant argillaceous micropeds plus coarse sand grains. The microscopic analysis of such a crust, combined with runoff and soil loss measurements, demonstrated that these laminae can be subjected to further evolution after deposition (Fig. 6): compaction and micro-illuviation of clay particles, and burial, are likely to promote the welding of micropeds
and the formation of continuous plasmic laminae. Finally, the thickness of the erosional deposits increased at the lowest points while the size of the remaining clods went on declining because of the impact of raindrops and waterlogging. The thin sections from a microtoposequence (Fig. 3), collected in the plot after the experiments, corroborated the analysis of the time sequence outlined above.

The dynamics of crust formation, both in space and time, is shown in Fig. 7. Three types of crusts could be discriminated:

1. A plasmic seal, composed of a compacted plasmic layer at the surface of the larger clods, which remained above the water layer and thus was unaffected by waterlogging.

2. A structural crust, in which the matrix of the clods was predominantly disturbed by the washing out of matrix materials. Such crusts were found at the beginning of the experiments, and, later on, at the lowest points of the microprofiles. The original structure of the clods was lost except in upper and lower parts, which were unaffected by oversaturation. As soon as a part of a clod was in contact with the waterlogged zone, it was incorporated into the structural crust. Consequently, the structure of the larger clods was greatly altered, and the smaller clods totally disappeared.

3. A depositional crust, exhibiting sorted and closely packed laminae parallel to the surface. It occurred at the top of the microprofiles that were sam-
Fig. 7. Evolution in both time and space of soil surface features in the tilled clay loam plot. (1) Undisturbed clod materials, (2) plasmic seal, (3) structural crust, (4) depositional crust.

...plied at the lowest points of the experimental plot. The depositional crust developed once over land flow had occurred.

It must be emphasized that crusts developed less rapidly during the last two storms than during the first one, even though a general trend to levelling off of the surface was observed. At the end of the experiments, the microtopography of the remnants of former larger clods was still perceptible (Fig. 3). The morphological changes, albeit conspicuous, were thus less pronounced than for the tilled sandy plot.

**Image analysis of porosity in three types of crust.** The micromorphometric void analysis provided evidence which assisted in the explanation and interpretation of the field experiments. Larger pores, with a diameter larger than 30 μm, were measured with image analysis in three thin sections (Fig. 8):

(1) One thin section was from the reference plot before the experiments, and the total porosity measured in the upper plasmic seal was 5.8%. Apart from the vesicles, the porosity of this layer consisted of only 0.1% of irregular-shaped pores within the 100–200-μm-diameter class.

(2) In another thin section from a clod remaining in the tilled plot after the experiments (Fig. 8b, top), the total porosity of the upper plasmic seal was 5.7%. The irregular-shaped pores (0.7%) were slightly larger in diameter (100–500 μm) than for the natural plot.

(3) The last thin section (Fig. 8b, bottom) was from a low point in the tilled plot and after the rainfall tests had been completed. A structural crust
topped with a thin depositional crust had a total porosity of only 0.4%. Moreover, the pore system in this top layer consisted predominantly of round vesicle-type vughs, ineffective for infiltration, because of their lack of continuity. As neither elongated nor irregular pores were present within this top layer, it is concluded that functional porosity was restricted only to micropores with diameters smaller than 30 µm.

For these three thin sections it also appeared that the crusts were comprised of a thin compact superficial layer almost deprived of functional voids, and more open underlying layers, especially, in the natural plot where the elongated pores could be related to animal activity. The results of porosity measurements showed that the pore system in the upper plasmic seal, which had formed on the remaining clods, resembled that found on the natural surface. An interesting point is that this plasmic seal, with a low total porosity (6.3%), did not include any elongated pores. Even worse in terms of infiltrability was the laminated crust, which presented a porosity thoroughly deprived of functional pores larger than 30 µm.

Image analysis of porosities enabled us to relate the different types of crusts to specific behaviours in terms of infiltrability. Under rainfall conditions, the saturated conductivity of the tilled plot remained slightly greater than that of the reference plot (Table III). However, in the tilled plot, the infiltration rate
Fig. 8. Distribution of the pores greater than 30 μm in crusts on the clay loam natural (a) and tilled (b) plots.

decreased rapidly when the structural crust developed so that runoff occurred after 25 mm of applied rainfall. Afterwards, the infiltration rate dropped even more sharply as a result of the formation of the tight depositional crust. As illustrated by image analysis, the larger part of the infiltration on the tilled clay loam plot resulted from the functional porosity of the remaining clods.

Under ponded conditions, the hydraulic conductivity of the tilled plot was lower than that of the natural plot. This result may be ascribed to the crusting effect of waterlogging, associated with the double-ring measurements. Therefore, it may be concluded that, in this soil, crusting was more severe under a thick water layer than under rainfall.

Tillage aggravated the vulnerability of this soil to water erosion (Table IV). Soil losses from the tilled clay loam soil were more than five times those from
the tilled sandy soil. Moreover, the sediments were mostly composed of very fine particles.

DISCUSSION AND CONCLUSIONS

Structure, genesis and physical properties of crusts

This study clearly indicated that, under subdesert conditions, surface crusting occurs quickly and extensively. Once destroyed by tillage, crusts are rapidly restored under rainfall. Although great textural differences may be encountered among selected soils, some common patterns occur. In both cases studied, the structural changes were associated with a dramatic decrease of the pore volume and increases in less favourable types of voids. Such structural alteration resulted in the occurrence of overland flow, even in the tilled plots. Likewise, disjunction and subsequent redistribution of plasma and skeleton affected the original materials, favouring a strong vertical differentiation among layers. Because of the sorting of components, plasmic concentrations, as well as residual accumulation of coarser particles occurred.

Among the common features of the crusts, particular attention should be paid to vesicular porosity. The various observations on vesicle occurrence suggest that they develop when air bubbles are trapped within wetted plasmic materials and take a shape with minimum potential energy. Moreover, as these circular vughs often occur in thin sections on the boundary between a sandy layer and underlying plasmic seal, they are likely to be formed before translocation and accumulation of fine particles. As already reported by Miller (1971), and by Figueira and Stoops (1983), it is worth emphasizing that this vesicular structure is strongly related to the number of cycles of wetting and drying. In the two examples, vesicles were more numerous and larger within the natural crusts which had undergone numerous cycles than within those newly formed in the tilled plots. Furthermore, the occurrence of a vesicular layer in the soil can be successfully used as a predicting criterion of very low infiltrability, as recently demonstrated by an extensive study on the hydraulic properties of soils in the arid zone of West Africa (Casenave and Valentin, 1989).

However, despite these common features, crust formation processes and properties differed among these two soils to some extent. Four types of crust could be thus distinguished in terms of structure, genetic processes and properties.

(1) Infiltration pavement

Various lines of reasoning demonstrated that surface crusting in the sandy soil resulted from the impact of rainfall. Evidence included the fact that no crust was formed under the double-ring infiltrometer. As micromorpholog-
cal investigations have shown, this surface differentiation was due to vertical winnowing of particles. This specific feature has been described as a filtration pavement (R. Bryan, personal communication, 1985) or as a three-layered structural crust (Casenave and Valentín, 1989). It should be noted that such a process is the reverse of the sedimentary sorting of particles, where finer materials are found above coarser particles. The residual accumulation of coarse grains on the surface limits the hazards of water and wind erosion. In this respect, the shallow plasmic seal has an ambiguous effect: on the one hand, it hinders water intake, increases runoff and water erosion hazards; on the other hand, its cohesiveness (Valentín, 1986) limits further impoverishment of fine particles. To some extent, the skin seal which capped the remnants of clods in the tilled plot in the clay loam soil resulted similarly from the combined effect of rainfall impact and subsequent accumulation and compaction of plasmic materials.

(2) Erosion pavement
In the case of the clay loam soil, some of the clay particles were removed by the selective effect of runoff and another part was compacted in a cohesive seal which limited further washing out. These processes resulted in the development of a sandy pavement-like layer at the expense of the original plasmic layer. This surface layer of fine sand grains is very vulnerable to wind erosion. Consequently, the further impact of wind will lead to the outcropping of the plasmic seal again, as it occurred before rainfall, in the natural clay loam soil. Such a cyclic pattern of wind and water erosion is very common in the arid zone (Valentín, 1985).

(3) Structural crust
Clods were shown to slake under ponding conditions independently of any impact forces, in the double-ring infiltrometer. Therefore, wetting must be considered as a major factor influencing this structural change which dramatically alters physical properties of the top soil. This process also affects the medium-textured soils of the temperate zone. The areal development of the crust, influenced by climatic conditions (i.e. depth and kinetic energy of rainfall) requires much more time to occur in the fields (Boiffin, 1984). Furthermore, as mentioned by Farres (1978), the structural crust formation processes are self-limiting so that the vertical development of this type of crust moves towards a steady equilibrium. As a result, this type of crust is found underlain by a more porous structure which comprises unaffected clods with large interconnected pores.

(4) Depositional crust
As shown by the experiments, the laminated crusts developed under overland flow which gave lateral translocation of particles combined with sorting.
These features may therefore be considered as depositional crusts, but not strictly sedimentary crusts. Deposition did occur in a laminar flow at the bottom and in turbulent flow caused by the impact action of the raindrops in the top water layer (Mücher and De Ploey, 1977). Such a depositional crust can be formed provided the microtopography is sufficiently rough. Otherwise, the runoff velocity may remain too high to allow deposition as in the case for the natural clay loam soil. After deposition, this type of crust may still evolve at the surface, by receiving subsequent depositional materials, or by being washed away when the runoff velocity increases. Also, deeper layers may be subjected to further compaction and to micro-illuviation of fine particles, thus promoting the formation of new plasmic fabrics. As illustrated by the micromorphometric data, this type of laminated crust may exhibit a very restricted porosity inducing depressed infiltrability.

**Consequences on crust control**

This work emphasizes some practical points in controlling crust formation. As it was shown that crusting processes depend on the texture of the materials, the strategy to combat this problem has to be adapted paying attention to this. Owing to the cohesionless structure of sandy soils, the duration of the positive effects of tillage in preventing crusting is extremely limited. Protecting soil surface from raindrop impact may be effective, but for sandy soils exclusively, as the experiments using mulch or mosquito gauze have demonstrated (Collinet and Valentin, 1984).

Few directions of surface managements of clay loam soils may be suggested from this work. As indicated by several authors (Johnson et al., 1979; Boiffin, 1984), tillage that forms large clods helps to control surface crusting. However, such practices seem to be efficient only when the structural stability of the top soil is sufficient to prevent slaking (Valentin and Ruiz-Figueroa, 1987). In addition, it must be highlighted that the major structural changes occurred during the first rainstorm. When antecedent soil moisture conditions were greater and for the subsequent storms, the intensity of crusting processes decreased. This may be related to the positive influence of the moisture content in preventing the breaking down of clods. Consequently, an optimal moisture content should be determined to minimize crusting hazards, especially under irrigation.

In contrast to the sandy plots, differences were found among the features of the natural and the tilled clay loam plots. This discrepancy may be ascribed to the microtopography of the plots. After the tests, the tilled clay loam plot was not completely levelled off. Higher rates of infiltration occurred in the remaining clods than in the depositional crust, as observed also by Falayi and Bouma (1975). However, the impact of surface roughness is ambiguous; although infiltrability is moderately enhanced, soil losses, together with clay impoverishment, are dramatically increased. Finally, waterlogging and runoff...
appear as the major factors influencing crusting for such arid medium-textured soils: therefore, planting on ridges, i.e. above the water layer, will probably reduce problems of seedling emergence and water infiltration.

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