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Research Article

Quantifying the Effect of Soil Ameliorants on Soil Crusting by Means of Field Experiments in a Wildlife Protected Area, South Africa

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Soil crusting (surface sealing) is widespread and serious in ecotouristic game parks and reserves in southern Africa, and especially South Africa. In this study, mineral soil crusts were found to be the problem in the Dinokeng Game Reserve (DGR), South Africa. Large areas of bare soil crusted areas were found in this reserve. The cause of this crusting was found to be historical agricultural practices such as cultivation with maize on non-arable soils and overgrazing by cattle. Negative impacts of soil crusting include reduction of water infiltration, leading to increased runoff and erosion and induced drought; inhibiting soil aeration; inhibiting germination and seedling emergence; and inhibiting root functioning and development. In this study in the DGR, a bare crusted area, where cultivation was abandoned 50 years before and there has been no recovery to rangeland since then, was selected for a field trial to determine the effectiveness of the application of various soil ameliorants on soil crust alleviation and improvement of water infiltration rate. The following ameliorants were evaluated: polyacrylamide (PAM) at levels of 5 and 20 kg/ha, gypsum at 2.5 t/ha, and molasses meal at 5 t/ha, as well as combinations of PAM and molasses meal, PAM and gypsum and gypsum and molasses meal. Brush packing, without any ameliorant applied, was also included as treatment, as well as a control with no treatments. PAM treatments increased final infiltration rate (FIR) by between 100–206%. The high efficacy of the lowest PAM treatment is at a cost of only USD 15 per hectare economically important. On the studied soil gypsum application reduced FIR by 81%, while molasses meal had minimal effect. These ameliorants can therefore not be recommended on such soil.

1. Introduction

Soil crusting (surface sealing) is an extremely serious and widespread problem throughout South Africa and neighbouring countries in Southern Africa [1] and also in East Africa [2] and further afield in Africa [3]. Laker and Nortjé [1] published a comprehensive review of existing knowledge of soil crusting in South Africa. The paper addresses all aspects related to soil crusting, such as the different types of crusts, soil properties which determine the vulnerability of a soil to crusting, environmental factors affecting crusting, soil management factors affecting crusting, practical (management) factors affecting crusting, practical and environmental impacts of crusting, amelioration and alleviation of crusts, etc.

Soil crusting in South Africa is a widespread and serious problem under various kinds of land uses, reviewed by Laker and Nortjé [1]. These include irrigated orchards under drip or microsprinkler irrigation [4] and annual field crops under overhead irrigation [5]. It is a problem under rainfed annual field crops produced on soils with crusting tendencies [6–9]. Soil crusting is also a problem in overgrazed rangelands under extensive livestock farming [10, 11].

Finally, soil crusting is becoming an increasingly more widespread and serious problem in rangelands in natural wildlife ecotourism areas, such as game parks and private game reserves [1, 12–14]. It urgently requires more research, since large areas have been observed which are still bare, devoid of any vegetation, more than 40 years after they have formed [1, 12]. The bare areas have negative impacts on the experiences of wildlife tourists. Bare areas are not aesthetically pleasing. Second, the lack of grazing material leads to very few antelope frequenting these areas. Due to the lack of antelope that serve as their prey, there is a lack of predators, such as lion. Thus, good wildlife sightings become limited. Without this, wildlife tourist numbers will decline, having negative economic impacts on game parks and private game reserves.

Crusted areas do not recover naturally [1, 12, 13]. Crusts cause three factors which lead to this: First, it causes poor soil aeration, leading to anaerobic conditions and consequently to poor seed germination [15]. It has high mechanical strength, inhibiting emergence of seedlings of small-seeded plants like grasses [1]. Third is very poor water infiltration [16], which results in dry soil, very low root water uptake, and dying of seedlings.

Because the crusted areas do not recover naturally, special measures have to be implemented to create a recovery process. In a wildlife tourist area, this poses special challenges, because a measure must not only be effective but also be aesthetically acceptable. Finding an acceptable solution to crusting problems in wildlife touristic areas is the topic addressed in this paper.

The serious, widespread problem of soil crusting and the forming of new bare areas in wildlife tourist areas within nature reserves and national parks, has received very little attention. No references related to technologies for alleviation of such situations were found. Situations in rangelands in extensive livestock farming are similar to those in wildlife game parks and reserves. Data regarding the use of ameliorants to reclaim crusting soils in rangeland livestock farming are also very limited. Harmse [17] and Harmse and Nel [18] found that bare areas in rangeland could be revegetated by applying phosphogypsum to alleviate soil crusting.

Data from cultivated agriculture consequently had to be used to identify ameliorants which could be evaluated for potential alleviation of soil crusting and reclamation of bare areas in wildlife areas. Products which have previously been studied in South Africa as ameliorants for sodic and crusted soils in cultivated agriculture include the following:

(i) Anionic polyacrylamide (PAM), also known as Superfloc [5–8, 19]
(ii) Gypsum ($CaSO_4.2H_2O$) or phosphogypsum, an industrial byproduct [4–8, 20]
(iii) Molasses meal, a byproduct from the sugar industry [20]
(iv) Coal-derived humic products [4, 19, 21]
(v) Compost [19]
(vi) Mulching [5, 6, 8]

Anionic PAM is a water-soluble polymer which has the dual capability to create soil structure by flocculating soil colloids and improve structure stability by bonding particles together (Mamedov et al., 2010). It is the only ameliorant on the list which can perform both these. To be effective, the PAM must have adequate negative charges and large molecules. PAM with an anionic charge density of about 30% and molecular weight of about 12 $Mg{\cdot}mol^{-1}$ is recommended [7, 8, 22]. The structure stabilizing effect of PAM is much like that of naturally occurring humus in soils. Coal-derived humic products are similar to naturally occurring humus in soils. Only humic products with large molecules are effective for structure stabilization and not small ones like fulvic acids.

Molasses meal is a byproduct from the sugarcane industry. Being high in polysaccharides, it is an excellent energy source for soil microbes [23]. Application of molasses meal thus stimulates high microbial activity, producing mycelia which bind soil particles into peds with high aggregate stability [20]. Compost is partly decomposed organic matter, which is further decomposed into humus by soil organisms after application, contributing to formation of stable soil structure [24, 25]. Mulching is application of large amounts of organic matter on the soil surface. It has two actions. First, it dissipates the energy of falling rain drops, preventing physical disaggregation of structure at the soil surface. Second, soil organisms incorporate a part of it into the soil surface and decompose it into humus.

Because of the large amounts of compost or mulching required, they would not be practically feasible for large areas. Of the others, PAM, gypsum, and molasses meal were selected for the present study. Weber and van Rooyen [20] found a combination of gypsum and molasses meal to be effective for reclamation of sodic soils, while they were individually not. Stern [6] had success with PAM and gypsum. Therefore, combinations of PAM + gypsum, molasses meal + gypsum and PAM + molasses meal were also evaluated in the present study.

A suitable representative area had to be identified for the study. It had to be in a game park or game reserve. It had to be a large area which has been barren for a long period without any recovery. It had to have a typical very thin (1-2 mm), very hard, dense crust. A suitable area was found in the Dinokeng Game Reserve (DGR). The DGR is a 35 000 ha game reserve in Gauteng province. It was formed by a number of private game lodges which took down their fences to form the combined reserve through which game can move freely. It is a Big 5 reserve, meaning that it has lion, leopard, elephant, rhino and buffalo, in addition to various other types of game. According to a knowledgeable informer the area was a maize field which was abandoned in about 1970, when the soil became physically so degraded that it could no longer be cultivated. It then became part of a livestock farm, but there was no recovery. It then became part of the land of the Pride of Africa game lodge, which became part of DGR, but still with no recovery that the present study was conducted in 2021/22, i.e. after about 50 years since being abandoned. A reconnaissance revealed that the reason for the lack of recovery was a very thin, very dense and hard crust (Figure 1) which was perfect for the study. More details about DGR, the study area and the study site are given in the Materials and Methods section.

Figure 1: Very thin crust (≤1 mm) in the study area.

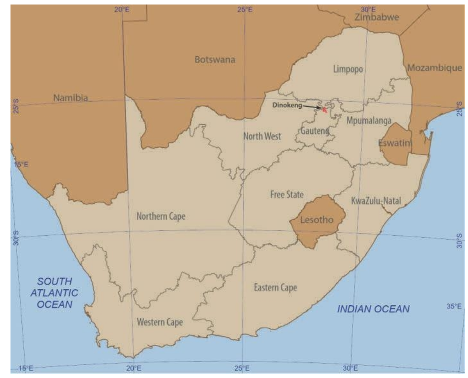

Figure 2: Location of Dinokeng Game Reserve.

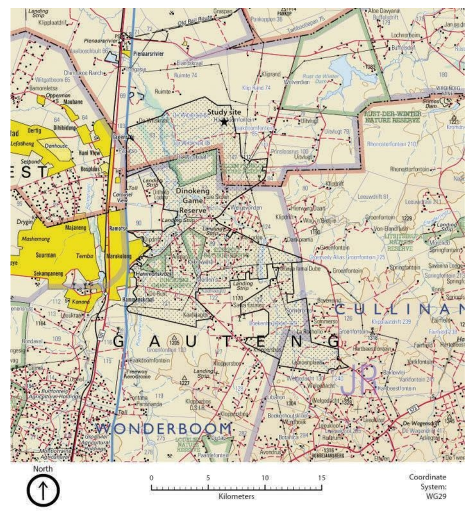

Figure 3: Location of the study site within DGR (Google Earth, 2023).

The study consisted of three experiments, two field trials and a laboratory experiment. The field trials are reported in this paper.

2. Materials and Methods

2.1. Locality of the Study Area. The area identified for the study is within the DGR. The largest part of the game reserve is situated in the north-eastern quadrant of the Gauteng Province of South Africa (Figure 2), with a small portion in the southwestern part of the Limpopo Province. DGR lies within the catchment area of the Pienaars and Elands rivers that flow into the major Olifants and Limpopo Rivers.

2.2. Locality of the Study Site. The study site is located on Pride of Africa land, which is privately owned, within the northern portion of the DGR that is in the Waterberg region of the Limpopo Province (GPS: 23°16′32.69″S 28°23′11.90″E) (Figure 3).

3. Field Trial 1

3.1. Study Site Selection for Field Trial 1. A degraded bare area with a hard dense soil crust was selected for the trial. It is very important to note that it was observed that virtually all topsoil had been removed from the bare area by means of sheet (interrill) erosion and that the Prismacutanic subsoil horizon was very close to the soil surface. Care was taken to select areas with similar surface crusting, soil type, slope, shade, and water runoff.

The soil on the trial site is of the Sterkspruit form according to the South African taxonomic soil classification [26, 27], consisting of an orthic A horizon abruptly over a Prismacutanic B horizon, with unspecified calcareous underlying material. It falls within the Solonetz Reference Group according to the international WRB classification [28]. Over almost the whole area of the trial site, the orthic A horizon had been removed by sheet erosion with a heavily crusted Prismacutanic B horizon now at the surface. These soils are highly unstable and prone to soil degradation, especially crusting and erosion.

3.2. Trial Layout. It was not possible to find a large enough contiguous area that conforms with all the requirements stipulated above. Consequently, the three trial blocks and the different experimental plots in each were fitted into suitable areas as close as possible to each other (Figure 4). They are thus not in straight lines or blocks, as would be found in field experiments in cultivated areas.

Once a suitable area for a block was identified, 3 × 3 m plots were measured out and marked with a round head wire nail (5.60 mm × 150 mm) through a washer (6 × 32 × 1.5 mm) on each of the four corners of the plot by hammering it level with ground level. The experimental plots are next to a road that is frequented by game drive vehicles and tourists do not want to see unnatural markers or exclosures [1, 29] in the veld.

The way in which the plots were marked, is not as visible to the untrained eye and most tourists would not see it. The markers would also not harm wildlife moving through the area or be removed by them. A small plastic marker (1.75 mm × 150 mm) was inserted at one corner of each plot to indicate the block and plot number.

3.3. Treatments. Nine treatments and combinations of treatments were tested, because different ones of them had been found to be effective by inter alia Green and Stott [22]; Stern et al. [7]; Stern et al. [5] or Weber and van Rooyen [20]. The rates of ameliorants applied are given in Table 1.

Figure 4: Block 2 with experimental plots 1 and 2 visible after application of treatments in the foreground and some more plots visible staggered further back; just beyond plot 1 on the right an untreated control plot was fitted in.

Table 1: Applied ameliorant products (treatments) and combinations thereof.

Ameliorant products and combinations thereof	Application rate	
	g/m^2	kg/ha equivalent
(1) PAM [0.5]	0.5	5.0
(2) PAM [2.0]	2.0	20
(3) PAM and molasses meal	0.5 + 500	5.0 + 5000
(4) PAM and gypsum	0.5 + 250	5.0 + 2500
(5) Gypsum	250	2500
(6) Gypsum and molasses meal	250 + 500	2500 + 5000
(7) Molasses meal	500	5000
(8) Brush packing	n/a	n/a
(9) Control	No amendment	No amendment

3.4. Method of Application of Treatments. The different treatments (products, controls) to be applied to different plots were weighed out beforehand into plastic zip lock bags. It was soon observed that the gypsum and molasses meal sweat in the plastic bags when left closed in the sun, which makes it harder to distribute them evenly during the application process. As a result, it was stored in the shade from then on. Gypsum and molasses meal were scattered by hand. Since it is of large quantities to work with, it is easy to ensure that it is scattered evenly.

PAM had two challenges; first, it consists of very fine particles, and second, the quantity to be applied is very small. To spread it evenly it had to be mixed with something with roughly the same particle size. Maize meal proved to be a good fit and was mixed with the PAM to have a quantity of material that was easier to distribute evenly during application. Beforehand a few test runs were done to determine the effective quantity of maize meal required to ensure effective application. The effective mass of maize meal required per m^2 was 52 g/m^2 with 468 g/m^2 needed for a plot of 9 m^2. A large tea strainer was used to apply the PAM-maize meal combination, since it had the right size openings to let the maize meal and PAM through unhindered.

After application of an ameliorant, a steel rake was used to break up the surface crust, to create fine crumbs in a thin surface soil layer and create shallow incorporation of the ameliorants. The maximum depth that was crumbed was 2 cm as the objective was to break and ameliorate only the very thin hard surface crust.

Due to the extremely hard dense nature of the crust, it was impossible to break the surface crust with a steel rake without wetting the soil first. A quarter or third of the surface area of a plot was wetted with a watering can with a standard head and then raked. If a larger area was wetted at a time, most of it dried out before it could be treated with the rake. The surface had to be wetted and the crust broken up and crumbed to enable the different products to react with the soil and also to incorporate them into the surface layer.

It was important not to leave the steel rake in the sun while applying products to the next plot, as the rake became too hot to handle. The surface crusts of the control and brush packing plots were not crumbed. The brush packing was done by using dead shrubs and branches that had been cut during road maintenance.

3.5. Experimental Layout and Design. The size of each experimental plot was 9 m^2, with provision of 0.5 m border areas around the centre of the plot. This left 4 m^2 of experimental plot area on which to take measurements. Due to the naturally high spatial variations which occur in soils in nature, it is the preferred procedure to use a randomised block design instead of a fully random design in field experiments. In this study, a randomised block design with three replicates was used.

The experimental plots were established and the treatments applied between 28 and 30 September 2021, i.e., at the beginning of the summer rain season, when vegetative growth commences. A rain gauge was installed. It is crucial to record rainfall incidents, since rain drop impact has a major effect on surface crusting [1]. It is also important for vegetative growth.

3.6. Measurements Recorded. Soil crust strength measurements were recorded at different times during the 2021/22 summer rain season and at the beginning of the 2022/23 rain season. Final infiltration rates were determined once during the 2021/22 season.

3.7. Soil Crust Strength Measurements. A Humboldt H-4212MH pocket shear vane tester was used for measuring the soil crust strength (Figure 5). The tester comes with 3 vanes, the standard vane is part of the tester and the small or large vanes can be attached to the tester over the standard vane if decided to use them. The tester can be used in a laboratory or in the field, provided that there are two inches or 5.08 cm in diameter of relatively flat surface. The standard procedure is to select the correct vane size, make sure the dial is on zero and press the tester into the soil until the blades are completely inserted. A constant pressure must be maintained and the outer ring rotated at an even force until failure occurs. The outer ring is then released slowly. The mark on the outer ring will stay in place, showing the shear value (in kg/cm^2) at failure [30, 31].

3.8. Final Infiltration Rate Measurements. A double ring infiltrometer was used for final water infiltration rate measurements [32, 33]. It had an inner circle diameter of 150 mm and outer circle diameter of 450 mm. Approximately, 20 litres of water was required to fill the infiltrometer (Figure 6). The normal procedure is to press the infiltrometer some distance into the soil to avoid leaking losses of water at the soil surface. In the present study this could not be done because the soil was too hard to push it in, even after prewetting. To overcome this problem, boot seal rubber was attached to the cutting edge of the infiltrometer to create a flexible bottom which could adapt to unevenness of the soil and give a tight fit with the soil surface upon weighting down with stones (Figure 6). The soil was slightly prewetted before putting the infiltrometer in place (Figure 6). Rubber ends were sealed with duct tape.

It was found that evaporation losses were so extreme during the middle of the day due to heat reflected from the light-coloured smooth soil surface that infiltration measurements could not be done between 10 am and 4 pm. Readings were recorded at 3 minute intervals until the readings per interval became constant.

As a result of the damaging nature of the infiltrometer measurements and the difficulty in finding level enough space in the plots, only one measurement could be made per plot. The plots are open for game and wild animals to move through. The resident large game like giraffe, buffalo, wildebeest, rhino, elephant, etc., frequently traverse the experimental plots when the soil is wet or muddy and their dried-out spoor make it impossible to find more than one level enough surface for the measurement per plot.

Figure 5: The Humboldt H-4212MH pocket shear vane tester (small vanes).

Figure 6: Infiltrometer measurement.

4. Field Trial 2

There was no seed germination in Field trial 1 plots even after good rain periods on plots in which stable structure was created at the soil surface. It was thus suspected that there was no viable seed bank left in the bare crusted areas. There could be two factors contributing to this. Excessive water movement was observed over the soil surface which could wash seeds away. Second, there was the extreme heat reflected from the soil surface. Consequently, a decision was made in January 2022, halfway through the summer rain season, to add a pilot study in which sowing in of grass seed was combined with soil treatment with ameliorants used to alleviate crusting. A degraded area similar and close to the Field trial 1 study site was identified for this trial.

The main objective with this study was to confirm whether there was actually no seed bank left in the crusted degraded area and that that was the reason for no seed germination. Only single products were tested and not combinations, for PAM only the highest level of $2.0\ g/m^2$ (Table 2). A specially formulated Dinokeng grass seed mix (Table 3), put together by Frits van Oudtshoorn from ALUT (Africa Land-Use Training and Working on Grass), was sown. The recommended average grass seed application rate for veld restoration of 20 kg/ha, i.e., $2\ g/m^2$ (van Oudtshoorn 2022, pers. comm.; [34] was used.

Plots were 1.5 m × 1.5 m in size. This size would allow for 0.5 m wide border areas with a 0.5 m × 0.5 m area in the centre of a plot to count the grass that germinated. Again, a randomised block design with three replicates was used.

PAM was mixed with maize meal as described earlier and applied to the respective plots with the tea strainer. After

Table 2: Applied ameliorant products in grass seed trial.

Ameliorant products	Application rate	
	g/m^2	kg/ha equivalent
(1) PAM [2.0]	2.0	20
(2) Gypsum	250.0	2500
(3) Molasses meal	500.0	5000
(4) Control	No amendment	No amendment

Table 3: Dinokeng grass seed mixture (ALUT).

No.	Species name	Common name	Variety name	Plant succession
1	*Cenchrus ciliaris*	Blue buffalo grass	Gayanda	Climax
2	*Chloris gayana*	Rhodes grass	Katambora	Sub-climax
3	*Digitaria eriantha* (tufted)	Smuts finger grass	Irene	Climax
4	*Digitaria eriantha* (stolons)	Creeping finger grass	Mixture	Sub-climax
5	*Eustachys paspaloides*	Brown rhodes grass	Tierhoek	Climax
6	*Panicum coloratum*	Small buffalo grass	Verde	Climax
7	*Panicum maximum*	White buffalo grass	Gatton	Sub-climax to climax
8	*Setaria sphacelata sericea*	Golden bristle grass	Phinda	Climax
9	*Sporobolus fimbriatus*	Dropseed grass	Tugela	Climax
10	*Urochloa mosambicensis*	Bushveld signal grass	Sabie	Sub-climax
11	*Urochloa oligotricha*	Perennial signal grass	Mixture	Climax
12	*Urochloa panicoides*	Garden signal grass	Mixture	Pioneer
13	*Eragrostis tef*	Teff grass	SA brown	Pioneer

making the respective ameliorant applications a correct amount of the seed mix was spread evenly over each plot, taking care to distribute the different types of grass seed evenly over the plot. Then the plot was watered with the watering can and a steel rake was used to break up the surface crust and to create crumbs on the surface. The control plots also received a seed mix application and were wetted and crumbed like the other plots.

The only procedural differences between Field trials 1 and 2, was that in the latter the control plots were also seeded, wetted and crumbed and all the plots were given an additional watering at completion of application (Figure 7). The wetting of the plots after application does not only help to bind the products initially and to give the soil a chance to create a crust again but also gives the newly sowed seed a slight moisture advantage, this late in the rain season.

During observation, it was found that the different products did not migrate out of their respected plots and the decision was made to count the entire plot and not only the centre 0.5 m × 0.5 m. A dowel stick and rope grid were made where the grid blocks are 0.5 m × 0.5 m to fit over the plot each time that seedling counts were done.

The seedling count in each plot commenced in the left corner subplot in the top line, then to the next subplot its right, followed by the right corner subplot, completing that row. After that, counting was done in subplots of the centre row from left to right and then in the last row from the left to the right. Counting was always done in the same sequence. A 60 cm steel ruler was used to slowly move over the grid from left to right and every seedling directly to the right of the ruler was counted, moving up and down the ruler to not miss a seedling (Figures 8 and 9).

Figure 7: Field trial 2 grass seed plots.

4.1. Statistical Analyses. For both field trials data were analysed statistically as a randomised block design, with the Proc GLM model (Statistical Analysis System) for the average effects. LSMeans and standard error were calculated and significance of difference ($P < 0.01$ = highly significant, $P < 0.05$ = significant, $P < 0.10$ = tendency) between means was determined by the Fischers test [35]. Repeated measures analysis of variance with the GLM model was used for repeated period measures. The linear model used is described by the following equation:

$$\text{One way: Yij} = \mu + \text{Ti} + \text{Bj} + \text{eij}, \quad (1)$$

where $Yijk$ = variable studied during the period, μ = overall mean of the population, T_i = effect of the ith treatment, B_j = effect of the jth block, and E_{ij} = error associated with each Y.

Figure 8: Counting grid on plot 4, with giraffe spoor.

Figure 9: Seedlings, 4 weeks after planting.

5. Results and Discussion

5.1. General Observations. It was observed that after the first, relatively light, rain the soil in the gypsum plots had lost their crumbs and formed a smooth crusted surface again. The light molasses meal had floated to the surface and was largely washed away from the plots where it had been applied, leaving plots with smooth surfaces. In contrast, when PAM plots were wetted after application mycelium type structures immediately formed which bound the surface soil into stable structural units (Figure 10). These persisted even after several heavy rainstorms.

With the first soft rain the crumb structure strengthened on the PAM plots, as a drying and wetting cycle causes the polymer chain to adsorb to the soil particles [22]. The PAM plots appeared darker in colour after a rainfall incident, longer than the other plots, as a result of more moisture uptake and less water that flows away (it is quite common for soils to have a darker colour in the moist condition than when dry). It was observed that less water flowed from the PAM plots, in comparison to the other treatments, after the first rain.

Where an elephant stood on a PAM treated plot, the soil became slightly compressed, but the individual structural units retained their integrity (Figure 11). It shows that PAM is a viable ameliorant to create a stable structure in crusted soil in game parks/reserves where wildlife roam freely. The ability of PAM to create stable structure in the crusted soil of the area, even at a low application rate, was confirmed in the laboratory study [13], which is not reported in this paper.

5.2. Mechanical Resistance of Crusts. Contrary to what was expected, the control plots had the lowest mechanical resistance values (Table 4 and Figure 12). Based on previous research, it was expected that the control plots would give the highest values [19, 20]. When doing the measurements, it was found that the crust of the control plots, although extremely thin (only about 1 mm), was extremely hard. Even after pre-wetting, extreme force had to be applied to push the shear apparatus vanes fully to their required depth into the soil. Much less force was required in the ameliorated plots.

The PAM treatments gave high mechanical strength values, despite the fact that little force was required to push the share vane apparatus into the soil. It indicates that the PAM did not only created stable individual peds but also formed stable bonds between peds.

The control plots had the lowest mechanical resistance values and would seem to have been the ones with the softest crust. In reality the control plots had the strongest and hardest, but very thin, crusts. The reason for this apparent anomaly was identified while the measurements were taken. For the Torvane shear apparatus to act correctly, the soil must apply the same force to all vanes to their full length and break away simultaneously, leaving a smooth, round hole. In the case of the thin, strong crust the crust alone exerts the full force until one or more vanes break away. Since it is unconfined at the surface, the moment a piece of crust fails at one vane the apparatus pops out and the other vanes pull/tear the rest of the surface crust out, scattering crust pieces around the measuring points (Figure 13). In some cases pieces of crust were scattered to as far as 50 cm from the measuring point, indicating the extreme force exerted at that moment. The apparatus furthermore recoils to some extent at that moment, giving abnormally low values. The hole has jagged edges. For easy comparison, the effects are summarised in Table 5.

5.3. Soil Water Infiltration. Final infiltration rate (FIR) was determined by means of the Double Ring Infiltrometer tests during the period 26 May 2022 to 20 June 2022. Results indicated a trend for the Control values to be lower than the PAM 0.5 g/m^2 and Molasses meal 500 g/m^2 combination (Table 6 and Figure 14).

Gypsum 250 g/m^2 was significantly lower than the PAM 0.5 g/m^2 and Molasses meal 500 g/m^2 combination and PAM 2.0 g/m^2. Gypsum 250 g/m^2 and Molasses meal 500 g/m^2 combination, PAM 0.5 g/m^2 and the PAM 0.5 g/m^2 and Gypsum 250 g/m^2 combination did not differ significantly from each other or any other treatment. Results indicated a trend for Molasses meal 500 g/m^2 to be lower than PAM 0.5 g/m^2 and the PAM and Molasses meal 500 g/m^2 combination. Most striking is the very low value for the gypsum treated plots, referring back to the observation regarding

Figure 10: Structure formation and stabilisation effect of PAM.

Figure 11: Elephant track in a PAM 2.0 g/m^2 treated plot.

Table 4: The influence of different treatments on Torvane shear test values.

	Treatments	Torvane shear test values (kg/cm^2)
1	PAM 0.5 g/m^2	1.74_2
2	PAM 2.0 g/m^2	1.75_3
3	PAM 0.5 g/m^2 and molasses meal 500 g/m^2	1.72
4	PAM 0.5 g/m^2 and gypsum 250 g/m^2	1.67_{14}
5	Gypsum 250 g/m^2	1.65^{a}_{5}
6	Gypsum 250 g/m^2 and molasses meal 500 g/m^2	2.07^{c}_{B45}
7	Molasses meal 500 g/m^2	1.58^{bc}
8	Brush packing	2.08^{ab}_{A1}
9	Control	1.37_{AB23}

^{ab}Column means with same superscript differ ($P < 0.05$). $_{AB}$Column means with same subscript differ ($P < 0.01$). $_{12}$Column means with same subscript tend to differ ($P < 0.10$). Standard error of the means ± 0.155.

redevelopment of a crust on these plots even after the first rain. The low value for the molasses meal plots also concurs with the similar observation for those plots.

In terms of numerical values PAM alone and in combinations increased FIR by between 100% and 206% above the control. Large reductions in runoff and large increases in FIR due to PAM application have been reported by Stern [6] and his co-workers and others. The increase of 100% by a PAM application of equivalent to only 5 kg/ha has important practical and economic implications. Gypsum reduced FIR by 71% compared with the control. Gypsum is normally expected to give positive FIR results, but less than PAM and other treatments (e.g [6] and his co-workers), but negative results with gypsum are not uncommon (e.g. [4]. Molasses meal gave a relatively small increase of 26% over the control. Gypsum and molasses meal in combination gave an increase of 81%, concurring with the findings of Weber and van Rooyen [20] that the two in combination gave positive results.

5.4. Seedling Emergence. After a light rain after planting there was some seedling emergence on the PAM plots, but none on any of the other plots. It showed that the PAM plots captured the little rain more effectively than the other treatments enable germination and seedling emergence. The seedlings were too small to count. Before they were large enough to count, they shrivelled to death during a hot, dry spell.

The first quantitative seedling count was done on 5 May 2022. Even though it was at the end of the traditional summer rain season, 7.5 mm of rain was measured between 22 April and 5 May 2022. The gypsum plots were significantly better than the control plots and highly significantly better than the PAM and molasses meal plots (Figure 15). The control plots were also highly significantly better than the PAM and molasses meal plots. The result for the control plots could be somewhat misleading, because two of the plots had thin washed-in sandy layers. The PAM plots could have been compromised because of the reduction of seed numbers after the germination and seedling emergence after the first small rain. Molasses meal plots had very little seedling emergence.

The second seedling count was done on 16 November 2022, after various good rainfall events in October 2022. The count was done this late in November to give an opportunity for germination and seedling emergence response to the early spring rains. During the counting, it was observed that there were older seedlings as well as new seedlings which emerged after the big rains. Despite the new seedling emergence there were much fewer seedlings in total than with the previous count at the end of the previous rain season on 5 May 2022. There were also dry, dead seedlings and young plants, which could not reach maturity as a result of how late in the growing season the seed was sowed, from the previous season that did not survive the dry winter. It could be as a result of not being able to have enough time to establish properly before the dry cold spells. The seedling die-off in especially the gypsum and control plots was big, with 69.3% and 68.4% respectively. This gave a statistically highly significant decline in seedling numbers under these treatments. Gypsum and the control plots were now in the same order as the PAM and Molasses meal plots, with no statistically significant differences between the treatments at this time (Figure 15). Molasses meal continued to give very poor results.

5.5. Effects of Brush Packing. Positive effects of brush packing can normally be ascribed to (i) reducing physical disaggregation of surface soil structure by dissipating raindrop energy and (ii) preventing of grazing of new growth before plants are well established. In the present study the positive impacts of brush packing were of very short duration (not

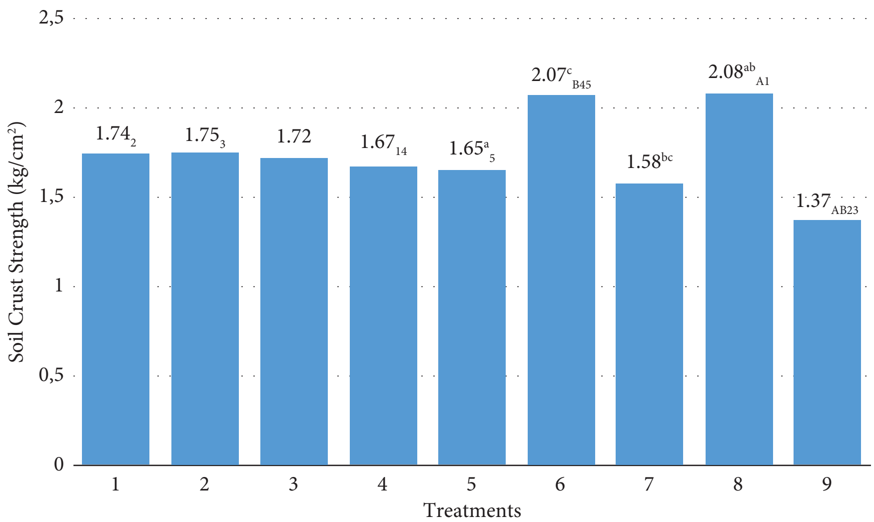

FIGURE 12: The influence of different treatments on Torvane shear test values.

FIGURE 13: Jagged edge hole with scattered pieces of surface crust at crust strength measurement in a control plot.

TABLE 5: Statistical significance of differences between treatment means in regard to crust strength.

1	There is a trend for PAM 0.5 g/m^2 to be higher than the control
2	There is a trend for PAM 2.0 g/m^2 to be higher than the control
3	PAM 0.5 g/m^2 and molasses meal 500 g/m^2 combination do not differ significantly from any other treatment
4	There is a trend for PAM 0.5 g/m^2 and gypsum 250 g/m^2 combination to be lower than gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination and brush packing
5	Gypsum 250 g/m^2 is significantly lower than brush packing and there is a trend to be lower than gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination
6	Gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination is significantly higher than molasses meal 500 g/m^2 and highly significantly higher than the control. There is also a trend for gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination to be higher than PAM 0.5 g/m^2 and gypsum 250 g/m^2 combination and gypsum 250 g/m^2
7	Molasses meal 500 g/m^2 is significantly lower than gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination and brush packing
8	Brush packing is significantly higher than gypsum 250 g/m^2 and molasses meal 500 g/m^2 and highly significantly higher than the control, with a trend to be higher than PAM 0.5 g/m^2 and gypsum 250 g/m^2 combination
9	The control is highly significantly lower than gypsum 250 g/m^2 and molasses meal 500 g/m^2 combination and brush packing, with a trend to be lower than PAM 0.5 g/m^2 and PAM 2.0 g/m^2

Table 6: The influence of different treatments on the double ring infiltrometer test values.

	Treatments	Final infiltration rate (mm/h)
1	PAM 0.5 g/m^2	7.37
2	PAM 2.0 g/m^2	10.00^{b}
3	PAM 0.5 g/m^2 and molasses meal 500 g/m^2	$11.33_{12^{a}}$
4	PAM 0.5 g/m^2 and gypsum 250 g/m^2	7.37
5	Gypsum 250 g/m^2	1.07^{ab}
6	Gypsum 250 g/m^2 and molasses meal 500 g/m^2	6.70
7	Molasses meal 500 g/m^2	4.67_{2}
8	Control	3.70_{1}

^{ab}Column means with same superscript differ ($P < 0.05$). $_{12}$Column means with same subscript tend to differ ($P < 0.10$). Standard error of the means ± 2.581.

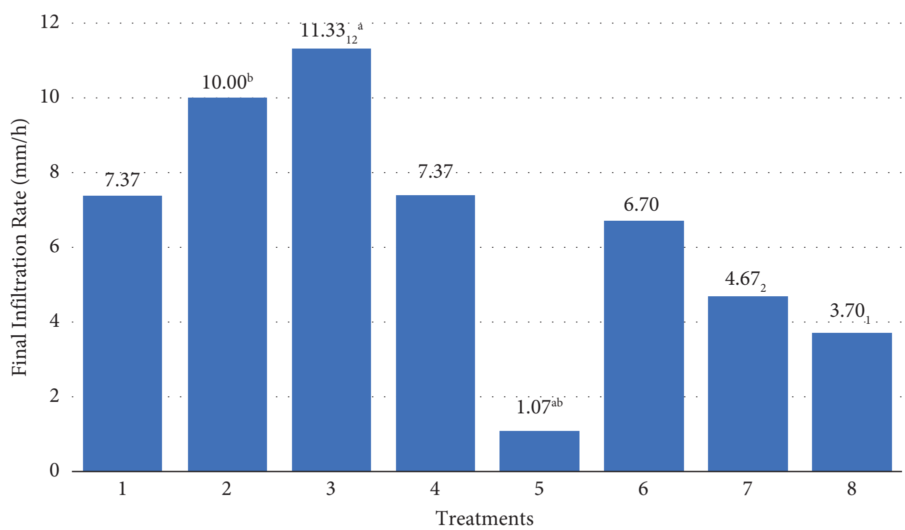

Figure 14: The influence of different treatments on the double ring infiltrometer test values.

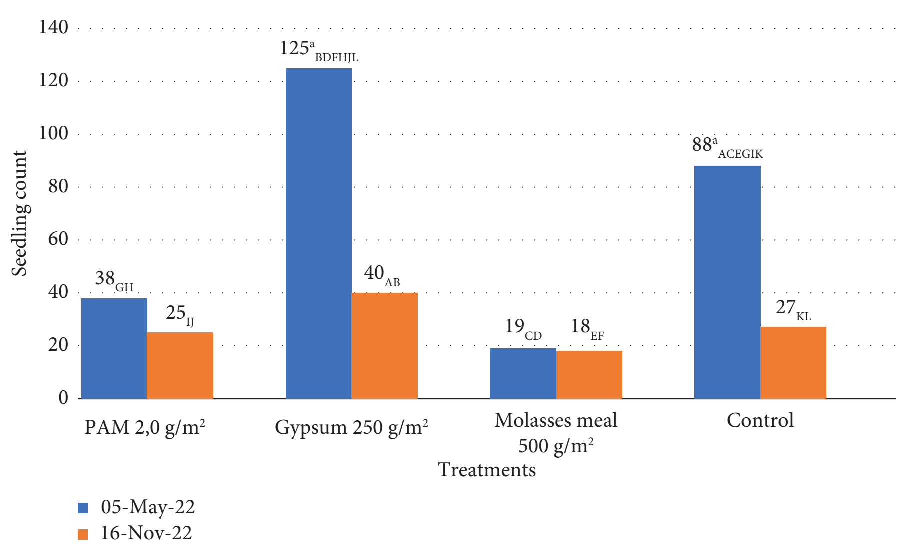

Figure 15: The influence of different treatments on seedling emergence.

even a full rain season) under conditions of a very high rate of runoff and sheet erosion through the brush packet plots in Blocks 2 and 3. Under more favourable conditions, as in the brush packing plot in Block 1, it was highly effective over the whole study period. Brush packing was very effective in assisting re-establishment of grass and weeds by trapping eroded sandy topsoil and seeds from overflowing water. In this case there was no strong continued water flow through the plot. Strong flow was diverted through a gully which was developing next to the plot.

6. Conclusions

The mechanical strength results indicate that a Torvane shear apparatus is not an appropriate instrument for crust strength measurements of extremely thin (≤1 mm), dense, and hard crusts. A flat tipped pocket penetrometer, pushed from the top, could perhaps be tested as an alternative. PAM seems to be an effective ameliorant to give stable structure that resists physical disaggregation by rain and implements.

The good results obtained with PAM (at both the low and high application rates) indicate that PAM is a viable ameliorant for alleviating soil crusting in such very difficult type of soil and can thus be recommended. The good results with the low application of 5 kg/ha rate improves the economic feasibility of PAM. At the present price equivalent to USD 3/kg, it amounts to 15 US dollars per hectare. The poor results obtained with gypsum and molasses meal indicate that these can be eliminated as potential ameliorants for this type of soil. The large amounts required per hectare probably also strongly reduce their feasibility for use on large areas.

Since there was no seedling emergence in any of the plots in the field trials throughout the whole summer rain season, except in the brush packing plots, where the seedling establishment was clearly associated with seed brought in with eroded topsoil, it was clear that there was no viable seed bank left in this area which had been barren for half a century. On soils which are very inhospitable to roots, like that in the present study, other types of vegetation with more robust root systems, like small shrubs or succulents should also be investigated as potential alternatives.

Looking forward, well-planned and executed crust alleviation trials should be repeated with the application of ameliorants in combination with sowing in of seeds to further support and confirm the recommendations made. Studies should include different types of soils. The trials should be repeated on soils with similar thin crusts and should preferably also be done on soils with thicker crusts. The proposed research should include other methods of crust strength measurements, in combination with the shear vane apparatus used in this study, in order to refine the measurement of crust strength of very thin, dense and hard crusts. Very important for seeding in studies is to plan according to the weather and longer period rainfall predictions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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