INTERNATIONAL SYMPOSIUM ON THE ASSESSMENT OF SOIL SURFACE SEALING AND CRUSTING

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SURFACE CRUSTING OF ARID SANDY SOILS

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ABSTRACT

An experimental study on crust formation was carried out in the field near Agadez (Niger). The natural surface crust was destroyed by ploughing. Rainfall simulation was conducted using a sprinkling infiltrometer. Samples were collected for scanning electron microscopy and micro-morphological analysis. The structure of this artificially formed crust was found to be similar to the undisturbed soil. Furthermore, theses observations suggest that for sandy soils crust formation mainly results from splashing of coarse particles and micro-illuviation of fine particles which accumulate above the zone being compacted by raindrops. Thus, rainfall can be considered as the prevailing factor of surface crusting since it leads to the vertical disjunction and to the textural sorting of particles. Secondarily, aeolian erosion may affect the uppermost sandy micro-layers. The eroded particles are then trapped by the irregularly distributed grass cover. As a result, bare crusted spots are encompassed with sandy micro-mounds. This surface heterogeneity which occurs mainly in the Sahelian zone can therefore be ascribed to wind action as affecting material which has been already sorted by rainfall.

INTRODUCTION

Sandy soils occur extensively south of the Sahara either on fixed dunes or on alluvial materials, in a belt up to 500 km wide. Several soil scientists (Bocquier, 1971, in Chad; Leprun, 1978, in Mali; Collinet et al., 1980, in Upper-Volta; Valentin, 1983, in Senegal) mentioned that despite their coarse textures, these soils present a pronounced susceptibility to surface sealing. However, since it is generally assumed that water infiltration is overall influenced by the physical properties of the soil bulk, these surface features have been merely ignored by most hydrologists. Nonetheless, some researchers (Gavaud, 1968;

Talbot and Williams, 1978; Bougère, 1979) reported that in contrast to the extremely porous nature of the parent material, significant surface flow may develop during rainstorms and even triggers accelerated erosion. The purpose of this paper is to provide some information on the mechanisms of crust formation and their effects on the water runoff on arid sandy soils. The study is based on two field experiments conducted in a sub-desert region (Agadez, Niger) and in the Sahelian zone (Oursi, Upper-Volta) using rainfall simulation.

SUB-DESERT ZONE

Materials and methods

Located in an alluvial plain, the pre-Saharian city of Agadez has to face flooding almost every year, not owing to the overflowing of the sufficiently embanked river, but surprisingly as a result of the low infiltration rate of the prevailing sandy soil. The mechanical analysis (Table 1) substantiated the very coarse texture of the horizons and indicated their very low content in organic matter.

TABLE 1 Mechanical analysis of the soil in Agadez

DEPTH	SIZE CLASS					GRAVEL	ORGANIC MATTER
	Clay	Silt		Sand			
		Fine	Coarse	Fine	Coarse		
(cm)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
0 - 10	5.0	2.3	3.9	36.7	53.1	4.7	0.1
10 - 40	5.5	3.0	7.2	51.3	33.0	2.0	0.1
40 - 55	2.5	1.0	2.2	43.4	50.9	7.1	-
55 -155	1.3	0.3	0.1	0.2	99.1	38.7	-

The scarce fine particles concentrate in horizontal lamellae. Micromorphological observations indicated that soil surface consists of three micro-layers which are very typical of surface features of arid sandy soils (Figure 1).

In an attempt to assess the influence of these surface differentiations on the hydraulic properties of this soil, experiments were conducted on two plots. The first was the natural reference with undisturbed surface. The second was conventionnally hoed to a depth of 10 cm so that the laminae were altogether destroyed. Identical size of plots (1m^2), slope length (1m) and slope angle (1.5 %) were selected. Rainstorms were simulated by means of a sprinkling infiltrometer especially designed for the tropical conditions of use (Asseline & Valentin, 1978). The experimental programme 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, namely, 150 mm. The patterns of the simulated

0 - 2.5 mm
58% gravel, 38% coarse sand, 4% fine sand. These particles are loose.

2.5 - 5.0 mm
29% coarse sand, 71% fine sand likely cemented with a very thin film of water.

5.0 - 7.0 mm
11% coarse sand, 9% fine sand inserted in cohesive plasma (80%)

Vesicle occur mainly in the boundary between the cemented fine sand micro-layer and the plasmic seal.

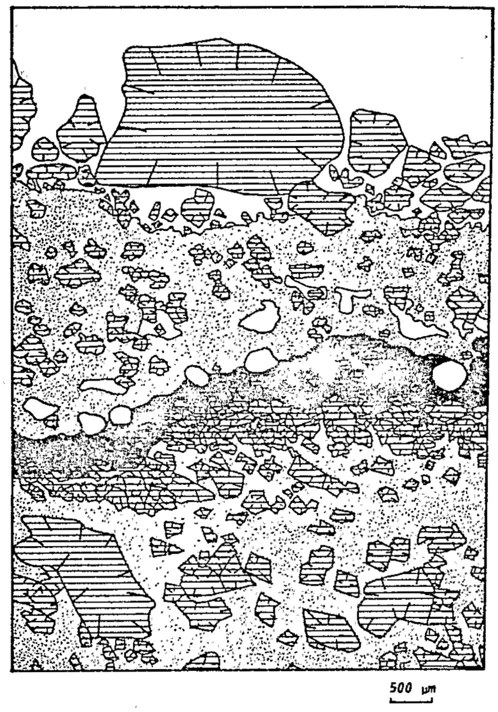

FIGURE 1 Natural surface differentiations. (after a thin section)

storms did not exceed the limits yielded by the intensity-duration curves. The kinetic energies were similar to those of natural rainstorms (Valentin, 1984). The measurements were carried out in March so that the first runs occured under very dry conditions. The experimental procedure (Table 2) was identical for both plots.

TABLE 2 Experimental procedure for rainfall simulation

	First run				Second run				Last run			
Intensity ($mm\ hr^{-1}$)	60	120	60	30	60	120	60	30	60	120	60	30
Duration (mn)	15	10	10	10	15	10	10	10	15	10	10	10
Interval (hr)	-	0	0	0	15	1	0.5	0.25	22	1	0.5	0.25

Runoff was collected in a buried reservoir which was equipped with a very sensitive water-level recorder while sediment samples were manually taken from the flume in 0.3 l-bottles at intervals that depended on the runoff rate. Undisturbed surface samples were collected at various stages during the tests from the irrigated buffer ring encompassing the plots, for micromorphological analysis (optical transmission and scanning electron microscopies).

Results and discussion

Mechanisms of seal formation Soil sealing occurs on the tilled surface rapidly. However, several stages can be outlined. First, small crumbs collapse under the impact of raindrops which riddle land surface with minute crater-like holes. As a result, soil particles are detached and moderately sorted in size. The bottoms of these 'craters' are lined with fine particles whereas their walls consist of sand. Simultaneously, a part of clay size particles is translocated to a shallow layer the depth of which is likely to be related to the depth of the compacted zone by rainfall impact. This illuviated clay fills the voids between the grains of skeleton but not the vesicles that have formed among fine sand with air being entrapped at the very beginning of rainfall. These observations suggest that the most important mechanisms in terms of seal formation on sandy soils arise before the runoff occurence.

After runs, soil surface differentiations of the tilled plot (Figure 2) are found to be similar to those of the undisturbed plot. They consist of a micro-layer (0–2 mm) of loose gravel and coarse sand, with no lamination and a thinner micro-layer (2–3 mm) of compacted fine particles enclosing fine sands (30 %) and vesicles ($\emptyset$ < 0.5 mm). This surface seal is underlain by the tilled layer which has been poorly affected by rainfall except it has been compacted.

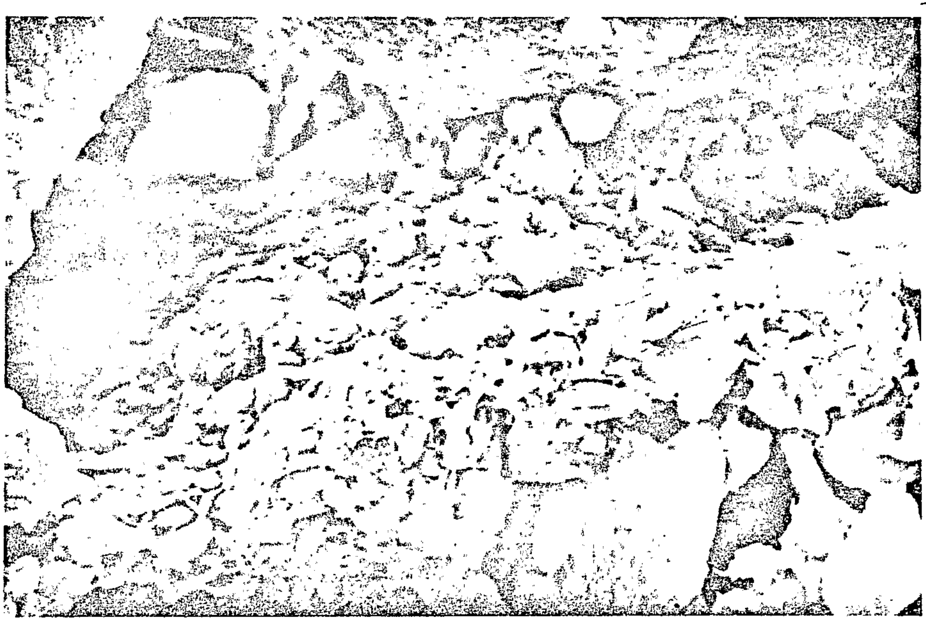

FIGURE 2 SEM microphotograph of the upper part of the seal formed on the tilled plot. Sand particles are underlain by compacted fine clayey particles which form a micro-layer with a much reduced porosity

Observations in the field, corroborated by the micromorphological examination, suggest that the segregation between coarse and fine particles of sandy crumbs required little energy and might therefore be achieved within a restricted number of rainstorms. Owing to the micro-illuviation of clay particles and the

the splashing of sand, the plasmic seal occured as underlying a sandy micro-layer.

Water runoff Runoff occured on the natural and on the tilled plot after 7.9 mm and 25.1 mm of rainfall respectively, during the first run. The cumulative runoff as a function of cumulative rainfall might be fitted on parallel lines for both plots, beyond 70 mm of rainfall, which means that the runoff coefficients were then equal (Figure 3). These results emphasize the great influence of surface sealing on runoff, even on tilled sandy soils.

Soil detachment by water Sediments from natural and tilled plots were 0.278 kg and 0.407 kg respectively. Those from the tilled plot contained 3.3 times as many clay particles as the first horizon of the soil whereas this ratio did not exceed 0.8 for the undisturbed plot. Consequently, destroying the surface seal by shallow ploughing may aggravate soil detachment. Even worse is the accelerated impoverishment in clay which may affect such a coarse textured soil.

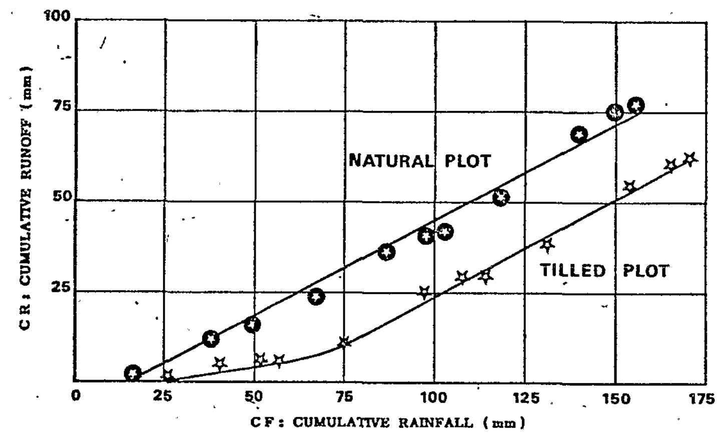

FIGURE 3 Comparison of runoff on both plots. Despite the variations of rainfall intensity, and interval before run, the curves might be fitted on lines:
natural plot: when 7.9<CI< 154, CR = - 8.15 + 0.53 CI n = 12 r = 0.995
tilled plot : when 75.0<CI<170, CR = - 28.73 + 0.53 CI n = 8 r = 0.995

SAHELIAN ZONE

On the fixed dunes of the Sahelian zone, land surface presents lateral differentiation which consists in sealed bare spots which are encompassed with sandy hummocks covered with grass (Figure 4). These features are likely to result from the combined effect of several processes involved in a cyclic pattern as observations in northern Senegal have suggested (Valentin, 1983). Owing to the rainfall impact, segregation between coarse and fine particles is fostered mainly where the vegetative cover is deficient. Consequently a sandy micro-layer develops over the seal. This fine sand is then easily wind drifted and entrapped by the surviving vegetation nearby. The seal is thus exposed on the surface whereas sandy micro-mounds are ever developing unless sufficiently wet periods occur and erode hummocks so that bare spots are covered again with sand and seeds, hence gradually with a protective grass layer.

In order to study the influence of these features on the runoff production, experiments were carried out in Oursi (northern Upper-Volta). One plot was set up on a bare sealed spot, another on a grass-free sandy micro-mound. The experimental plan was analogous to that in Agadez, except for the number of runs. Since the mean annual rainfall is 450 mm, approximately 30 rainfall events were simulated within 10 days.

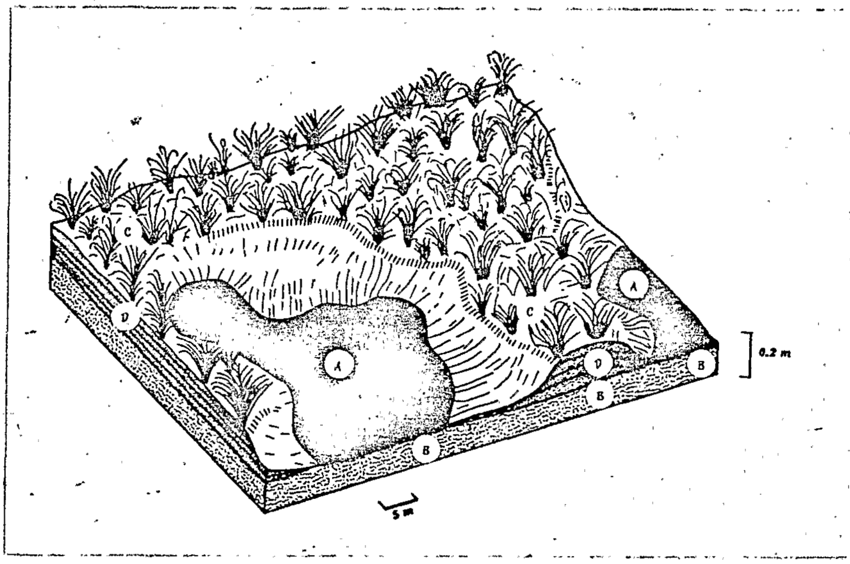

FIGURE 4 Land surface differentiations in the Sahelian zone. The bare spot (A) is covered with a cohesive plasmic seal (B) which usually comprises vesicles. This seal may be found even at the bottom of the micro-mounds (C) which are gradually shifted. Thin and brittle seals (D) occur on and within these hummocks since aeolian deposits which contain some fine particles may be subjected to sealing, when vegetation is still scanty, before being buried in turn.

Under very dry conditions, runoff occured on the sealed plot and on the sandy micro-dune after 1 mm and 31 mm of rainfall, respectively. Strong correlations were found between cumulative runoff (CR) and cumulative rainfall (CF) expressed in millimeters:

bare sealed plot: $CR = 2.49 + 0.78\ CF$, $n = 28$, $r = 0.999$

micro-dune plot: $CR = -17.88 + 0.45\ CF$, $n = 26$, $r = 0.991$

For an amount of 450 mm of rainfall, water intake was 99 mm for the sealed plot and 285 mm for the micro-mound. This difference might have been still greater if the hummock were covered with grass. These results clearly emphasize the overriding importance of the soil surface differentiation on the hydrodynamics of arid sandy soils.

CONCLUSION

This study has shown that despite the very low content of fine particles, soil sealing occurs extensively even either on the desert alluvial coarse deposits or on the Sahelian aeolian deposits of fixed dunes. In contrast to sedimental features, these surface seals reflect a vertical size-sorting due to the effect of rainfall which leads to the formation of coarse textured laminae above fine textured micro-layers. An additional horizontal differentiation may affect soil surface where the herbaceous vegetation covers a notable part of land but still remains irregularly distributed, namely within the Sahelian zone. It consists of bare crusted spots surrounded with sandy micro-mounds which result from the wind action.

Observations associated with experiments have demonstrated that sandy soils cannot be invariably considered as yielding negligible water flow since the surface seal may greatly hamper the influence of the porous substrate. Likewise, tillage cannot be regarded as likely to alleviate the sealing problem. Owing to the very rapid development of the surface seal under rainfall, water intake into the tilled soil is poorly increased when compared to the undisturbed one, while soil detachment, mainly of fine particles, is strongly enhanced.

Surface sealing hinders further impoverishment in fine particles of sandy soils insofar as clay is concentrated in the form of closely packed and cohesive laminae. Furthermore, since surface crusts produce high runoff rates, they foster natural water harvesting. The meagre rainfall which by no means might be sufficient to raise any crop, is collected over a large area and concentrated in very pervious river beds. Water is stored in deep water-tables and evaporation loss is thus exceedingly limited. In fact, surface sealing should not be virtually accounted woeful since it enables runoff farming and thus human life even in the extremely dry regions.

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