

STUDIES ON CRUSTING IN A KAOLINITIC SOIL FROM ZIMBABWE AND THE EFFECT OF DIFFERENT CONDITIONERS

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Raindrop impact energy and clay dispersion are known to promote crust formation in many soils. Appropriate management practices and/or application of high ionic strength electrolytes or polycations have been suggested to reduce soil susceptibility to crusting. On this basis, the effects of gypsum, basic Al polychlorosulfate, and iron sulphate on a Rhodic-Kandiustalf soil from Zimbabwe were studied, on small runoff plots. Other plots were prepared from untreated soil (control), mulched surface and material from the Bt horizon replacing the top 15 cm of the Ap horizon. All conditioners had similar effects in reducing runoff in comparison with the control (15% and 30% respectively for storms of moderate intensity). Runoff from all conditioner plots increased with time and intensity of rainfall approaching the control values. Bt material significantly reduced runoff in comparison to the conditioners. The effectiveness of mulching (constant runoff about values of 5%) emphasises the importance of raindrop impact on the disintegration of soil aggregates. Laboratory investigations suggested that clay content, formation of phosphate-metal complexes, and presence of low molecular weight humic substances also contributed substantially to crust formation.

INTRODUCTION

Crust formation in soils exposed to raindrop impact in semiarid regions is due to two main complementary mechanisms: (i) breakdown of the soil aggregates and compaction and reconsolidation of the upper soil layer (McIntyre, 1958); and (ii) physical-chemical dispersion of the soil clays which migrate into the soil pores with the infiltrating water, (Agassi *et al.*, 1981; Kazman *et al.*, 1983). In this process the slaking that occurs during wetting due to compression of entrapped air must be taken into account (Le Bissonais, 1990). Enhancement by the stirring effect of raindrops, of aggregate disintegration and clay dispersion, also plays a fundamental role. These processes, however, have complex relationships with the nature of adsorbed cations and electrolyte concentration of the rain and/or irrigation water (Shainberg, 1985). Therefore, considering only clay dispersion, it is difficult to accurately predict potential infiltration rate and soil susceptibility to runoff (Levy *et al.*, 1993). Recently inorganic anions (particularly phosphates) and low molecular weight humic substances have been found to promote clay dispersion (Shanmuganathan and Oades, 1983). These compounds have particular relevance in soils with predominantly pH dependent charges and low ESP (<1) where the dispersing effect of Na-cations is negligible.

Methods that successfully prevent crust formation include: i) soil surface mulching, ii) addition to soil of electrolytes of high ionic strength, particularly gypsum, (Shainberg *et al.*, 1989; Alcordo and Rechcigl, 1993) or of polycations of Al and Fe, capable of raising the zero point of charge (ZPC) to pH values above the pH of the soil (Shanmuganathan and Oades, 1983). In both cases the compression of the electric double layer around the colloidal particles allows flocculation.

For soils from Zimbabwe, this work investigated the effectiveness of different inorganic soil conditioners in preventing clay dispersion and compared their effect on crusting with that of a mulch cover. From this we assessed the relative importance of the two different mechanisms in promoting crust formation in this particular soil. Additional experiments used a more stable Bt horizon of the same soil, to investigate the chemical-physical processes determining structure degradation and increasing clay dispersibility. We also assessed the effect on crusting of bringing the Bt horizon to surface.

MATERIALS AND METHODS

Experiments were conducted on a cultivated Rhodic-Kandiustalf soil (Soil Survey Staff, 1990) in a field with a 2% slope, in the Hamilton section of Mazowe Citrus Estate, near Harare. Selected mineralogical, physical and chemical properties of the Ap and Bt horizons appear in Tables 1 and 2.

Table 1. Particle size distribution and chemical characteristics of Ap and Bt horizon of Mazowe soil

Sample	Sand %	Silt %	Clay %	pH H ₂ O	CEC c.mol kg ⁻¹	ESP %	C Total %	C Humic %	C Acids %	C Fulvic %	Total P mg kg ⁻¹	P ads. max mg kg ⁻¹
Ap	42	31	27	6.3	7.5	0.9	1.10	0.27	0.20		345	208
Bt	20	38	42	5.8	5.6	0.9	0.44	0.14	0.03		155	520

Table 2. Chemical and mineralogical composition of particle size fractions of different horizons of Mazowe soil

Fractions	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	Mineral composition			
SAND Ap	0.44	0.58	5.02	89.66	0.05	0.49	0.36	0.23	0.06	3.11	Q8	K1	I1	OX0
Bt	0.40	0.57	4.30	89.89	0.01	0.44	0.21	0.19	0.06	3.93	Q8	K1	I1	OX0
SILT Ap	0.16	1.17	10.63	81.26	0.07	1.07	0.34	0.62	0.11	4.57	Q6	K3	I1	OX0
Bt	0.12	1.70	12.91	77.14	0.02	1.31	0.21	0.68	0.10	5.81	Q4	K4	I1	OX1
CLAY Ap	0.12	2.10	32.20	41.23	0.18	1.49	0.61	1.33	0.25	20.50	Q1	K7	I1	OX1
Bt	0.15	1.76	32.54	41.95	0.05	1.11	0.35	1.32	0.18	20.59	Q0	K8	I1	OX1

Q = Quartz; K = Kaolinite; I = Illite; OX = Crystall iron oxides.

Field experiments

To determine the effect on crusting of different inorganic conditioners, small runoff plots (1.2 m²) were constructed as in Stern *et al.* (1991). Gypsum, locally produced for agricultural purposes, WAC (basic Al polychlorosulfate produced by ATOCHEM, France) and Glotal ([Fe₂(SO₄)₃, 65%; CaSO₄·2H₂O, 35%), produced by Rumianca (Italy) were soil applied to plots in the seedbed. Application rates were: 2.5 and 5 t ha⁻¹ for gypsum; 500 L ha⁻¹ for WAC and 2.5 t ha⁻¹ for Glotal. For comparison, other plots were: i) left untreated (control), ii) straw mulch covered and iii) prepared by replacing top 15 cm of Ap layer with soil taken from Bt horizon. Runoff from all plots was measured for each effective storm of the rain season (November 1992- March 1993). Early in March the straw was removed from the mulched plots and gypsum (5 t ha⁻¹) was applied. All plots were hoed to the first 5 cm from the surface and the runoff measurements were continued until April. The experiments were conducted in duplicate in a randomized block design. During the dry season the plots were left untouched and shear strength, by pocket torvane, and penetrometer resistance, by hand cone penetrometer (Yamanaka KM, Kiya Seissakusho Ltd.; cone sizes: base diameter 18 mm and height 40 mm), were measured. Twenty measurements were taken on each plot.

Laboratory experiments

Clay dispersibility in distilled water (CD) was determined on samples from untreated Ap and Bt horizons by adding 10 g of soil and 150 ml of distilled water to plastic bottles which were shaken for 1 hour in a horizontal shaker. The suspension was transferred into cylinders which produced 10 cm water columns and left to stand for 4 hours at 20°C. An aliquot of 30 ml of the suspension was siphoned from a depth of 5 cm and clay was determined gravimetrically. The measurements were carried out in triplicate. Clay dispersed in distilled water was expressed as a percentage of total clay content that was determined using the same procedure, after removing organic matter by H₂O₂ and dispersing with Na-hexametaphosphate at pH 9. Clay dispersibility was also determined: i) on three artificial mixtures of the Ap and Bt horizons and ii) on Bt samples after addition of fulvic acid (0.25 and 0.5% w/w) or Ca-phosphate enough to saturate the maximum phosphorous sorption capacity of the soil (500 ppm), determined by fitting the sorption data to a Langmuir isotherm. The Ap/Bt mixtures were obtained by bringing to 1000 g, with Bt, 750, 500, and 250 g respectively of Ap, and thoroughly mixing. Ca-phosphate (CaH₂PO₄) and fulvic acid (extracted and purified from a podzol) were added to 1000 g of Bt samples as solutions, (adjusted to the same pH of the soil with a few drops of 0.01M KOH) in quantities calculated to attain the desired concentration of the two compounds in the samples. In plastic pots, the Ap/Bt mixtures, the Bt phosphate and fulvic acid systems, as well as pure Ap and Bt, were then wetted with distilled water, homogenized and dried at 50°C. This operation was repeated 3 times. CD was measured on these samples, as described above. In the samples, total carbon was determined by dry combustion, with a Carlo Erba CHN autoanalyzer, and humic and fulvic acid concentration by extracting the humic fraction of soil organic matter by 0.1 M NaOH and 0.1M Na-pyrophosphate followed by the separation of the two components by acid precipitation.

RESULTS AND DISCUSSION

Field experiments

Runoff measurements, as percentages of the total rainfall, appears in Figures 1 and 2. Figure 1 gives the data from (a) a high intensity 18 mm storm (40 mm h^{-1}) and (b) a moderate intensity 50 mm storm (18 mm h^{-1}). Both events occurred in December.

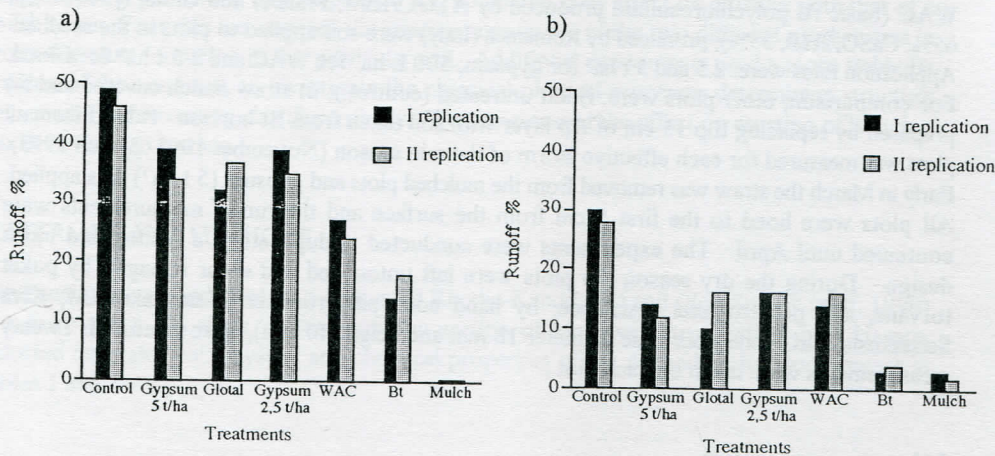


Fig. 1. Influence of rainfall intensity on runoff percentage: a) high intensity rainfall; b) moderate rainfall

Conditioners had similar runoff reducing effects especially at moderate storm, in spite of more cumulative rainfall. In both cases, the percentage of runoff from gypsum treated plots was not related to the amount of gypsum applied. Less runoff was observed on Bt and mulch covered plots. This seems to confirm that the Bt horizon had a good water stability and that, in the Ap horizon the role played by raindrop impact, in promoting aggregate breakdown and clay dispersion, was very important.

The percentage of runoff recorded at the end of February for a moderate intensity rainfall of 15 mm is shown in Fig. 2. The percent runoff significantly approaches that of the control, independent of the intensity of rain, in all plots treated with conditioners and even in Bt plots, the mulch covered plots being the exception.

Shear strength gave values lower than controls (50.2 kPa) only in Bt and WAC plots (22.4 and 33.8 kPa respectively). This provides further evidence that the beneficial effect of gypsum and Glotal was greatly reduced. This can be due to the partially different mechanism involved in controlling clay dispersion, as WAC could act more as a polycation, thus promoting some aggregation, rather than a simple electrolyte that can be leached from the surface. The data from Bt plots suggest that, in this horizon, only the mechanical breakdown of aggregates and compaction by raindrop impact operates and is responsible for a seal formation while the underlying soil maintains its good structural properties.

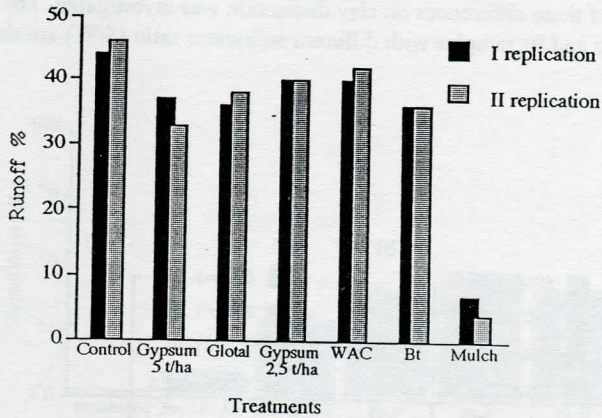


Fig. 2. Amount of runoff measured at the end of February 1993 for a moderate intensity rain.

The runoff data obtained at the end of March, after all plots were hoed, mulch removed and gypsum applied to mulched plots, confirm the previous findings. The cumulative runoff percentages from four storms in March showed good gypsum effectiveness compared to the control, in plots previously covered with mulch. Even where gypsum was applied at the beginning of the experiments there was some effect. This was expected because on hoeing gypsum was still found at a depth of about 2-3 cm. No effect remained on WAC and Glotal plots. The Bt horizon had runoff percentages comparable to those recorded at the beginning of the experiments.

Shear strength measurements, made at the end of dry season, showed that only Bt plots differed significantly from the control (17.6 kPa and 45.2 kPa respectively). Penetration resistance was found similar to the control (33.8 kg cm⁻²) for all plots with the exception of Bt plots (5.15 kg cm⁻²) and of Gypsum 5 t ha⁻¹ after mulch removal plots (130 kg cm⁻²). The higher value of penetration resistance of these last plots was unexpected although similar results were obtained in laboratory rain simulation experiments (Giordani *et al.*, personal communication). The low rainfall received from March to the end of the dry season, may not have removed gypsum from the upper soil layer. Therefore the flocculated state maintained by the high electrolyte concentration, coupled with severe dehydration on the bare surface, could promote a rearrangement of the soil fabric during drying with a tighter packing of particles and a consequent increase in cohesion.

Laboratory Experiments

To better understand the chemical-physical properties and the mechanisms responsible for clay dispersion and for the consequent formation of seal and/or crusts, CD was determined on Ap and Bt samples and on their mixtures. These two horizons differ mainly in particle size distribution, the mineralogical and chemical characteristics being quite similar in the correspondent fractions (Tables 1 and 2). Some differences were only found in the total carbon content, in the humic to fulvic acids ratio, in the amount of total phosphorous and in maximum sorption capacity of this

element. The role of these differences on clay dispersion was investigated. The percentages of clay dispersed in Ap and Bt samples with different soil/water ratio (S/W) are shown in Fig 3.

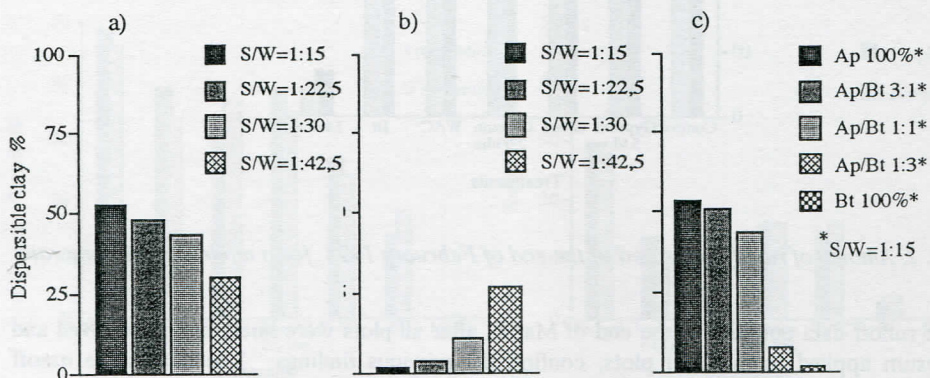


Fig. 3. Influence of soil/water ratio (S/W) on clay dispersion: a) Ap; b) Bt. Influence of mixing Ap and Bt horizons on clay dispersion for S/W of 1:15, c).

It can be seen that, for the Ap horizon (Fig. 3a) the percentage of dispersible clay slightly decreased up to a S/W of 1:30. Conversely for the Bt (Fig. 3b) it increased. These findings suggest that different mechanisms are involved in the aggregation of clay particles in the two horizons. In the Ap horizon, some clay forms aggregates, which are probably stabilized by organic compounds and may not be dispersed on shaking in distilled water even if the S/W changes. Conversely, the non-aggregate clay fraction is easily dispersible, in the absence of electrolytes, because the negative charges, probably due to fulvate and/or phosphates, prevail on colloidal surfaces. In the Bt samples the soil aggregation depends on flocculation processes which are less effective if the S/W ratio decreases. In this horizon the content of fulvic acid is very low compared to humic acid.

The presence of dispersing substances in the Ap horizon seems confirmed by the CD of Ap/Bt mixtures (Fig. 3c). The percentage of dispersed clay changes slightly from the values of the pure Ap samples, even in the 1:1 Ap/Bt mixture, whereas it should be much lower if calculated from the percentages of total dispersed clay obtained for the two separated samples.

As pointed out before, some anions such as phosphates and low molecular weight humic substances, particularly fulvic acids, can act as dispersing agents by increasing the negative charge at the surface of soil colloids. In this soil the presence and the role of these substances was demonstrated in two ways: i) by treatment of 1:1 Ap/Bt mixture with 5% H_2O_2 to remove organic matter; ii) by addition of phosphate and fulvate anions to pure Bt horizon material. In the first

case the amount of dispersed clay was reduced from 43% to 15%; in the second, a considerable increase of water dispersible clay was observed (Fig. 4).

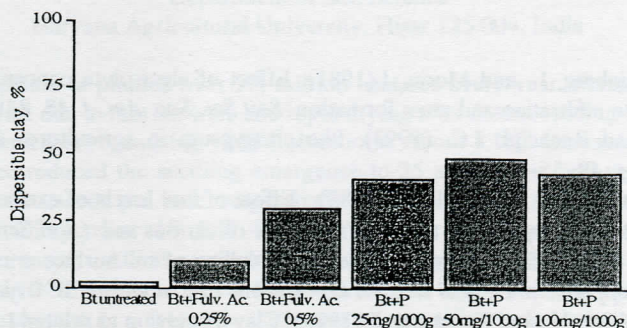


Fig. 4. Influence on clay dispersion of Bt horizon of different amounts of phosphates and fulvic acids.

CONCLUSIONS

For the soil studied the interdependence of the two main mechanisms involved in crust formation was demonstrated by field and laboratory experiments. Crusting and/or sealing did not occur if the soil was protected from raindrop impact, despite the chemical-physical properties of the colloidal fraction, as shown by mulched plots. On the other hand, in the presence of chemical-physical conditions unfavourable to dispersion of colloidal particles the raindrop impact had an effect limited to the surface whereas soil structure underneath remained unaffected, as shown by the properties of Bt soil horizon at the end of the season.

The most effective method for preventing crust in this type of soil was the mulch cover. Application of gypsum was also effective, but not to the same extent. Excessive hardening of the soil during the dry season was seen in one case. Application of compounds acting mainly as polycations, was favourable at the beginning but their efficacy was rapidly lost when the soil was reworked.

A dual role of humic substances in influencing soil structure seemed confirmed by our results. A fraction, which was highly polymerized and therefore formed complexes and tight bonds with mineral surfaces, contributed to stabilization of soil aggregates. Conversely dispersed low molecular weight humic materials lowered the ZPC below soil pH, and were probably responsible (with inorganic anions) for clay dispersion in Ap horizon.

Although the Bt horizon exhibits favourable physical properties, mixing with the Ap may not be advisable as these good characteristics could be rapidly lost, when soil is subjected to the ordinary agronomic practices, which include phosphate application, leading to a rapid turnover of organic matter.

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