EVALUATION OF THE EFFICACY OF SELECTED AMELIORANTS TO ALLEVIATE SOIL CRUSTING, WITH A VIEW TO RECLAMATION OF DEGRADED LAND, IN DINOKENG GAME RESERVE

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I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

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I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

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Abstract

Soil crusting is a serious problem throughout South Africa in crop farming, rangeland and wildlife reserves, leading to reduced water infiltration, increased runoff and erosion, inhibited soil aeration, germination and seedling emergence. Crusted soils often do not recover after several decades as seen in Dinokeng Game Reserve (DGR) where the study was conducted.

Selected ameliorants which are effective in the amelioration of soil crusts in cropping areas were assessed. These were PAM at two levels, Gypsum, Molasses meal and combinations thereof, and also brush packing. The methods used in testing the efficacy of the ameliorants in the field study were crust strength and final infiltration rate. Structure stability tests were done by means of wet sieving. Seedling emergence of sown in grass was determined in the field.

All amendments, except gypsum and gypsum + PAM, were statistically significantly effective in creating stable soil structure. PAM performed well in the field trial and pilot study. The high efficacy of the lowest PAM treatment is economically important.

Key words: Soil crusting, polyacrylamide, gypsum, molasses meal, brush packing, structure stability, final infiltration rate, seedling emergence, Torvane shear tester, double ring infiltrometer, wet sieving.

Opsomming

Grondkorsvorming is 'n ernstige probleem regdeur Suid Afrika in gewasverbouing, weidingsgebiede en wildreservate. Dit lei tot verminderde waterinfiltrasie, verhoogde afloop en erosie en swakker gronddeurlugting, ontkieming en opkoms van saailinge. Grond met korse herstel dikwels selfs nie na etlike dekades nie, soos gesien kan word in DGR waar die studie gedoen is.

Grondverbeteraars wat effektief is in die opheffing van grondkorse onder gewasverbouing is getoets. Dit was PAM op twee vlakke, Gips, Melassemeel en kombinasies daarvan asook ook takke pak.

Die metodes wat gebruik is om die doeltreffendheid van die middels te toets in die veld proewe was korssterkte en finale infiltrasietempo. Struktuurstabiliteitstoetse was gedoen deur middel van natsif toetse. Saailing op-koms van ingesaaide gras was in die veld gedoen.

Alle middels buiten gips en gips + PAM was statisties beduidend effektief in die skep van stabiele grondstruktuur. PAM het goed presteer in die veldproef en loodsstudie. Die doeltreffendheid van die laagste PAM-behandeling is ekonomies van belang.

Sleutelwoorde**:** Grondkorsvorming, poliakrielamied, gips, melassemeel, struktuurstabiliteit, takke pak, finale infiltrasietempo, saailing opkoms, torvane skeurmeter, dubbelring infiltrometer, natsif.

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Abbreviation	Designation
ALUT	Africa Land-Use Training
Ca	Calcium
DGR	Dinokeng Game Reserve
FIR	Final infiltration rate
IWUE	Irrigation water use efficiency
Na	Sodium
PAM	Polyacrylamide
PG	Phosphogypsum
PoA	Pride of Africa

CHAPTER 1
GENERAL INTRODUCTION

1.1 General

Sustainable land use requires that land degradation must be avoided or minimised. Therefore, an important management practice in any land use set up is soil conservation. Soil is the foundation for land use activities, ranging from crop or livestock farming to wilderness/wildlife tourism and many more. Absence of sound soil conservation practices will lead to various forms of soil degradation, such as erosion, (both sheet and dongas), soil crusting (surface sealing), etc.

This study will focus on soil crusting which results in bare soil areas in wilderness/ wildlife tourism areas. The serious, widespread problem of soil crusting and the forming of new soil crusts in rangelands in natural areas, especially wildlife tourist areas within nature reserves and national parks, has received very little attention. It urgently requires more research, since large areas have been observed which are still bare, more than 40 years after they have formed (Nortjé, 2014; Laker and Nortjé, 2019). Bare areas form in wildlife tourism areas due to overgrazing of vulnerable areas on which animals concentrate. In many cases the bare areas were formed before an area became a wildlife tourism area, due to incorrect land management while it was farmland. The main examples of these are injudicious cultivation of some areas, such as cultivation of non-arable areas (areas which are not suitable for cultivation) or implementation of inappropriate cultivation techniques, or overgrazing.

The study area is in Dinokeng Game Reserve (DGR). The area is in the north of the reserve and in a degraded state as a result of advanced crusting that already transformed into erosion with soil loss. According to available history of the area, it was utilised as agricultural land, ploughed and maize and sunflower planted. This was done without a land suitability evaluation or land use planning that would have showed that the sodic soil was not suitable for cropping. During the 1970s cropping was abandoned "as a result of not enough rain", but there were no drought conditions, it was in fact a very wet period with above average rainfall. The cultivated area faced an agricultural drought as a result of crusting, which prevented effective water infiltration into the soil. After the cropping era they tried to re-establish grass, which was not successful, since the water flowed away without infiltrating the soil and took the grass seed with it. The grass seed that was lost as a result of the soil crust and the water flow, might be a contributing factor to failure of re-establishing vegetation. Other factors inhibiting establishment of grass might be that the soil is too dry and inadequately aerated to enable seed germination, with high mechanical resistance from the crust impeding emergence of the weak seedlings from the small seeds from breaking through the crust (Laker and Nortjé, 2019).

The next owner was a cattle farmer who divided the area into different camps, but as a result of overgrazing, bare patches re-emerged. The previous owner, in changing to game farming, ripped the area in his efforts of breaking up subsurface compaction, which might have been a problem as a result of the previous cropping. They also packed gabion-like structures (which they called "worse", i.e., sausages) to combat the erosion. This was done during the 1990s, with the present situation showing that 30 to 40 years later the gabions had no positive effects, the soil crusting problem being even greater and gully erosion having developed due to impacts of the gabions. Soil surface sealing is the issue here and no amount of ripping can salvage it on this soil type, since after the first rain a new soil crust will be formed. Since the study area is now part of DGR, with the experimental plots on both sides of the small gravel road, which game drive vehicles frequent, it is not feasible to put up barriers or exclosures [in other words, an area from which intruders, such as browsing animals are excluded by fencing or other means] (Wigley-Coetsee *et al.*, 2022) that can keep certain levels of game out, as these would not be aesthetically acceptable to tourists.

The importance of doing the study in DGR is that any success achieved with it will not only be applicable to DGR, but could serve as blueprint for solving similar problems which are found widespread in wildlife tourist areas throughout South Africa. It is also valuable to do the tests in a wilderness area, with all the variables that will be present when a game reserve official uses the products for crust amelioration afterwards. Another positive is that it is close to Pretoria, thus enabling frequent monitoring at the research site.

The following soil ameliorants which are used with success in crop production in the commercial agriculture sector to alleviate soil crusting (Laker and Nortjé, 2019) were tested for efficacy in the wilderness area: Polyacrylamide (PAM), Gypsum and Molasses meal.

1.2 Motivation

South Africa is in a very fortunate position with various National Parks, Nature Reserves, private game farms and rangeland, but with that comes the huge responsibility to conserve the environment and the soil in particular. The reason for this study is to find suitable environmentally friendly solutions for alleviating and combatting soil crusting in natural wildlife tourist areas, so as to reclaim bare areas in ways that are aesthetically acceptable to tourists, while keeping it as cost- and labour-effective as possible. Since such areas often do not recover naturally even after 40 or more years, as observed elsewhere and in the selected area in DGR, successful application of these measures would be the only way in which they can become well vegetated again. This will make them productive, enabling the keeping of higher wildlife numbers, and aesthetically more pleasing.

The consequences of not conducting the research, is that the old way of handling crusting and erosion will cause these issues to persist. Very labour and time intensive practices will continue, where cut branches, rocks, gabion-like structures or old tyres are packed in dongas or on crusts, with very limited success in some cases. These practices are functional in catching and collecting transported material, but have no effect on solving the crusting and erosion issues. With the alleviation of soil crusting, the direct result will be better water infiltration with less water runoff and less erosion or transported material, as well as a better vegetative cover.

1.3 Research Question

Evaluate the efficacy of selected ameliorants to alleviate soil crusting in wildlife tourist areas.

1.4 Aim and Objectives

The aim of this study is to find a solution to the soil crusting problems in wildlife tourist areas that is effective, environmentally and visually acceptable and cost-effective, by comparing and assessing selected environmentally friendly and easily obtainable products that have been found to be effective in the amelioration of soil crusts in cropping areas.

The objective of this work is therefore, to:

1. Identify appropriate methods for the reclamation of land degraded by erosion and crusting; and
2. Quantify the efficiency of the selected soil amendments (soil conditioners) in (1) alleviating crust formation in soil and (2) reclaiming the degraded land on crusted soil with acceptable technologies in a wildlife reserve.

1.5 References

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CHAPTER 2
LITERATURE REVIEW

2.1 Soil Crusting

Laker and Nortjé (2019) did a comprehensive review on existing knowledge of soil crusting in South Africa, covering all aspects thereof.

Soil surface crusts or surface seals, are typified by a greater density, finer pores and lower saturated conductivity than the underlying soil layer (Hillel, 1982). As a result, water infiltration is impeded, even if the underlying soil layer is highly permeable. The two main groups of crusts are mineral crusts and biological crusts (Laker and Nortjé, 2019). The former can be divided further into three types. The first type is depositional crusts, which form as a result of the chemical dispersion of the soil and is formed by sedimentation of particles from slow flowing or standing water (van der Watt and Valentin, 1991). The second type is structural or disaggregation crusts, which form as a result of physical impact of water drops, from irrigation or rainfall. The third type forms due to slaking, which occurs when large unstable soil aggregates become immersed in water, causing the clay to swell upon wetting and the air in the aggregates is expelled in bursts.

Even though there are different variables and factors influencing the development of the different crust types, all the crusts have the following in common: very poor water infiltration (de Villiers *et al.*, 2003), which results in very low root water uptake and huge water runoff. Secondly, it causes poor soil aeration, leading to poor seed germination (Al-Nasser and Al-Kafagi, 2020). Thirdly, it has high mechanical strength, inhibiting emergence of seedlings of small-seeded plants like grasses (Laker and Nortjé, 2019). These result in bare patches, excessive runoff and accelerated erosion.

Nortjé and Nortjé (2017), observed that soil surface crusts and sub-soil compaction are not isolated problems, but widespread in southern and eastern Africa. Serious soil degradation problems like soil erosion, sub soil compaction and soil surface crusting exist in private conservation areas, as well as National Parks. Studies conducted in the Kruger National Park showed that soil crusting and sub-soil compaction are long term problems, that as a result of low soil resilience or recovery potential, do not recover without help (Nortjé, 2014).

Soil organic matter content plays a key role in stabilising soil structure, which then prevents its physical, chemical and biological degradation (de Villiers *et al.*, 2003). Curbing of soil crusting in high clay content and clay-loam soils happens when soil organic matter is increased (Laker and Nortjé, 2019; Hanay *et al.*, 2004).
Soils with high salt/sodium contents carry pastures which are more palatable and nutritious than pastures on other soils. The ecological impact of salt/sodium accumulation in the soil is that abnormally high animal numbers concentrate on these areas, causing overgrazing of these vulnerable areas, which leads to accelerated degradation of the rangeland and soil through trampling and erosion. Human impacts aggravate the situation by constructing water holes in the saline/sodic soil areas, thus concentrating even larger animal numbers on these vulnerable areas and constructing roads on the sensitive sodic soils because of better viewing possibilities in comparison to adjacent areas (Nortjé, 2014; Laker and Nortjé, 2019).

2.2 Amelioration and Reclamation of Sodic and Crusted Soils

Products which have been studied in South Africa as ameliorants for sodic and crusted soils in cultivated agriculture include the following:

- Polyacrylamide (PAM), also known as Superfloc (Stern, 1991; Stern *et al*., 1991a,b; Stern *et al*., 1992; Nortjé and Schoeman, 2016). PAM is a commercial product which is *inter alia* produced in South Africa and is freely available.
- Gypsum ($CaSO_4.2H2O$) or phosphogypsum, an industrial by-product (Stern, 1991; Stern *et al*., 1991ab; Stern *et al.*, 1992; Laker and Vanassche, 2001; Weber and van Rooyen, 1971).
- Molasses meal, a by-product from the sugar industry (Weber and van Rooyen, 1971).
- Coal-derived humic products (Laker and Bredell, 1990; Laker and Vanassche, 2001; Nortjé and Schoeman, 2016).
- Compost (Nortjé and Schoeman, 2016).
- Mulching (Stern, 1991; Stern *et al*., 1991b; Stern *et al*., 1992).

Polyacrylamide is a water-soluble polymer with the dual capability to (i) flocculate colloids, thus creating soil structure, and (ii) improve soil structure stabilization, through bonding of particles together (Mamedov *et al*., 2010). It is the only one of the ameliorants on the list which can perform both these actions. PAM is a homo-polymer consisting of identical acrylamide units, which can be formulated with co-polymers to give specific charges and molecular weights. Their molecular weight and charge give any specific type of PAM its different characteristics. A specific type of PAM can be formulated to suit the requirements of a specific purpose best. High molecular weight anionic PAM is most effective for creating and stabilising soil structure (Green and Stott, 1999; Green *et al*., 2000; Mamedov *et al.*, 2010).

The charge density of PAM is instrumental in its adsorption to soil (Green and Stott, 1999). Thus, an anionic PAM with an anionic charge density of about 30% and a molecular weight of about 12 Mg mol^{-1} is recommended for use to create and stabilise structure in soils. (Stern *et al.*, 1991a,b; Green and Stott, 1999; Laker and Nortjé, 2019). The way the polymer adsorbs to the soil is fundamental in its effectiveness as a soil amendment. Anionic PAM and the clay surface being negatively charged would be expected to reject each other. However, each negatively charged clay surface is surrounded by so-called double layer of cations, i.e., positively charged ions, which bind the negatively charged anionic PAM and negatively charged clay particles together through cation bridging. Thus, for anionic PAM to adsorb effectively, there needs to be multivalent cations available, with divalent calcium ions being the most abundant in soils. The divalent cations source can be present in the soil, in PAM or through a direct application of gypsum to the soil if needed.

The adsorption of PAM to the soil particles is influenced by both PAM and the soil particles. The soil properties affecting the PAM adsorption are texture, clay type, organic matter content and type of ions in the soil. It was found that a complete drying cycle induces inner sphere complexes between soil and PAM. Drying compresses the double layer, bringing the physical van der Waals forces, which are extremely strong over very short distances, into play. This has an irreversible sorption of PAM to the soil as a result (Green and Stott, 1999; Inbar *et al.*, 2015).

Sodic soils are defined as soils which contain significant amounts of exchangeable sodium, but have low soluble salt contents (Richards, 1954; Brady, 1984; Marshall and Holmes, 1979). They have very high pH levels (>8.5 and even up to 10). They often have a relatively clayey texture. Exchangeable sodium results in the soil undergoing dispersion and its structure losing its stability. The dispersed soil becomes very dense, resulting in reduced water conductivity and permeability. Leaching is the most effective way for removal of excessive soluble salts and/or sodium. Gypsum is the most commonly used amendment to remove excess sodium from the soil's cation exchange sites.

To reclaim sodic soils, excess Na has to be removed. The Na has to be replaced by a flocculating cation (Ca) on the soil's cation exchange sites and then leached out. Gypsum is the usual source of Ca in soil reclamation (Levy and Nachshon, 2022). Van der Merwe (1965) showed that the gypsum solubility is too low to reach the threshold electrolyte concentration required to flocculate the soil and that additional sodium chloride needs to be added to the irrigation water to achieve an adequate electrolyte concentration (Laker and Nortjé, 2019). Hanay *et al.* (2004) confirmed that a gypsum application alone restored the chemical properties of the soil, but has no effect on the physical and biological properties. When the soil is treated with a combination of gypsum and compost, the physical, chemical and biological properties are restored.

Molasses meal is a by-product from the sugar cane industry (Weber and van Rooyen, 1971). It is high in polysaccharides, which are excellent energy sources for soil microbes (Botha *et al.*, 1979). Thus, application of molasses meal stimulates high microbial activity and growth, which produces microbial mycelia that bind particles in very high aggregate stability (Laker and Nortjé, 2019).

Several factors can contribute to structure formation in soils, but humus is the main product which creates stable soil structure (Laker and Vanassche, 2001; Laker, 2021). Coal is petrified decomposed organic matter and humic products extracted from coal can, therefore, be expected to be as effective as humus in soils in creating stable soil structure (Laker and Bredell, 1990).

Compost is partly decomposed organic matter which is often just viewed as a good organic fertiliser, providing a large variety of essential plant nutrients when incorporated into soil (Thompson and Troeh, 1978). It is, however, also further decomposed into humus by soil organisms and contributes to formation of stable soil structure (Thompson and Troeh, 1978; Hanay *et al.*, 2004; Nortjé and Schoeman, 2016).

Mulching is usually discussed in terms of its effect of minimising water losses from the soil and/or on minimising wind and water erosion (Thompson and Troeh, 1978; Marshall and Holmes, 1979; Brady, 1984). However, it also combats crust formation

(Thompson and Troeh, 1978). This is mainly due to its impact of dissipating the physical force of falling water drops from rain or overhead sprinkler irrigation, thus limiting physical disaggregation of surface soil structure. Bühmann *et al.* (1996) emphasised that this process of destruction of soil structure should be referred to as disaggregation and not as dispersion. It should be kept in mind that the bottom part of an organic mulch is in contact with the soil surface where it is decomposed by soil organisms. Humus is formed which stabilises structure in the surface soil layer.

Humus and humus-like products, including those from coal-derived humic products, compost and organic mulches, create stable soil structure according to the domain model described by Marshall and Holmes (1979). The model in Fig. 2.1 provides a basis for how the particles are held together to behave as a unit. Clay is arranged in domains and attached to each other and to larger particles of sand and silt by bonds as indicated in the model. The bond may be through the medium of organic matter as at *A*, *B* and *C*. The bond may also be electrostatic between the positive edge charges on one domain and negatively charged face of another at *D* (Marshall and Holmes, 1979).

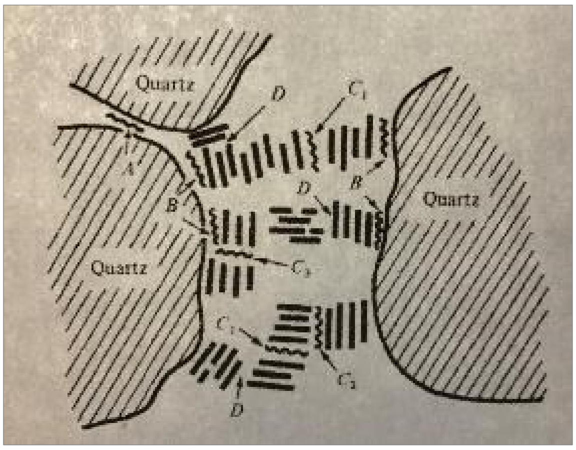

Figure 2.1: Possible arrangements of quartz, clay domains and organic matter in an aggregate

The versatility of PAM makes it suitable for use under different land use types, like furrow irrigation, rain-fed agriculture, road cuts, construction sites, mine environments and other disturbed soils (Green and Stott, 1999; Santos *et al.*, 2001; Inbar *et al.*, 2015; Sulaiman and Khalaf, 2022).

PAM can be used to ameliorate surface sealing and crusting, increase water infiltration, increase seedling emergence, and reduce runoff, nutrient and soil losses, which can prevent groundwater contamination (Stern *et al.*, 1991ab; Green and Stott, 1999; Green *et al*., 2000; Mamedov *et al*., 2010; Kim *et al.*, 2015; Nortjé and Schoeman, 2016).

It is important to keep PAM's limitations in mind when using it as a soil amendment, for instance a single application is not a permanent erosion control measure, because PAM can be degraded mechanically by sunlight, but is still a useful tool. Cationic PAM works well as a flocculent but is toxic to aquatic life which limits its use as a soil amendment (Green and Stott, 1999). In contrast to anionic PAM, cationic PAM cannot be bound to soil colloids by means of cationic bridges. They therefore, remain in solution and leach from the soil, thus causing pollution (Green and Stott, 1999).

Stern *et al*. (1991b) conducted different field studies on the effect of PAM, phosphogypsum and mulch on runoff from kaolinitic and illitic soils. In the first experiment, phosphogypsum was applied at a rate of 5 t/ha and the straw mulch at a rate of 3 t/ha in field runoff plots on two kaolinitic soils and one illitic soil. Runoff was determined after several individual rainstorms from each. Average runoff from untreated control plots was 32.9% and 63.6% respectively from the two kaolinitic soils and 56% from the illitic soil. The values for the PG treated soils were 18.3% and 35.9% for the two kaolinitic soils and 33.8% for the illitic soil. This means that PG reduced runoff by 44% relative to runoff from the control plots for both kaolinitic soils and 40% for the illitic soil. This is a major and very constant reduction in runoff, which is important in reducing erosion. It also means an approximate 40% increase in water infiltration into the soil. Straw mulching almost completely eliminated runoff, reducing it to 3.5% and 4.6% for the two kaolinitic soils and 1.4% for the illitic soil.

In the second experiment, PAM was applied at a rate of 20 $kg.ha^{-1}$, the usually recommended rate, on the first kaolinitic soil (Stern *et al.*, 1991b). Runoff from the control plots was 40.2% and 20.7% from the PAM treated plots. In other words, PAM reduced runoff and increased infiltration by almost 50% compared with the control. In the third experiment they applied PAM at rates of 5 $kg.ha^{-1}$ and 20 $kg.ha^{-1}$ respectively to the illitic soil. Runoff from the control was 40.9%. It was 11.6% where 5 $kg.ha^{-1}$ PAM was applied and 15.3% at 20 $kg.ha^{-1}$ PAM. This means that PAM reduced runoff and increased infiltration by between 63% and 72% relative to the control value. The good result with the very low PAM application is of great economic significance.

In the fourth experiment Stern *et al*. (1991b) compared an application of PAM at 20 $kg.ha^{-1}$ with PG at 5 $t.ha^{-1}$ on the second kaolinitic soil. Runoff from the control plots was 72.5%, 27.9% from the PAM plots and 37.7% from the PG plots. This means that PAM reduced runoff and increased infiltration by 62% relative to the value for the control plots and PG by 48%.

The decreases in runoff/increases in infiltration of rainwater are very important in cropping areas with marginal rainfall. It was also observed that PAM treated plots had a rough aggregated surface in comparison to the smooth surface on control plots.

Stern *et al*. (1992) studied the effects of PG at 5 $t.ha^{-1}$, PAM at 20 $kg.ha^{-1}$ combined with PG and pitting plus PG on runoff and wheat yields under irrigation. The runoff from 5 sequential irrigations was 36.1% from the control plots, 12.8% from the PG plots and 1.4% from the PAM + PG plots. This means that 87.2% of the applied water infiltrated in the PG plots and 98.6% in the PAM + PG plots. PG did not increase grain yield and irrigation water use efficiency significantly above the control. PAM + PG Increased both grain yield and irrigation water use efficiency (IWUE) significantly over the control, giving increases of 42% for yield and 45% for IWUE respectively. Pitting + PG reduced runoff to almost zero, but did not give a higher grain yield or IWUE than PAM + PG. It is more expensive and difficult to implement than the latter and therefore not recommended. Phosphogypsum increased the electrolyte concentration in the soil solution, to values above flocculation value for the clay. Flocculation of the soil is a precondition for the stabilisation of aggregates at the soil surface by PAM. The effect of PAM in maintaining stable aggregates at the soil surface was clearly observed.

Kumar and Saha (2011) conducted a study on the effect of PAM, gypsum and a combination of PAM and gypsum on surface runoff, sediment yield and nutrient losses in a hilly area with steep slopes. The PAM was applied at 20 kg/ha and gypsum at 2 500 kg/ha. The PAM treated plots only showed reduction in runoff in the range of 3.4 % to 16.7%, compared to the control for all the storm events, with 56.4% to 93.3% reductions by gypsum. The PAM gypsum combination was the most effective in decreasing the loss of major nutrients, sediment yield and runoff, closely followed by gypsum, supporting the good results with it obtained by Stern *et al*. (1992).

Even though Weber and van Rooyen (1971) compared molasses meal to a variety of other soil reclamation agents, emphasis will only be on the comparison to gypsum. Molasses meal was applied at 44 tons/ha and gypsum at 25 tons/ha. Qualitative observations three to four weeks after application showed that the molasses meal treated plots had partially broken and moderately structured topsoil, where it was previously hard and dense. The gypsum treated plots showed a slight improvement. With regard to the Modulus of Rupture measurements, the molasses meal treatment gave a desirable degree of aggregate stability, with gypsum intermediate. Molasses meal gave a statistically highly significant increase in infiltration, compared to all the other treatments, with a 100% increase compared to the control. Molasses meal promoted plant growth as a result of better aeration and as a result of changed physical soil conditions.

In a field study on a strongly crusted soil in a citrus orchard, Laker and Vanassche (2001) compared the efficiency of a coal-derived humic product with gypsum. The ameliorants were applied on the surface and the crust scratched loose. The crust was extremely dense, with severe water ponding under micro-sprinkler irrigation. Root development of the trees was very poor. The humic product increased yields significantly and improved root development, the latter ascribed to improved soil aeration. Gypsum slightly reduced yields compared with the control and negated the positive effect of the humic product where they were applied in combination. A large number of coal-derived humic-products were screened in laboratory and greenhouse studies before one was found that could be tested in the field (Laker and Bredell, 1990). It is important to note that coal-derived humic products differ widely and only very few, produced under specific conditions, are effective.

Nortjé and Schoeman (2016) compared the efficiencies of PAM at rates varying from 5 kg/ha to 20 kg/ha, a coal-derived humic acid, compost and combinations of PAM with humic acid or compost for the alleviation of soil crusts in avocado and macadamia orchards. Water infiltration rate showed significant differences between the treatments. Compost application gave by far the highest water infiltration rate. Water infiltration rates under the PAM treatments increased as the PAM application rate was increased from 5 kg/ha to 20 kg/ha. With the crust strength tests, the compost and compost and PAM combination treatments performed the best. The PAM treatments also gave good results, with the 20 kg/ha PAM the best PAM treatment. The humic acid did not give significant responses in terms of improving infiltration or reducing crust strength. In view of the findings of Laker and Bredell (1990) and Laker and Vanassche (2001), this was probably simply due to not using a humic acid that has been proven to have the necessary properties to give positive results. Compost on its own performed the best in alleviating soil crusts, but was also the most expensive per unit area treated. The PAM treatments cost 5-10% of the compost per unit area treated and performed excellent with alleviating soil crusts. These results showed that PAM is very cost effective to use, as opposed to the very expensive compost treatment. This is due to the very small quantities of PAM required, as opposed to the very large quantities of compost.

Soil conditioners like PAM and gypsum are able to improve soil properties to better withstand erosion (Stern *et al.*, 1991b, 1992), but are not substitutes for sound soil conservation practices. Conditioners should be used in support of other practices, or as temporary stabilisation practice on disturbed soils, until permanent vegetation cover has established (Baumhardt and Blanco-Canqui, 2014).

2.3 Measurement Methods

2.3.1 Aggregate stability

Stern *et al.* (1991b) employed sonication to determine aggregate stability over a specific time period. The aggregate dispersibility was used to classify the different soils in the study, into different reactive groups, soils with low dispersibility, soils with intermediate dispersibility (displaying initial stability with subsequent dispersibility) and soils with high dispersibility. There appears to be a connection between the disintegration of aggregates and the development of soil surface seals leading to a fast decrease in infiltration rate.

2.3.2 Mechanical resistance of crust

Page and Hole (1977) compared three different techniques for measuring soil crust strength. The conventional Modulus of Rupture (MOR) measurements are not appropriate for measuring the strength of rain induced soil crusts, since the formation of the crust requires that some modifications must be made to the method. The MOR method breaks a briquette of soil with known dimensions, loaded as a horizontal beam to find the maximum fibre stress. A problem is that crusts are usually extremely thin (only 2-3mm). During the second method, a fish line is buried 2 cm deep in the soil, with the crust forming over the fish line. With the pulling upwards of the fish line, the crust is broken, the maximum loading give the index of crust strength. Use of a shear vane instrument is the third method. With the shear vane technique, a vane is pushed into the soil past the shoulder of the vane. The torque applied to ruptures the soil, gives a measurement of the shear strength of the crust.

Page and Hole (1977) did these tests were done in a laboratory with soils that were known to cap after heavy rains. A series of soils were used and each under two treatments, with one part treated with polyvinyl alcohol, a soil conditioner which is known to prevent crusting under heavy rains. With the MOR tests, the briquettes were too fragile and hence a large number of replicate tests had to be made. The fishing line method always only needed three replicate tests. For the shear vane method 20 to 30 replicates were required for each soil. With the obtained data it suggests that the shear vane method values were less variable than those obtained from the other methods. A further test was to sow *Brassica rapa*, with the same soils subjected to the same treatments as the other soil samples, except a further 200 ml of water was added to each seed tray to enable germination. Although this would temporarily affect the soil crust, probably making it weaker, moisture content at the time of emergence was the same as that of the soils used for the soil crust strength measurements and it could be expected that the crust strength was the same.

There was not a good correlation between the emergence and any of the crust strength methods. Since the differences between the correlation coefficients were so small, there is not enough evidence to suggest that one method was significantly better than another. Of the methods tested, the fishing line method comes closest to subjecting the soil crust to similar kinds of forces to those exerted by emerging seedlings. The simplest method to use in the laboratory and field is the shear vane method. Page and Hole (1977) concluded that the shear vane method, which is in essence a torque meter, with the advantage of less variability, would be the method of choice until some more appropriate tests are devised.

According to Al-Nasser and Al-Kafagi (2020) the main methods to use when measuring the crust hardness, are the Modulus of Rupture, penetration resistance with a pocket penetrating device and seedling emergence, by measuring seedlings' ability to break through the crust.

Zimbione *et al.* (1996) tested two torvane shears, a hand vane tester and a pocket penetrometer. They found that the torvane shears always gave the lowest values and the penetrometer the highest values, which was expected as the torvane shears applies a torsional shear, where the penetrometer creates compressive and shear failure. They also confirmed the soil surface moisture content affect the performance of the shear strength devices; increased moisture content resulted in a decrease of shear strength.

Stefanow and Dudziński (2021) found that some test methods were sensitive to soil anisotropy and the main factors that affect results were shearing speed, geometry and the kinematics of the tester.

2.3.3 Final infiltration rate

The infiltration rate is measured with a double ring infiltrometer. The double rings are inserted to an average of 5 cm deep, where the soil permits. The rings are filled with water, taking care not to damage the soil surface in the filling process. The speed of infiltration is measured at intervals from the inner circle and starts immediately. The outer ring prevents the water from the inner ring to spread laterally after infiltration (Royal Eijkelkamp, 2022). The water level in both the rings should be the same and sufficient water be available, so that the rings do not run dry during measurements.

Chowdary *et al*. (2006) observed that with a single ring infiltrometer the lateral flow component ranges from 31.8% to 67.9%, which is unacceptably high, giving vastly incorrect readings. With a double ring infiltrometer it was 11.7% to 11.9%, which is within acceptable experimental error range.

Gregory *et al*. (2005) devised a method of a double ring infiltrometer with two Mariotte siphons, one for the inner ring and one for the outer ring. With this method one person can take measurements and maintain the head.

2.4 Grass as a Tool to Reclaim Degraded Land

There are two basic approaches in reclaiming degraded land, according to van Oudtshoorn (1994). Improve the vegetation cover with better veld management or veld rest when there is a good recovery potential or rip or plough the degraded area and sow with indigenous grass species suitable for combatting erosion. To reclaim such areas, the main causes have to be addressed and the soil moisture increased, before vegetation can be established. When soil crusting was as a result of mechanical processes, the use of a mulch may be effective and when chemical processes was the cause, a suitable ameliorant will be more effective. Soil structure and aggregate stability can also be enhanced with the correct organic polymer.

Van Oudtshoorn (1994) recommends grass species like *Cynodon dactylon* and *Pennisetum clandestinum* (not indigenous) for reclamation work because of their versatility in many different scenarios. Rhizome-bearing and stolon forming grass species are recommended for degraded areas like earthen embankments, steep slopes and areas where the runoff rates are high. Climate, the planned use and management of the area, play a role in the species composition for reseeding. Perennial indigenous grass should be used.

Kellner and de Wet (2001) found that *Digitaria eriantha*, *Chloris gayana* and *Panicum maximum* performed well on high clay soils and they also found that all of them performed different over a three-year period. Msiza *et al.* (2021) also had good results with *Chloris ciliaris*, *C. gayana*, *D. eriantha* and *P. Maximum* towards veld restoration and as a food source. *C. gayana* and *D eriantha* performed the best during restoration treatments, which included ripping, over-sowing, brush packing and organic material (van den Berg and Kellner, 2005).

In the study of Khomo and Rogers (2005), the most common grass species on the sodic patches was *Tragus berteronianus*. This specific grass species is usually the first colonizer on hard compacted soil and grows in disturbed places such as bare ground and road verges.

2.4.1 Physical disturbance of the soil

Physical disturbance of the soil surface, to such an extent that the sub surface material is exposed, can bring dormant seed to the surface and create a favourable germination environment (du Toit *et al*., 2003). These disturbances can be small, such as the imprint from the hoof of an animal to large events such as the uprooting of trees. The latter can create a reduced competition space for new seedlings to establish.

Kinyua *et al* (2010) also found that tilling alone produced large increases in plant biomass, mostly annuals, as a result of the breaking up of the surface crust.

Good results with only tilling and no seeding were obtained by Visser *et al* (2004) in the Nama Karoo.

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CHAPTER 3
STUDY AREA

3.1 Experimental Area

The area identified for the study is within the Dinokeng Game Reserve (DGR). The largest part of the game reserve is situated in the north-eastern quadrant of the Gauteng Province of South Africa (Fig. 3.1), with a small portion in the south-western part of the Limpopo Province.

Dinokeng Game Reserve lies within the catchment area of the Pienaars and Elands rivers that flow into the major Olifants and Limpopo Rivers.

Figure 3.1: Location of Dinokeng Game Reserve

3.2 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) (Fig. 3.2). The approximate size of the study site is 3 hectares.

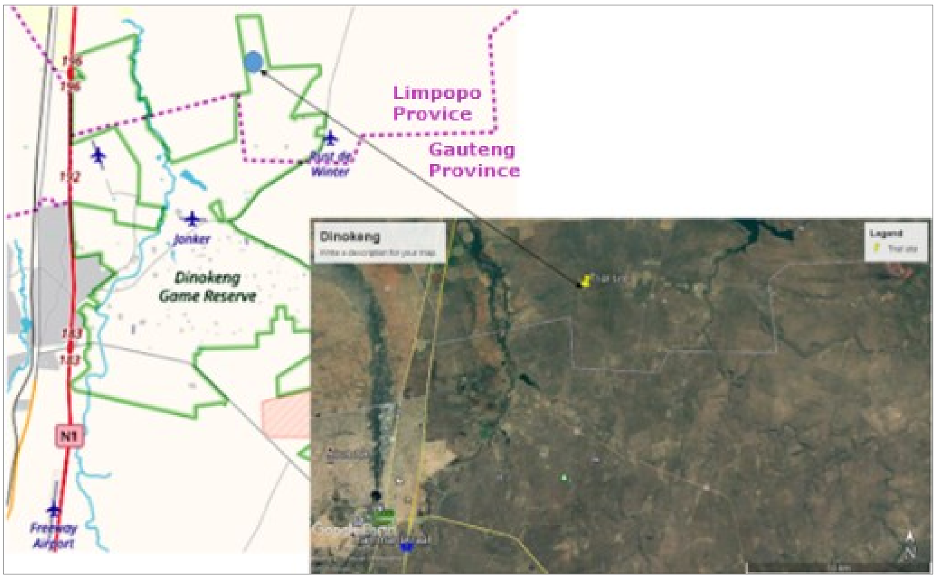

Figure 3.2: Location of the study site within DGR (Google Earth, 2023)

3.3 Description of the Study Area

3.3.1 Climate

3.3.1.1 Temperature

The long-term annual temperatures at the DGR differs between mean minimum of 0ºC and mean maximum of 40ºC with a long term daily average temperature of 21ºC (DGR, n.d.).

The closest South African Weather Services weather station to the study area that records temperature is the Wonderboom Airport Station. The temperature data over a period of 14 years for Wonderboom Airport (Dlamini 2022, pers. comm.; Letsatsi 2022, pers. comm.) are given in Fig. 3.3.

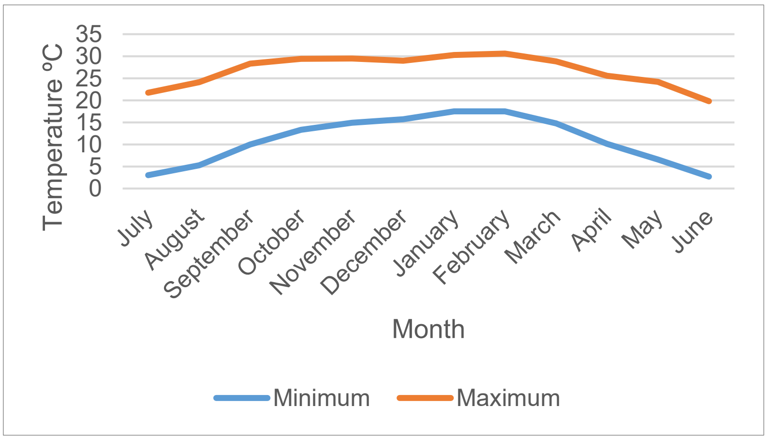

Figure 3.3: Wonderboom Airport average annual/monthly temperature distribution over 14 years (2008-2021)

3.3.1.2 Rainfall

The area has a short summer rainy season with thunderstorms and almost no rain during the winter months (Fig. 3.4). The annual rainfall at the DGR varies from 350-750 mm (DGR, n.d.).

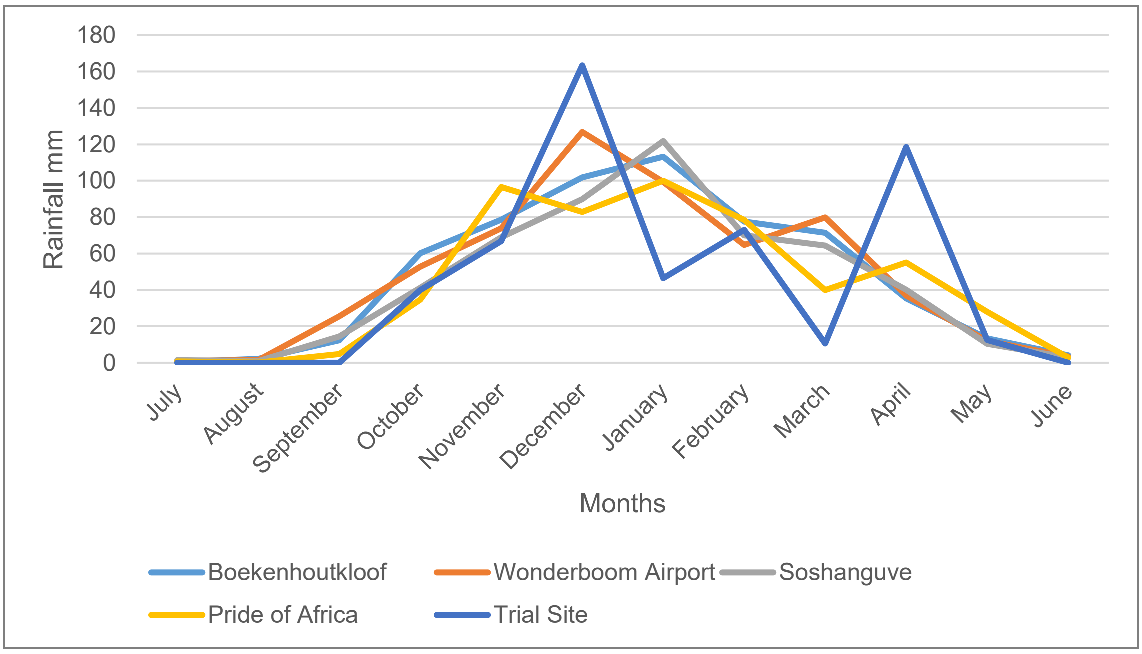

Figure 3.4: Average rainfall for Boekenhoutkloof, Wonderboom Airport and Soshanguve stations, and Pride of Africa and the trial site

The closest South African Weather Services weather stations that record rainfall, to the study area are the Wonderboom Airport station, Soshanguve (Tswaing) station and Boekenhoutkloof station. The Boekenhoutkloof station recorded rainfall from March 1988 to February 2020 and is the closest South African Weather Services station to the study area. The Soshanguve (Tswaing) station recorded rainfall from September 2009 to December 2021 and the Wonderboom Airport station recorded rainfall from June 2008 to December 2021 (Dlamini 2022, pers. comm.; Letsatsi 2022, pers. comm.).

The Pride of Africa rainfall data are from January 2014 to December 2022 (Appelcryn 2022, pers. comm.). During the study period they always recorded more rain than was measured at the trial site, although they are close to the site.

3.3.2 Geology and soil

The soil on the trial site is of the Sterkspruit form, consisting of an orthic A horizon abruptly over a Prismacutanic B horizon, with unspecified calcareous underlying material (MacVicar *et al.*, 1977; Soil Classification Working Group, 1991). Over almost the whole of the 3 hectare 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.

Parent material comprises underlying weathered shale from the Ecca Group of the Karoo Supergroup (Norman and Whitfield, 2006). According to information which was shared with the researcher by the DGR, it is indicated as sodic soils on shales (Boshoff 2021, pers. comm.). The smooth rolling, almost flat and featureless landscape is indicative of geomorphological maturity (Norman and Whitfield, 2006).

3.3.3 Vegetation

The vegetation forms part of the Mixed Bushveld Savanna biome (Low and Rebelo, 1998). The vegetation varies from a dense bushveld to an open tree savanna. *Combretum apiculatum* (Red bushwillow) dominates on the very shallow soils found in some parts. Other trees include *Senegalia caffra* (Common hook-thorn), *Dichrostachys cineria* (Sikle bush), *Sclerocarya birrea* (Marula) *and various other* Grewia (Raisin bushes) species.

The herbaceous layer is dominated by highly palatable, highly nutritious sweetveld grasses, like *Digitaria eriantha* (Finger grass) and various *Aristida* (Three awn grass) and *Eragrostis* (Love grass) species (Low and Rebelo, 1998). Fire and grazing determine the structure of this vegetation type (Low and Rebelo, 1998), especially degradation due to overgrazing of the sweet grass.

Although the trial site is a badly degraded area, the non-degraded areas surrounding it have good vegetation cover (Fig. 3.5).

Figure 3.5: Non-degraded veld adjacent to Block 1 of the study site

3.3.4 Physical-biological condition of the study site

The site is badly degraded, with large bare areas with no vegetation cover (Fig. 3.6). The degraded areas have reportedly been in this condition for the past 50 years, with no recovery evident. Erosion continually increases after each rainfall event and needs to be addressed as soon as possible.

Sheet erosion is the most prominently visible form of erosion at the site, where the topsoil layer was removed by water and to a lesser extent by wind. It is clearly visible from aloes, shrubs and trees growing on little elevated pedestals of remaining top-soil (Figs. 3.6 and 3.7).

Figure 3.6: Large bare and crusted soil area with limited vegetation

Figure 3.7: Aloes and shrubs on pedestals, showing how much top soil has been lost from the bare areas as a result of sheet erosion

Coupled with the sheet erosion is soil surface crust formation, also known as surface sealing (Fig. 3.8). With the very thin, very hard dense crust at the surface, water infiltration is very limited (no infiltration in places), which increases runoff after each rainfall incident. The increased runoff not only removes more surface soil, but also creates rills (small dongas) that aggravate the situation even more.

Figure 3.8: Crust formation as well as erosion that has progressed to rills (small dongas)

3.3.5 Overview of the land use history of the study site

In order to gain an understanding of the reasons for the badly degraded status of the site an overview study of the land use history of the area was undertaken. This was done by conducting an unstructured interview with Mr Robert Rakgantsho (2020, pers. comm.) prior to commencement of the study in 2021. He has been involved with farming activities in the selected study area since the time when it was cultivated and is presently still employed there. Maize and sunflower were planted on the site between 1953 and the 1970s, when cultivation of the area was abandoned. It was then converted to extensive cattle farming until about 1990, after which it became a game farm and then part of the Pride of Africa game park, which forms part of the DGR.

3.3.6 Study of gabion-like structures

It was observed that gabion-like structures were installed over long distances along contours in the degraded areas. These consist of cylindrical sheaths of chicken wire mesh filled with fairly large smooth round stones, which were just simply put on the ground (Fig. 3.9).

Figure 3.9: Gabion-like structures installed along contours at the degraded areas

Mr Rakgantsho (2020, pers. comm.) explained that the structures were installed in the early 1990s on the degraded areas (where cropping was done prior to the 1970s) to combat erosion. The intended strategy was to move the gabions to new positions when adequate soil had collected behind them and dense enough stands of pioneer vegetation became established, with the objective of rehabilitating the whole area in that way. This was never done, because the intended benefits with the gabions were never achieved. It was observed that the gabions in fact had several serious negative impacts. These were recorded very intensively during the present study.

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CHAPTER 4
MATERIALS AND METHODS

4.1 Introduction

The aim of this experiment was to determine whether the hard dense soil crust could be alleviated by means of application of certain ameliorants and whether this could enable rehabilitation of the bare areas and the re-establishment of a dense vegetative cover, mainly grass.

4.2 Sample Collection and Soil Classification

Soil samples were collected for standard soil chemical analyses (Ca, Mg, K, Na, S-value and pH) and particle size analysis. Three profile pits were dug at representative sites and soil descriptions made for taxonomic soil classification according to the 1977 South African soil classification system (MacVicar *et al*., 1977) and international World Reference Base for Soil Resources system (WRB, 1998) (Fig. 4.1). It was observed that roots grow horizontally above the prismatic structured subsoil horizon and did not penetrate into this horizon. This was also observed in erosion gullies in the study area.

Figure 4.1: Profile pit 2 of a Sterkspuit soil form (SA classification; Solonetz, WRB), with evidence of roots growing horizontally above the prismatic subsoil

4.3 Main Experiment

4.3.1 Identification of suitable representative experimental areas

Large degraded bare areas with a hard dense soil crust were selected for the experimental plots. It is very important to note that it was observed that virtually all topsoil had been removed from the bare areas by means of sheet (inter-rill) erosion and that the Prismacutanic 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. It was not possible to find large enough contiguous areas that conform with all the requirements stipulated above. Consequently, the three blocks and the different experimental plots in each were fitted into suitable areas as close as possible to each other (Fig. 4.2). They are thus not in straight lines or blocks, such as would be found in field experiments in cultivated fields.

Figure 4.2: 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

Once a suitable area for a block was identified, 3 x 3 m plots were measured out and marked with a round head wire nail (5.60 mm x 150 mm) through a washer (6 x 32 x 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 the tourists do not want to see unnatural markers or exclosures (Laker and Nortjé, 2019; Wigly-Coetsee *et al*., 2022) 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 x 150 mm) was inserted at one corner of each plot to indicate the block and plot number.

4.3.2 Treatments

Eight products and combinations of products were tested, because different ones of them had been found to be effective by *inter alia* Green and Stott (1999), Stern *et al*. (1991), Stern *et al*. (1992), Weber and van Rooyen (1971), and/or van den Berg and Kellner (2005), (Table 4.1).

Table 4.1: Applied ameliorant products and combinations thereof as discussed in Chapters 1 and 2.

Ameliorant products and combinations thereof	Application rate	
	g/m²	kg/ha
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 + 5 000
4. PAM and Gypsum	0,5 + 250	5.0 + 2 500
5. Gypsum	250	2 500
6. Gypsum and Molasses meal	250 + 500	2 500 + 5 000
7. Molasses meal	500	5 000
8. Brush packing	n/a	n/a
9. Control	No amendment	No amendment

4.3.3 Method of application of treatments

The different products to be applied to different plots were weighed out beforehand into plastic zip lock bags. It was soon observed that condensation took place when the gypsum and molasses meal were left in the closed plastic bags in the sun, which made it harder to distribute them evenly during the application process. As a result, it was subsequently stored in the shade. Gypsum and molasses meal were scattered by hand. Since quantities to work with are large it is easy to ensure that it is scattered evenly.

PAM has two challenges, firstly it consists of very fine particles and secondly the quantity is very small. To spread it evenly it had to be mixed with something with roughly the same particle size. Mealie 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 mealie meal required to ensure effective application. The effective mass of mealie meal required per m² was 52g/m² with 468g/m² needed for a plot of 9m². A large tea strainer was used to apply the PAM-mealie meal combination, since it has the right size openings to let the mealie meal and PAM through unhindered.

An ameliorant was applied to an entire plot. A steel rake was then used to break up the surface crust, to create fine crumbs in a thin surface soil layer and create shallow incorporation of the ameliorants (Fig. 4.3). The maximum depth that was crumbed was 2 cm as the objective was to break and ameliorate only the very thin hard surface crust.

Figure 4.3: Incorporating of ameliorants into the surface soil after product application (photo credit Dr GP Nortjé)

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 in order to prevent them from being blown away by wind or washed away by rain. The surface crust of the control and brush packing plots were not crumbed. The brush packing was done by using dead shrubs and branches that had already been cut during road maintenance. The vegetation used in the brush packing was continuous over the entire plot with approximately 75% cover.

4.3.4 Experimental lay-out 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 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 from 28 to 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 (Laker and Nortjé, 2019). It is also important for vegetative growth.

4.3.5 Measurements taken

4.3.5.1 Mechanical resistance of crust

A Humboldt H-4212MH pocket shear vane tester was used for measuring the soil crust strength (Fig. 4.4). The tester comes with 3 vanes, the standard vane is part of the tester and the small or large vanes are attached to the tester over the standard vane. The tester can be used in a laboratory or on site as long as 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. Then the outer ring is released slowly. The mark on the outer ring will stay in place, showing the shear value (in kg cm^{-2}) at failure (HCMTE, n.d.; Page and Hole, 1977).

Figure 4.4: The Humboldt H-4212MH pocket shear vane tester (small vanes), pressed into the soil, with blades completely inserted

A major difficulty encountered in taking the measurements, using the standard procedure, was that the soil crust was so hard and dense that the vanes could not be pressed through the dry crust. The only way to get the vanes through the crust, was to use a spray bottle and wet the surface. As standardised procedure, the spray bottle's nozzle was set on medium to fine and five squirts given. The tester was then pressed into the soil until the blades were completely inserted, taking measurements after 3 minutes. For each plot three measurements were done each time within a 150 mm radius.

The initial measurements were taken with the standard vane, but the variation in readings led to testing of the large and small vanes as well. The most consistent readings were obtained with the small vane, which was then used for all other measurements during the study.

Even though the pocket shear vane tester is a simple, straightforward and easy to use piece of equipment, it is very important to be extremely consistent when taking measurements. The force exerted, putting it into the soil at a 90º angle, speed at which the dial is turned and moisture content, all play an enormous role and can affect readings greatly (Zimbone *et al*., 1996).

Measurements were done at a few intervals during the rainy season to monitor the effectiveness of treatments over time, after successive major rain events. The measurements were done after the surface soil had dried out and the soil had drained to field capacity after a rainfall event.

4.3.5.2 Final infiltration rate

A double ring infiltrometer was used for doing infiltration measurements (RE, 2022; Gregory *et al*., 2005). It had an inner circle diameter of 150 mm and outer circle diameter of 450 mm. Approximately 20 litres of water were required to fill the infiltrometer.

The standard procedure to install the double ring infiltrometer is to put the cutting edge facing down on the soil. Put the driving plate on top and use an impact-absorbing hammer to insert the infiltrometer about 50 mm into the soil (RE, 2022). Someone can be asked to stand on it to help with driving it into the soil. It must be i done in such a way to disturb the soil as little as possible. The infiltrometer should be inserted to below a disturbed or crusted top layer or a layer with macro-pores. In the present study these requirements were irrelevant since the whole aim was to determine the differences in infiltration rate between the crusted and ameliorated soil. During simultaneous measurements, the different infiltrometers should be 2 to 10 m apart. First fill the outer ring with water and then the inner ring, ensuring the rings do not go dry. Start measuring immediately, by noting the time and water level in the inner ring. When filling with water protect the soil surface with a cloth or by hand and make sure there is sufficient water available, if needed to add. Keep the water level in both the rings at a similar level. The water in the outer ring is to prevent water from the inner ring, where the measurements are taken, from spreading laterally. With a higher water level in the outer ring a decrease in infiltration rate in the inner ring will be experienced. Stop measuring when the infiltration rate has reached a constant value or a change < 10% (RE, 2022; Chowdary *et al*., 2006; Gregory *et al*., 2005).

The same problem as with the shear vane tester was experienced, namely that the soil crust was too hard and dense to drive the infiltrometer into the soil. Since a soil surface is not perfectly level and smooth, the infiltrometer could not simply be placed on top of the soil. 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 (Fig. 4.5). Rubber ends were sealed with duct tape.

When the infiltrometer was put in place for a measurement it was weighed down with rocks to create a proper seal (Fig. 4.5). A steel ruler attached with magnets was installed in the inner ring, with every measurement, to get the ruler at the exact depth for that plot. The rocks as weights worked very well, since they can be packed differently on the infiltrometer for each different plot, in such a way that the rubber sealed well. Before the infiltrometer was installed, the test area was lightly watered with a watering can, to assist the rubber in sealing.

Figure 4.5: The first experiment with the boot rubber on the infiltrometer (photo credit Dr GP Nortjé)

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, such as 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. The one negative effect with the rubber seal at the bottom on top of the soil instead of the metal ring inserted into the soil, was that the soil surface needed to be quite level.

It was found that on hot days during the warmer summer months, it was not feasible to take infiltrometer measurements on the study area. The high temperatures and the constant wind, made it impossible to take accurate measurements. It was found that the high temperature and low relative humidity in conjunction with the wind resulted in an extremely high rate of water loss through evaporation and the wind created small eddies, which made it extremely difficult to take accurate readings. As a result, infiltrometer measurements could only be done during the cooler winter months or early in the mornings when it was still.

4.3.5.3 Determination of seedling emergence and vegetative growth

The intention was to do a plant/seedling count 10 days after emergence, in a quadrant (1m x 1m) (Barbour *et al*., 1987) in the centre of each plot and to determine the above ground biomass 2 weeks later, in the same squares. This was eventually not done, for reasons discussed in Chapter 5.

4.4 Determination of Structure Stability

Structure stability tests were done with wet sieving machine (JE Gerber, +Co. Zurich, Suisse, Dr N. Gerber Original), in the Soil Laboratory of the Univ. of Pretoria.

A bulk sample of thin crusted surface soil was collected for laboratory scale soil structure stability studies by means of wet sieving. The soil was collected between Block 1 and Block 2 and consisted of surface crust soil that was collected 1-2 cm deep. The soil was air dried and sieved through a 2 mm sieve. Different 400g soil batches were placed in 2 litre containers, and the different ameliorants or combinations thereof added (Table 4.2). The optimum quantity of water was added to provide crumbing during mixing. A small multi-tined piece of equipment was used to thoroughly mix and crumb these.

The soil was then incubated in a controlled temperature room at 24ºC for one week. Laker & Bredell (1990) compared incubation times of one week up to six months and found no significant difference. A system of alternative wetting and drying was used, where the soil was wetted each afternoon, using a spray bottle with its nozzle set on medium to fine.

Table 4.2: Ameliorant products and combinations thereof applied for determination of soil structure stability by means of wet sieving

Ameliorant products and combinations thereof	Application rate	
	g/m²	g/400g crust soil
1. PAM [0,5]	0,5	0,01
2. PAM [1,0]	1,0	0,02
3. PAM [1,5]	1,5	0,03
4. PAM [2,0]	2,0	0,04
5. Molasses meal	500	11,11
6. Gypsum	250	5,56
7. PAM [0,5] and Molasses meal	0,5+500	0,01+11,11
8. PAM [0,5] and Gypsum	0,5+250	0,01+5,56
9. Gypsum and Molasses meal	250+500	5,56+11,11
10. Control	No amendment	No amendment

After the week's incubation, the soil was oven-dried for 24 hours at 50ºC. During an initial study, soil samples were dried at 105ºC as described by Angers *et al.* (2008) and Laker and Bredell (1990) for 24 hours. Reports in recent literature indicate that drying at 105ºC may cause unwanted artificial effects and that drying at lower temperatures, even as low as 50ºC, may give more acceptable results (Yoon *et al.*, 2015).

It was then decided to change to drying at 50ºC. It was studied to see if drying for 24 hours at 50ºC would be sufficient to dry the samples or whether drying for 48 hours would be needed. The differences in mass between after 24 hours and 48 hours drying ranged from zero to negligible. It was thus concluded that drying at 50ºC for 24 hours was adequate.

Three samples of 50 g each of the oven dried soil from each treatment were then used for wet sieving.

The wet sieving was done through a 0,25 mm sieve with a 200 mm diameter on a mechanical wet sieving machine, with a vertical dipping action (Fig. 4.6). The sieving was done for 4 minutes at 60 oscillations per minute. The soil that was left on the sieve was transferred to a glass beaker with the use of a laboratory water bottle. It was then oven dried for 24 hours at 50ºC and weighed.

Figure 4.6: Wet sieving machine in operation

In an initial study it was found that 100 mm diameter sieves were too small to facilitate effective sieving with the amount of soil used. Therefore, the subsequent sieving was then done using 200 mm diameter sieves. This worked well. After a month's incubation, the exact same procedure was followed as after a week's incubation.

4.5 Pilot Study with Sowing in of Grass Seed

With no seed germination on the experimental plots after a good rain period, it was suspected that there was no seed bank left in the bare crusted areas. Consequently, the decision was made in January 2022 to add a pilot study in which sowing in of grass seed was added to soil treatment with ameliorants used to alleviate crusting. The main objective with the pilot 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.

The pilot study was established on 7 February 2022 with sown in grass seed, the week before saw nice soft rain over a few days with 80 mm recorded at the farm office some distance from the study site. However, the soil was bone dry when planting was done. It is unsure whether this was just due to very poor water infiltration at the study site or due to much lower rainfall at the site. Rainfall could not be measured at the site because the rain gauge at the trial site was once again destroyed by an elephant.

Due to the dry condition of the soil it had to be wetted by watering can to facilitate incorporation of amendments and seed and for crumbing the crust. Afterwards the soil was again wetted to enable germination. A new rain gauge was installed. During the period between planting and the next visit on 23 February 2022 only 0.7 mm rain was recorded. The crumb structure was still visible with the coloured grass seed embedded in the crumbs, but with no sign of germination or seedling emergence.

Only single products were tested and not combinations, for PAM only the highest level of 2.0 g/m^2 (Table 4.3). A specially formulated Dinokeng grass seed mix (Table 4.4), put together by Frits van Oudtshoorn from ALUT (Africa Land-Use Training and Working on Grass) was sown at a rate of 2.0 g/m^2 (Kellner and de Wet, 2001). The recommended average grass seed application for veld restoration is 20 kg/ha, i.e., 2 g/m^2 (van Oudtshoorn 2022, pers. comm.; van Oudsthoorn, 1994). Thus, 4,5 g grass seed was applied per plot.

A degraded area similar and close to the main experiment's study site was identified and plots marked out. The plots were 1,5 m x 1,5 m. This size allows for 0,5 m wide border areas with a 0,5 m x 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.

Table 4.3: Applied ameliorant products

Ameliorant products	**Application rate**	
	g/m²	g/2,25 m²
1. PAM [2,0]	2,0	4,5
2. Gypsum	250,0	562,5
3. Molasses meal	500,0	1125
4. Control	No amendment	No amendment

Table 4.4: 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

PAM was mixed with mealie meal as described earlier and applied to the respective plots with the tea strainer. After the PAM application, the seed mix was spread evenly over the plot, taking care to distribute the different types of grass seed evenly. 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. Apart from spreading the gypsum and molasses meal without addition of maize meal, the same procedure as with PAM was followed. The control plots also received a seed mix application and were wetted and crumbed like the other plots.

The only procedural difference in the main experiment and the pilot study, was that in the pilot study the control plots were also seeded, wetted and crumbed and all the pilot study plots were given an additional watering at completion of application, on 7 February 2022 (Fig. 4.7). The wetting of the plots after application, not only helps to bind the products initially and to give the soil a chance to create a crust again, but also gives the newly sown seed a slight moisture advantage, this late in the rain season.

Figure 4.7: Pilot study grass seed plots, established 7 February 2022

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 x 0,5 m. A dowel stick and rope grid were made where the grid blocks are 0,5 m x 0,5 m to fit over the plot and indicate the centre 0,5 m x 0,5 m where the seedling count would be done. The seedling count commenced in the northern top left corner and then to the next grid block to the right, completing that row, after that, centre row from the left to the right and then 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 (Figs. 4.8 and 4.9).

Figure 4.8: Counting grid on plot 4, with Giraffe spoor

Figure 4.9: Seedlings, 5 May 2022

4.6 Statistical Analysis

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 (Samuels, 1989). Repeated Measures Analysis of Variance with the GLM model were used for repeated period measures.

The linear model used is describe by the following equation:

One way: $Y_{ij} = \mu + T_i + B_j + e_{ij}$

Where: Y_{ijk} = variable studied during the period

μ = overall mean of the population

T_i = effect of the i^{th} treatment

B_j = effect of the j^{th} block

e_{ij} = error associated with each Y

4.7 References

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CHAPTER 5
RESULTS AND DISCUSSION

5.1 Results and Discussion

5.1.1 Mechanical resistance of crust

5.1.1.1 Comparison of the impacts of different treatments on crust strength

Contrary to what was expected, the control plots had the lowest mechanical resistance values as measured with the shear apparatus (Table 5.1 and Fig. 5.1). Based on previous research it was expected that the control plots would give the highest values (Nortjé and Schoeman, 2016; Weber and van Rooyen, 1971).

During 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, force had to be applied to push the shear apparatus vanes fully to their required depth into the soil.

When comparing the results in Table 5.1 and Fig. 5.1 the control plots have the lowest value and would seem to be the ones with the softest crust. In reality the control plots have the strongest and hardest, but very thin crust. Since the crust is so thin, it is very difficult to get a reliable value with the Shear vane.

The moment a piece of crust fails at one vane, the resistances on the other seven vanes are not enough to continue the measurement and the vanes pull/tear the rest of the surface crust out and throw the crust pieces out.

This action then gave a much lower reading. During a higher value reading, the measurement left a smooth round hole in the surface and not a jagged edged hole as in Fig. 5.2. The surface crust fails simultaneously at all eight of the vanes, resulting in a higher reading and a smooth round hole. The failed crust that is stuck on the Torvane Shear tester, after the measurement, also had a smooth surface and not as rough as in Fig. 5.2.

Table 5.1: The influence of different treatments on Torvane shear test values

	Treatments	Torvane shear test values (kg/cm²)
1	PAM 0,5g/m²	1.74_{2}
2	PAM 2,0g/m²	1.75_{3}
3	PAM 0,5g/m² and Molasses meal 500g/m²	1.72
4	PAM 0,5g/m² and Gypsum 250g/m²	1.67_{14}
5	Gypsum 250g/m²	1.65^{a}_{5}
6	Gypsum 250g/m² and Molasses meal 500g/m²	2.07^{c}_{B45}
7	Molasses meal 500g/m²	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

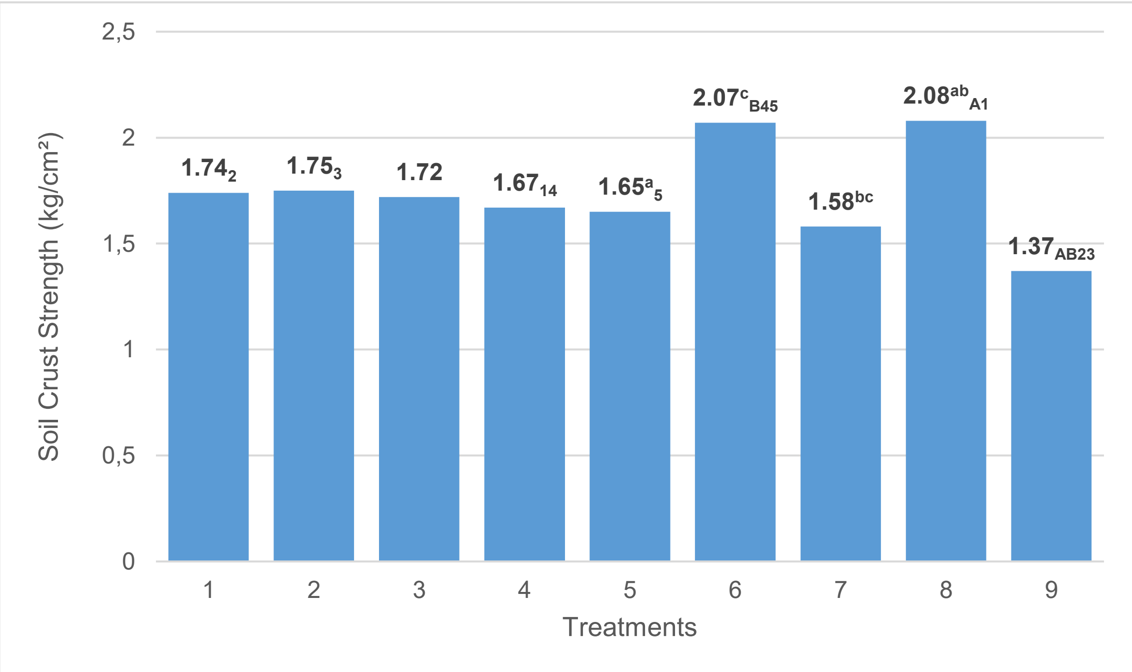

Figure 5.1: The influence of different treatments on Torvane shear test values

Figure 5.2: Jagged edge hole with scattered pieces of surface crust

Although the surface crust in the study area is very thin (±1 mm) (Fig. 5.3), it has the same effect of no or limited water infiltration and no gas exchange as the crusts with thickness of 1 cm and more reported by inter alia Al-Nasser and Al-Kafagi (2020). Van der Watt and Valentin (1991) also found that the thin <1 mm - 30 mm crusts had a high strength and very low porosity. Thin crusts such as in the study area are widely distributed throughout South Africa (Laker and Nortjé, 2019).

Figure 5.3: Very thin surface crust with visible sub-surface air bubbles

The brush packing results show the highest reading, where the crust was expected to have the same strength as that of the control. The treatment that the brush packing plots received were dead branches stacked on the surface of the plots, the crust was not crumbed like in the other treatments or disturbed in any way, which is then the same as the Control with loose branches on top. What the branches did was to trap sand and other material that was transported by wind or water. In effect, the top layer that was measured was uncrusted sandy soil deposited on these plots. This material was more appropriate for the Shear vane to give a more accurate reading. For the sake of easy reference, the differences between the effects of different treatments are summarised in Table 5.2.

Table 5.2: Statistical significance of differences between treatment means

1	There is a trend for PAM 0,5g/m² and PAM 2,0g/m² to be higher than the Control
2	PAM 0,5g/m² and Molasses meal 500g/m² combination do not differ significantly from any other treatment
3	There is a trend for PAM 0,5g/m² and Gypsum 250g/m² combination to be lower than Gypsum 250g/m² and Molasses meal 500g/m² combination and brush packing
4	Gypsum 250g/m² is significantly lower than brush packing and there is a trend to be lower than Gypsum 250g/m² and Molasses meal 500g/m² combination
5	Gypsum 250g/m² and Molasses meal 500g/m² combination is significantly higher than Molasses meal 500g/ m² and highly significantly higher than the Control. There is also a trend for Gypsum 250g/m² and Molasses meal 500g/m² combination to be higher than
6	Molasses meal 500g/m² is significantly lower than Gypsum 250g/m² and Molasses meal 500g/m² combination and brush packing
7	Brush packing is significantly higher than Gypsum 250g/m² and Molasses meal 500g/m² and highly significantly higher than the Control, with a trend to be higher than PAM 0,5g/m² and Gypsum 250g/m² combination
8	The Control is highly significantly lower than Gypsum 250g/m² and Molasses meal 500g/m² combination and brush packing, with a trend to be lower than PAM 0,5g/m² and PAM 2,0g/m²

5.1.1.2 Mechanism of soil structure formation and stabilisation by PAM

PAM was applied in dry powder form and reacted immediately with the soil particles when the soil was wetted thereafter to enable crumbing of the soil by rake. The soil particles were bound together into crumb structure units through a spider web glue like substance, which formed when the PAM became wet (Fig. 5.4).

Figure 5.4: Structure formation and stabilisation effect of PAM

A week and 17 mm of rain after establishing the plots, the PAM plots kept their micro crumb structure unlike the other treatments, where the crumb structure was lost. Even after the passing of a herd of buffalo and an elephant, the surface soil structure persisted, becoming somewhat compressed but not destroyed (Fig. 5.5). On the dry surface smaller crumbs could be seen, from animal tracks that break the structure into smaller units, but the soil retained the microstructure and did not disaggregate into a crust.

Figure 5.5: Elephant track on plot 8 block 2, treatment 2 (PAM 2,0g/m²)

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 (Green and Stott, 1999). The PAM plots appeared darker in colour after a rainfall incident, for longer than the other plots, as a result of more moisture uptake and less water that flows away (it is usual for soils to have a darker colour in the moist state than when dry). It was observed that less water flowed from the PAM plots, in comparison to the other treatments, after the first rain. When taking the measurements with the Torvane Shear Tester, less water was necessary on the PAM plots to enable insertion of the vanes into the soil and less force was required to push the vanes to full depth into the soil than with the other treatments.

Over time, the soil in the test plots started to look like the soil in the areas surrounding the research blocks, except for the PAM plots that looked slightly coarser on the surface, with close inspection.

The PAM 0,5g/m² and PAM 2,0g/m² soil strength values in Table 5.1 are virtually identical, which indicates that the lower concentration is as effective as the higher concentration and will be more economical to use, similar to what Nortjé and Schoeman (2016) and Stern (1991) found.

5.1.1.3 Effect of Gypsum on the soil crust

During initial observations, the impression was gained that gypsum did not have an effect, as the crumb structure disappeared and a crust was formed again as can be seen in Fig. 5.6, taken after the first light (17 mm) rain. On closer inspection it was found that there was some microstructure left where gypsum was applied, even in combination with molasses meal or PAM.

Figure 5.6: Physical disturbance of the soil crust by a hoof print in a gypsum treated plot

A bit later in the season, the soil in the gypsum plots also appeared darker than the soil in other treatments after a rain incident, but smoother than the PAM plots and not as dark as the latter.

The soil strength values of the gypsum plots were not much higher than those of the control plots, because a new strong crust was formed soon after the treatments were applied. The strength of the crust gave the same problems with the apparatus as described for the control plots. It is similar to what Hanay *et al.* (2004) and Nortjé and Schoeman (2016) found, namely that gypsum is successful in restoring the chemical properties of a soil, but cannot restore its physical and biological properties on its own. Thus, gypsum cannot prevent a crust from forming.

5.1.1.4 Effect of molasses meal on the soil crust

Molasses meal is an energy rich substance that stimulates microbial growth. During the microbial growth, microbial mycelia are produced that create highly stable aggregates (Laker and Nortjé, 2019).

During initial observations it appeared as if there were stable micro structural units formed in the soil of the molasses meal plots (Fig. 5.7). Unfortunately, these did not last long, as it was only the organic matter in the molasses meal that kept the crumb structure in place temporarily.

A thin, hard, dense crust thus reformed soon in the soil of the molasses meal treated plots. As in the case of the control and gypsum plots, much force was needed to push the vanes of the shear tester into the soil. And similar to the control and gypsum plots the soil of the molasses meal plots had relatively low shear meter values, for the same reason.

Two factors inhibited the efficiency of molasses meal as ameliorant. Firstly, the meal dries out quickly after application in the heat of the area. The dry meal, being a light organic material, was easily washed away by the excessive runoff rain water from the smooth, bare surface (Fig. 5.8) and also blown away by wind.

Figure 5.7: Micro structure formed at the soil surface in molasses meal treated plots

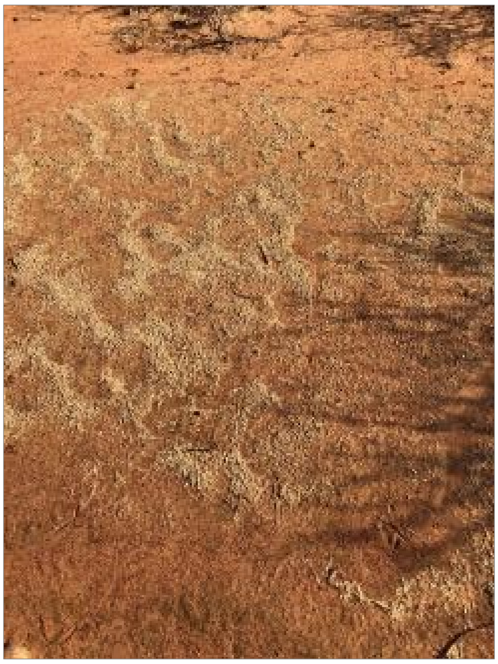

Figure 5.8: Water transported Molasses meal

Secondly, the soil was apparently almost sterile, with virtually no microbial activity to use the molasses meal as energy material to produce mycelia which could create and stabilise soil structure. The dense, hard, thin crust is in existence for roughly the past fifty years. So for that period, (i) almost no water infiltration could take place, (ii) gas exchange was very poor, as shown by the air bubbles below the crust, and (iii) the soil contained basically no organic matter, creating a very unfriendly, uninhabitable environment for microbial soil organisms. Thus, there were apparently no active soil microbes to utilise the molasses meal energy source. Consequently no microbial mycelia were produced to assist with improving aggregate stability. In addition, some of the molasses meal was also washed away by heavy rains during the early part of the trials.

This is in stark contrast to what Weber and van Rooyen (1971) found. They had very good results with Molasses meal. Three to four weeks after application, the hard and dense polygonal plates in their soil were partially broken and moderately structured, with the process continuing and five months later the crumbs were porous, friable, soft and water stable, with the end result of open, loose and well aggregated soil to an average depth of 30 cm. The tobacco plants on the Molasses meal plots continued growing throughout the drought period while the plants on the other plots died or experienced severe growth retardation. The active soil microbes in the soil, utilised the energy source and produced microbial mycelia to create a well aggregated soil. It is important to note that Weber and van Rooyen (1971) worked on a completely different soil type in a completely different situation. Their findings were done on soil that was under intensive cultivation for years.

5.1.1.5 Effect of brush packing on the soil crust

The brush packing plots were established on the same bare, crusted soil, as the rest of the test plots. A randomised block design was used to distribute the three brush packing plots throughout the three blocks.

A reasonable amount of sand was collected on all three the plots after the first rain event. This sand was topsoil that was removed elsewhere through erosion and washed downstream (surface slope of 0,9º) and trapped by the brush packing.

There was seedling emergence within the first rain season on all three brush packing plots. The seedlings were a combination of grass, shrubs and paper thorns. The brush packing plot in Block 3 had the first emergence of grass seedlings, together with a shrub and paper thorns. However, very few seedlings survived on this plot. The brush packing plot in Block 2 had the same combination, with mostly paper thorns that survived. The brush packing plot in Block 1 also had the same seedling combination, but with more grass seedlings and a better grass seedling survival rate. Some of these grass seedlings in here grew well and completed their life cycle and produced seed. The comparative trends for the three brush packing plots during the rainy season are depicted in Figs. 5.9a to 5.9g, Figs. 5.10a to 5.10g and Figs. 5.11a to 5.11g. Comparison of the situation at the end of the season (Figs. 5.9g, 5.10g and 5.11g) is especially important.

a. 28 Sept 2021 Before

b. 28 Sept 2021

c. 27 Oct 2021

d. 30 Dec 2021

e. 31 Jan 2022

f. 23 Feb 2022

g. 14 Apr 2022

h. 3 Nov 2022

Figure 5.9: Block 1 Plot 5, 28 September 2021 to 3 November 2022

a. 29 Sept 2021 Before

b. 29 Sept 2021

c. 27 Oct 2021

d. 30 Dec 2021

e. 31 Jan 2022

f. 23 Feb 2022

g. 14 Apr 2022

h. 3 Nov 2022

Figure 5.10: Block 2 Plot 4, 29 September 2021 to 3 November 2022

a. 30 Sept 2021 Before

b. 30 Sept 2021

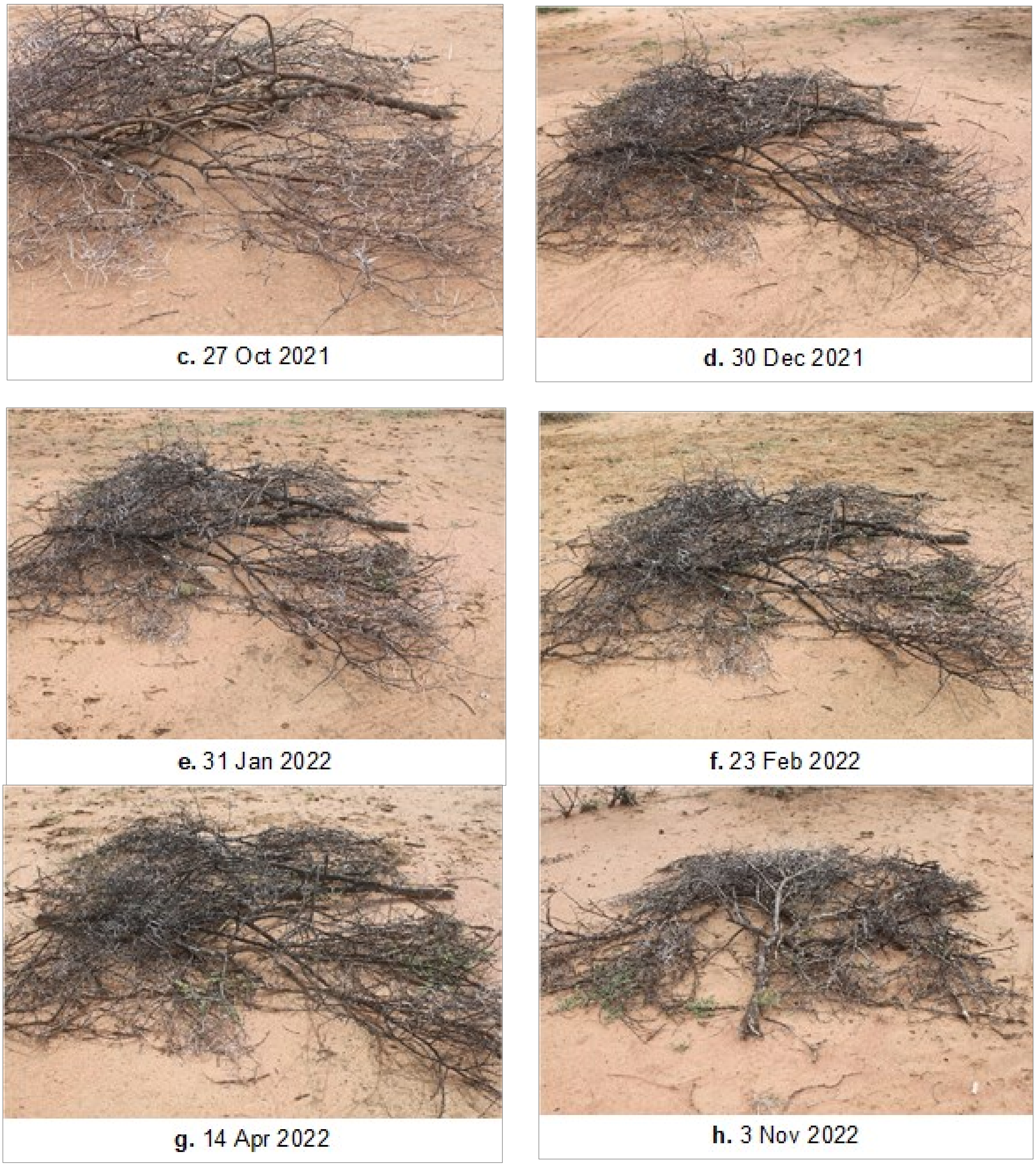

Figure 5.11: Block 3 Plot 9, 30 September 2021 to 3 November 2022

The three brush packing plots started the second rain season on different footings. The brush packing plot of Block 1 had some strong vegetation left from before winter (Fig. 5.9h). The grass was dry after the winter season, which is normal for the area. It can also be seen that the grass has seeded. It is noticeable that a fairly thick accumulated topsoil layer had been preserved and that the brush packing was still intact. The branches used as brush packing did not deteriorate that fast and the vegetation helped to keep the washed in topsoil in place. A little rill running diagonally upstream from the plot had become bigger after the first rains and most of the water that would have flowed over the plot during a big rain storm and removed its soil and shifted its brush packing flowed away through the rill. In a way, it preserved the plot's topsoil from the previous season, creating a more favourable micro habitat for new seedling emergence. With trees and shrubs in close vicinity the plot also has a greater percentage shade during the day, compared to the other brush packing plots. The branches on the other two plots deteriorated much faster over time and with that the cover that the branches provided (Figs. 5.10h and 5.11h). Not only had their soil and seed trapping capability diminished, but also the protection against raindrops and the protection against water that washed the topsoil away, leading to exposure of the original crusted soil again at the soil surface.

The first big rain storm of the second rain season removed most of the sand that washed onto the brush packing plots of Blocks 2 and 3 and with it most of the limited vegetation from the previous season (Figs. 5.10h and 5.11h). Some of the branches were so deteriorated that they lost volume and washed from their original positions, exposing the soil surface even more.

Thus, the brush packing had limited and short-lived success in Blocks 2 and 3. It did not prevent or reduce erosion and failed to enable establishment of permanent vegetation.

Even though all three blocks had the same crusted soil and same environmental factors impacting in on it, there were important differences that played huge roles. The brush packing plot in Block 1 has relatively tall trees in its vicinity that provided a much-needed shade during the hot afternoons. The brush packing plot in Block 3 has some trees some distance away, providing limited protection from the early morning sun only. Thus, the trees did not have the same positive effect as in the case of Block 1. It might be the reason for the brush packing plot of Block 3 being the first plot with seedling emergence, but the advantage was lost early in the season. A few minutes more shade during the day makes a huge difference in seedling emergence, because the surface temperature can stay a few degrees cooler for longer, resulting in a higher seedling survival rate. Moisture was also available for a bit longer. The vegetation used for the brush packing was available following road maintenance activities. In contrast to the situation at the brush packing plot of Block 1, those in Blocks 2 and 3 have large flat open areas above them, where excessive runoff accumulates before flowing.

Figure 5.9 showed that there was enough water infiltration in the trapped sand, to allow some vegetation to complete their life cycle. Even though the brush packing has the highest value on Table 5.1, which would indicate that the crust is very dense and hard, water infiltration very low (Figs. 5.10 and 5.11).

5.1.2 Final infiltration rate

The Double Ring Infiltrometer tests were done during the period 26 May 2022 to 20 June 2022.

5.1.2.1 Statistical significance between treatment means for final infiltration rate

There is a trend for the Control values to be lower than the PAM 0,5g/m² and Molasses meal 500g/m² combination (Table 5.3 and Fig. 5.12). Gypsum 250g/m² is significantly lower than the PAM 0,5g/m² and Molasses meal 500g/m² combination and PAM 2,0g/m². Gypsum 250g/m² and Molasses meal 500g/m² combination, PAM 0,5g/m² and the PAM 0,5g/m² and Gypsum 250g/m² combination do not differ significantly from each other or any other treatment. There is a trend for Molasses meal 500g/m² to be lower than PAM 0,5g/m² and Molasses meal 500g/m² combination.

Table 5.3: The influence of different treatments on the double ring infiltrometer test values

	Treatments	Final infiltration rate (mm/h)
1	PAM 0,5g/m²	7.37
2	PAM 2,0g/m²	10.00^{b}
3	PAM 0,5g/m² and Molasses meal 500g/m²	11.33_{12}^{a}
4	PAM 0,5g/m² and Gypsum 250g/m²	7.37
5	Gypsum 250g/m²	1.07^{ab}
6	Gypsum 250g/m² and Molasses meal 500g/m²	6.70
7	Molasses meal 500g/m²	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

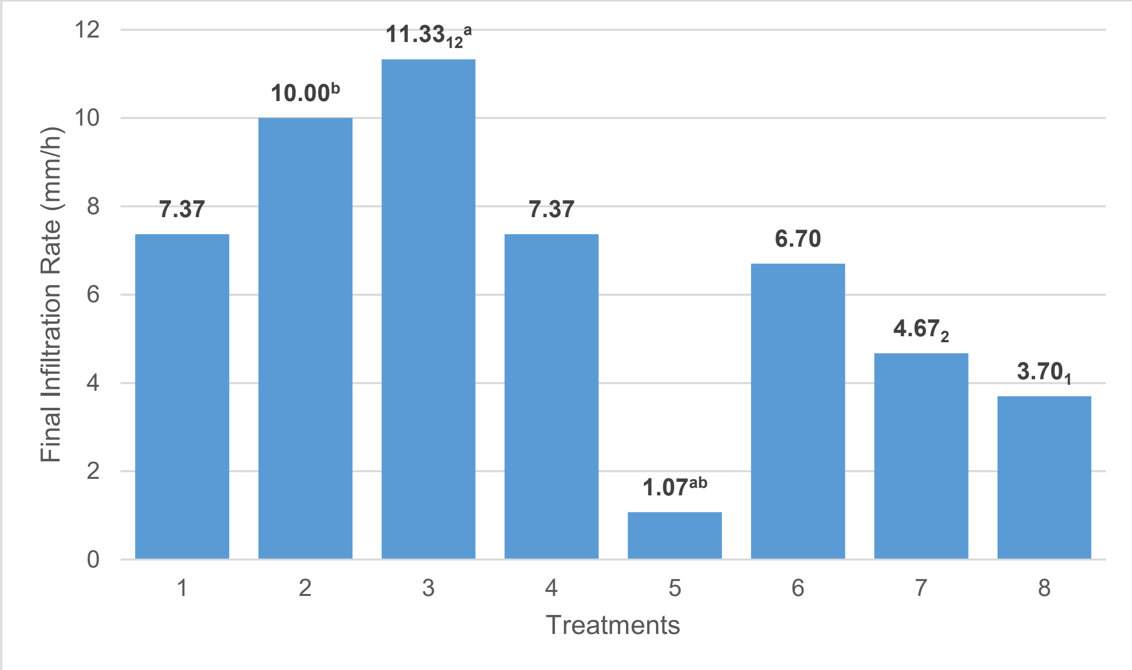

Figure 5.12: The influence of different treatments on the double ring infiltrometer test values

5.1.2.2 PAM

The PAM plots had the best final infiltration rate of all the treatments (Table 5.3 and Fig. 5.12). The value for PAM 0.5 g/m^2 was 2x and for PAM 2.0 g/m^2 2.7x as high as that for the control. Due to the high coefficient of variation the differences between the measurements are not statistically significant. It could, however, be of practical importance to take note of them. The PAM 0.5 g/m^2 and Molasses meal combination performed overall the best on this soil, with the value for PAM 2.0 g/m^2 practically identical to it. PAM 2,0g/m^2 performed somewhat, but not significantly, better than PAM 0,5g/m^2. Stern *et al*. (1991) and Nortjé and Schoeman (2016) found that PAM 5 kg/ha was efficient and that the standard application of PAM 20 kg/ha was not essential. The finding with the low PAM treatment is of economic importance, as also indicated earlier.

5.1.2.3 Gypsum

The very low infiltration value for the gypsum treatment is similar to what Hanay *et al.* (2004) and Nortjé and Schoeman (2016) found; namely, that Gypsum is successful in restoring chemical properties of a soil, but that it cannot restore soil physical and biological problems on its own. It even performed worse than the Control. Laker and Vanassche (2001) similarly found that gypsum was unable to alleviate crusting and infiltration problems in a strongly crusted soil and gave poorer, though not statistically significant, results than the untreated control.

During initial observations it was perceived that gypsum inhibited the positive effects of the other ameliorants with which it was used in combination. However, from Table 5.3 and Fig. 5.12 it is evident that the Gypsum 250g/m² and Molasses meal 500g/m² combination performed better than Gypsum and very slightly better than Molasses meal on their own, but these differences were not statistically significant. This tends to be in agreement with the findings of Weber and van Rooyen (1971), who found that the combination gave highly significant better results than either on its own. In the PAM 0,5g/m² and Gypsum 250g/m² combination the Gypsum did not add value and the combination performed the same as the PAM 0,5g/m² on its own. Laker and Vanassche (2001) found strong positive results with the application of a coal-derived humic product to a strongly crusted soil. However, in combination with gypsum the gypsum totally negated the effect of the humic product, giving a value almost identical to that of the untreated control. It is clear that combinations of different products should always be studied carefully and that no general statements can be made.

5.1.2.4 Molasses meal

With the crust in place for the past fifty years, limited infiltration, no gas exchange as can be seen in Fig. 5.2 and no vegetation, no soil microbes can survive or be active, resulting in no microbes that could utilised the molasses energy source. Molasses meal on its own performed well, but not significantly, better than the control, which is the opposite from what Weber and van Rooyen (1971) found (discussed in 5.3.1). The difference the Molasses meal makes in the infiltration rate when in combination with PAM is remarkable, as discussed below.

5.1.2.5 General discussion

The infiltration tests were the most difficult tests to do during this study. It was found that there are various external factors that influence the outcome of each test. During initial attempts it was found that when the temperature is too high the water evaporates too fast to enable realistic results. This was unfortunately the case with the major parts of the hot summer days during the first period after the treatments were applied. It was found that there was extreme heat close to the soil surface due to reflectance from the smooth, light coloured soil surface. Measurements were consequently taken only during the following winter season. It was found that it was difficult to take accurate readings during windy conditions, because the surface of the water was unstable.

Another factor was that it was discovered that there were cracks between the prismatic structural units below the soil surface, but that these were obscured by the crusted surface and it was difficult to see on some plots were there were a large number of cracks close to the soil surface. In some instances, it was not visible at all but when the test commenced the water infiltrated at an extremely high rate and then stabilised very quickly at a low rate. That was due to the water filling the cracks very quickly and the clays swelling immediately, closing the cracks (Fig. 5.13) and reducing water infiltration to a very low final infiltration rate. It is a characteristic of Prismacutanic horizons to have strong swell-shrink properties (Laker, 2021).

Figure 5.13: Cracks between dry strong Prismacutanic structural units exposed after starting to wet the soil

5.1.3 Determination of seedling emergence and vegetative growth

As discussed in Chapter 4, the intention was to do a seedling count 10 days after emergence and to determine the above ground biomass 2 weeks later, in the same square in a 1 m x 1 m square in the centre of each plot.

There was no seedling emergence on any of the plots. The only seedling emergence was much later on the Brush packing plots as discussed in 5.3.1.

The initial expectations were that there would be enough seed produced by the large areas with grass growing right next to the plots to give a viable existing seed bank in the bare soil areas, which could react to the treatments. The very dense strong crust is, however, of such a nature that seed cannot enter the soil through the soil surface. Thus, they get either blown away by wind or swept away by water. The seed that might be in the soil beneath the crust, will have no chance of germination as a result of the seal effect of the crust causing no water infiltration and poor aeration. Furthermore, the strength of the crust will be too high for a small seedling to break through the crust in the event that they manage to germinate (Laker and Nortjé, 2019). In addition, the extreme heat at the soil surface could destroy the germination potential of any seed.

As a result of no seedling emergence, a pilot study was done, where grass seed was added to the treatments to see if the reason for no seedling emergence was in fact a non-existent seedbank. The results of the Pilot study will be discussed in Section 5.5.

5.2 Determination of Structure Stability

Wet Sieving tests for determination of structure stability were performed from 1 June 2022 to 4 July 2022.

5.2.1 Statistical significance of differences between treatment means for the wet sieving test results

All PAM treatments alone, as well as molasses meal alone and the combination and gypsum and molasses meal, as well as the combination of PAM and molasses meal, improved structure stability significantly or highly significantly compared to the control (Table 5.4 and Fig. 5.14). With gypsum alone there was a positive trend, with the only one falling out being PAM 0.5 g/kg plus Gypsum 250g/m², although they still performed better than the control. This supports the poor results with gypsum in the field study.

Table 5.4: The influence of different treatments on the wet sieving test values

	Treatments	Wet Sieving test values (g)
1	PAM 0,5g/m²	11.61^{bc}_{CJ}
2	PAM 1,0g/m²	12.10^{d}_{EL2}
3	PAM 1,5g/m²	11.98^{e}_{FM3}
4	PAM 2,0g/m²	12.48_{GNR}
5	PAM 0,5g/m² and Molasses meal 500g/m²	13.66^{ac}_{OPQ123}
6	PAM 0,5g/m² and Gypsum 250g/m²	11.22_{DKO}
7	Gypsum 250g/m²	11.29_{BIQ4}
8	Gypsum 250g/m² and Molasses meal 500g/m²	$15.48^{a}_{ABCDEFG}$
9	Molasses meal 500g/m²	$15.12_{HIJKLMN1}$
10	Control	9.84^{bde}_{AHPR4}

^{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 Means is ± 0.589

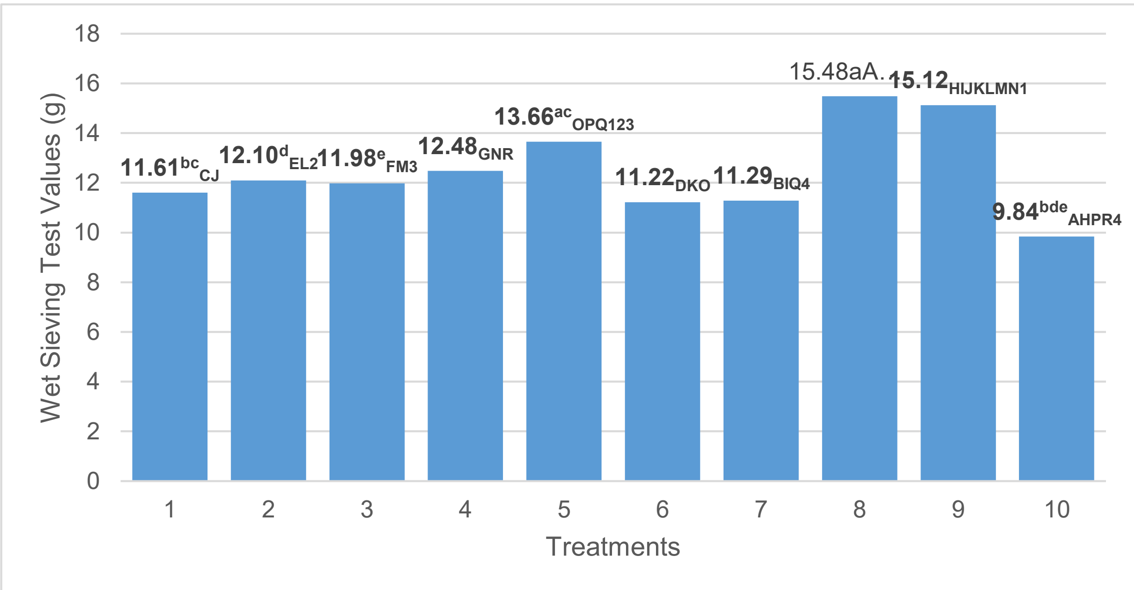

Figure 5.14: The influence of different treatments on the wet sieving test values

5.2.2 PAM

The different PAM concentrations and the PAM 0,5g/m² and Molasses meal 500g/m² combination performed relatively well in comparison to the Control with structure stability tests. It correlates well with the field trials where the different PAM concentrations and the PAM 0,5g/m² and Molasses meal 500g/m² combination also gave similar positive results during the soil crust strength tests and the final infiltration tests. Again, the good results with even the lowest PAM application, is important to note.

5.2.3 Gypsum

Only the Control has worse structure stability results than Gypsum 250g/m² and the PAM 0,5g/m² and Gypsum 250g/m² combination in comparison to the rest of the treatments. It differs from the field trials where the crust strength for Gypsum 250g/m² and the PAM 0,5g/m² and Gypsum 250g/m² combination was not significantly lower than the different PAM concentrations.

However, it agrees with the final infiltration rate results, where Gypsum 250g/m² gave a very low final infiltration rate with the PAM 0,5g/m² and Gypsum 250g/m² combination exactly the same as PAM 0,5g/m². It also concurs with the results of Laker and Vanassche (2001) who found no positive results with gypsum and gypsum and a coal-derived humic product, a large anionic organic molecule, like PAM.

5.2.4 Molasses meal

Molasses meal 500g/m² and Gypsum 250g/m² and Molasses meal 500g/m² combination performed very well, which is similar to what Weber and van Rooyen (1971) found. The opposite was found during the field trials, where the Molasses meal 500g/m² and Gypsum 250g/m² and Molasses meal 500g/m² combination did not perform well with the crust strength or final infiltration tests.

The Molasses meal 500g/m² that was in the test samples during the wet sieving tests could not escape the sieve, as was possible during a rain event in the field trials (Fig. 5.15). For that reason, the organic matter part of the molasses meal was weighed and seen as part of the aggregates remaining on the sieve, possibly giving somewhat false values.

Figure 5.15: Molasses meal on sieve, post wet sieving

5.3 Pilot Study with Sowing in of Grass Seed

As discussed earlier, there was no seedling emergence in any of the plots in the field trial throughout the whole summer rain season, except in the brush packing plots. In the latter the seedling establishment was clearly associated with seed brought in with washed in topsoil. It was thus deduced that the lack of seedling emergence on the bare plots was due to absence of a seed bank in the bare soil.

Towards the end of the rain season a small pilot study with sown in seed was conducted just to determine whether there would be effective seedling emergence when seed was sown in and to confirm that the problem was actually absence of a seed bank in the soil. In the area the end of the rain season is normally in the second half of April and the start of the next rain season in the second half of October.

There were three prominent time periods in this study, namely:

1. A three-month period from planting to the end of the rain season in middle May 2022;
2. The dry rainless winter period from middle May 2022 to middle October 2022;
3. The first month of the next summer rainfall period from middle October to middle November 2022.

5.3.1 The first three-month period from planting to the end of the rainy season

The first qualitative observations of seedling emergence were made on 22 March 2022, with only 20 mm of rain recorded in the previous 12 days. It was evident that the seed reacted to these first small rains. All the plots, except for the molasses plots, had seedling emergence. The three PAM plots had more than double the number of seedlings in comparison to the rest of the plots. It was concluded that the PAM plots responded stronger than the others to the small rain because of their higher water retention, referred to earlier. In all plots with seedlings, the seedlings consisted of broad and narrow leaf grass seedlings with the majority being narrow leaf seedlings. The seedlings had just germinated and emerged in response to the light rain and were still extremely small. It was therefore not considered feasible to do quantitative seedling counts at that stage.

This was unfortunately followed by a short period between 22 March 2022 and the next visit on 4 April 2022 which was very dry with extremely high temperatures. It rained on 4 April 2022 during the visit. The qualitative observations made on 4 April 2022 indicated that very few of the seedlings present on 22 March 2022 survived this hot, dry spell. The few remaining seedlings were bigger and stronger than on 22 March 2022.

The next qualitative observations were made on 14 April 2022, with 80 mm of rain measured at the farm office between 4-14 April 2022, i.e., the short hot, dry period was followed by a wet period. All the plots, except the molasses plots, reacted positively to the bigger rains in terms of seedling emergence. The PAM plots had fewer seedlings than the Gypsum plots. It was concluded that the PAM plots were compromised because of the larger number of seeds which germinated after the first rain, with most of these seedlings not surviving the dry period. The Gypsum plots not only had the most seedlings, but their seedlings were also bigger and stronger in comparison to the rest. The control plots had seedling emergence but not as many as the PAM and Gypsum plots.

The Molasses meal plots also responded to the large rains, still with no seedling emergence, but instead with formation of a blue/green/grey organic crust (Fig. 5.16).

Figure 5.16: Organic crust in molasses meal plots (14 April)

Qualitative observations on 22 April 2022, with 38 mm of rain measured between 14 and 22 April, showed that the PAM and Gypsum plots still displayed their crumb structure and the borders between the plots were still easy to distinguish (Fig. 5.17). Similar to the field trials, the PAM plots had a coarser crumb structure and appeared darker for longer, subsequent to a rain event. The 3 slightly darker PAM plots and the white coloured Gypsum plots were easy to distinguish, with well-defined plot borders (22 April 2022) (Fig. 5.17). The number of seedlings on the PAM plots appeared to be more than on the other plots. The Gypsum plots still had the strongest and longest grass seedlings of all the plots as was the case on 14 April (Fig. 5.18). Control plot 5 had the best grass cover of the Control plots, probably as a result of a significant amount of sandy topsoil that was washed in to this plot during previous hard rain events.

Figure 5.17: The 3 slightly darker PAM plots and the white coloured Gypsum plots (22 April 2022)

Figure 5.18: Gypsum plot with big and strong seedlings (14 April 2022)

5.3.2 First quantitative seedling count, 5 May 2022

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 count emphasised how successful the Gypsum plots were eventually but could unfortunately not indicate how successfully the PAM plots performed initially. The Gypsum plots were significantly better than the Control plots and highly significantly better than the PAM and Molasses meal plots (Fig. 5.19). The Control plots were also highly significantly better than the PAM and Molasses meal plots.

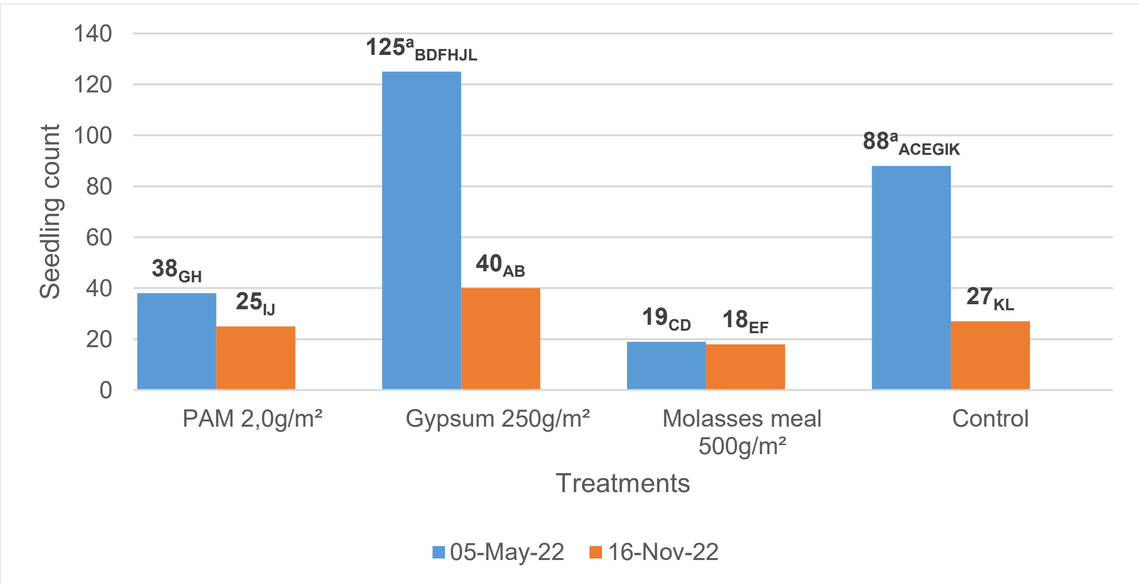

Figure 5.19: The influence of different treatments on seedling emergence

5.3.3 The second seedling count, 16 November 2022

The second seedling count was done on 16 November 2022, with the commencement of the new rain season. The first rainfall event was from 24 to 27 October 2022, when 30 mm was measured, with an additional 22 mm after 31 October 2022. These were measured at the farm offices. From beginning November to 16 November 2022, 81 mm of rain was measured at the study area itself with a newly installed rain gauge. The count was done this late in November to give an opportunity for response to the first of the 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 many fewer seedlings in total than with the previous count at the end of the previous rain season on 5 May 2022 (Fig. 5.19). 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 sown, 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, especially in the Gypsum and Control plots was large 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 (Fig. 5.19).

5.3.4 PAM

The PAM plots appeared darker in colour for longer after a rainfall event (Fig. 5.17) and were the first to show seedling emergence. The PAM plots had a variety of broad and narrow leaf seedlings, with prominently more narrow leaf seedlings than the other plots. The reason for the better initial seedling emergence might be that the PAM plots had better water infiltration and could react better to the small rain than the other plots. The better infiltration and water holding capacity increased water available for the seed, where the seed in the other plots did not receive enough moisture at this stage to emerge.

After the initial rainfall event with the successful germination rate, there was a very dry and warm spell, during this period all the plots had lost seedlings, with the PAM plots the most, since they had the highest previous continuous germination rate and also the highest seedling count. As time progressed, with more rain the other plots caught up. The reason the PAM plots may appear average this season, was that they utilised more of their seeds during the early phases, leaving them with less available seed in the soil (Kellner and de Wet, 2001).

The PAM plots kept their coarse crumb structure the longest, which also helped with better water infiltration and larger surface areas for the grass seed to be in contact with moisture and thus larger soil areas for germination. The PAM plots unfortunately already lost a lot of their seedlings before the first official count.

5.3.5 Gypsum

The Gypsum plots were the most successful later in the first rainy season and kept their success rate into the new rainy season. A possible reason for the later seedling emergence was that the Na was displaced by the Ca in the Gypsum, in the soil surface, after the initial soft rain and that the Ca resulted in flocculation of the clay in the surface layer, thus creating a more beneficial environment for the seedlings and in the process set them up for later success. Although all three Gypsum plots were successful, plot 10 did extremely well. It was realised that plot 10 had shade for longer during the morning and was the only plot that had this advantage. As a result of the longer shade period, dew was available for longer to the seedlings and their exposed period to the extreme heat and high surface temperatures was less than what the other plots had to endure. For that reason, plot 10 was handled as an outlier during the statistical analysis.

The Gypsum plots kept their crumb structure longer than the Control and molasses meal plots, but not as long or coarse as the PAM plots. But kept it much longer when in comparison to the Gypsum field trial plots.

5.3.6 Molasses meal

The Molasses meal plots remained bare without any seedlings the longest. As a result of the poor physical condition of the soil, there were no existing active soil microbes that could utilise the molasses meal as energy source. Five weeks into the pilot, study a grey/blue/green organic crust was observed on the Molasses meal plots. The warm and humid conditions temporarily create a suitable environment for algae at the soil surface to utilise the molasses meal as energy source. That might have been the reason for development of the organic crust on top of the existing mineral crust. After a few warm and sunny days, the organic crust was burned away by the sun.

Seedling emergence was very late in the season, with limited seedlings and they were not thriving. The same with the new rainy season, limited seedling emergence and the seedlings struggled.

Li *et al*. (2020) found that a low Condensed Molasses Soluble concentration can have a significant increase in plant biomass, root vigour and root development, while a high Condensed Molasses Soluble concentration can have an inhibiting effect on plant growth. Weber and van Rooyen (1971) had very good results with soil structure stabilisation, but not with soil reclamation using the same Molasses meal concentration as was used during the study. It should be kept in mind that they worked with irrigated soil under dense plant cover and with high soil microbial activity.

5.3.7 Control

On the control plots, the Dinokeng seed mix was also sown, wetted and the crust crumbed. The successful seedling emergence on the Control plots upon sowing in of seed indicated that there was definitely no available seedbank in the soil itself. Plot 5 was the most successful Control plot as a result of the sand and grass seed that was washed in after a rainfall event.

The crumb structure did not last long on these plots. This made it even more remarkable for plot 1, which lost its crumb structure right after the first watering and immediately crusted again, that there was seedling emergence.

5.3.8 Grass seed

The specially formulated Dinokeng grass seed mix that was used in the study, contained grass seed from pioneer, sub-climax and climax species. All the seed will not germinate at the same time, but be staggered over time and seasons, for survival of the species at the location (van Oudtshoorn, 1994).

Although the seedlings were still too small for positive identification, the species composition contained some of the same species that Kellner and de Wet (2001), van den Berg and Kellner (2005) and Msiza *et al.* (2021) used with success. Kellner and de Wet (2001) also found that seedling emergence between species over time were different.

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CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Mechanical resistance of crust

All the PAM treatments, either alone at both the low and high rates, or in combination with gypsum or molasses meal, performed well, with low values measured. Contrary to what was expected, based on previous research, the control plots had the lowest mechanical resistance values as measured with the Torvane shear apparatus due to the nature of the way of breaking of the extremely thin crust by the shear vanes (Fig. 5.1).

6.1.2 Final infiltration rate

All the PAM alone at both the low and high rates and PAM combination treatments performed very well regarding increasing of FIR in comparison to the control and gypsum plots (Table 5.3 and Fig. 5.12).

6.1.3 Short-lived positive effects of brush packing

Brush packing temporarily became very effective in assisting re-establishment of grass and weeds by trapping seeds and eroded sand from overflowing water during the early part of the rainy season. The positive impact thereafter decreased over time as the vegetation used for brush packing degraded and could no longer retain the sand, which provided a favourable growth medium against the fast flowing runoff.

6.1.4 Determination of structure stability

All four levels of PAM treatments alone, as well as molasses meal alone and the combination and gypsum and molasses meal, as well as the combination of PAM and molasses meal, improved structure stability to highly significantly levels over the control (Table 5.4 and Fig. 5.14). Gypsum alone and the PAM + gypsum combination were the only treatments which did not improve structure stability significantly. This supports the poor results with gypsum in the field study. The above positive stabilisation capability of molasses meal indicates that, at least theoretically, molasses meal should perform better under ideal field conditions.

6.1.5 Pilot study with sowing in of grass seed

The PAM plots had the most seedling emergence initially, but during a very dry and warm spell most seedlings, died off. It is concluded that the PAM plots responded the best to the light rain because it created a better soil water regime than the other treatments. During the following heavier rains, the rest of the plots including the control plots had seedling emergence. The PAM plots were performing average now, in the same order as the rest of the plots, probably having been compromised by the loss of seed which germinated after the small rain.

6.2 Recommendations and Future Actions

6.2.1 Recommendations

From observations in the study area, it is clear that physical structures alone cannot arrest the sheet erosion on the type of unstable soil found in the area (Chapter 3). Inappropriately designed gabion-like structures (stone bunds), existent in the study area, were constructed a long time ago by farmers for erosion control purposes (these structures are currently broken), they were only effective in reducing erosion for a certain time. Currently, in their broken condition they actually aggravate the problem. The wire-mesh holding the stones broke over time due to rusting, with the result that some stones and even 1-2-meter-wide pieces of stone bunds were washed away. Now they are acting as erosion hot-spots, to the extent of becoming the start of erosion gullies. The problem with these specific stone bunds were that they were wrongly designed. When correctly designed and applied as in other areas in Africa, they work much better.

These stone bunds by itself can thus not be recommended as plan of action to re-claim such area. Correctly designed stone bunds can help in preventing erosion as proven in other parts of Africa. Application of the ameliorant and sowing in of seed should be done early in the rain season, to give the seedlings enough time to de-velop and mature. The most important factor is to sow the seed when rain and cool weather is predicted for a couple of weeks post sowing, since a hot dry spell will kill the newly emerged seedlings, which will not only be an economical loss and time wasted but means less seed left to germinate. The latter would then require sowing of seed again.

Since chemical ameliorants were effective in alleviate the soil crust and creating a structured soil surface, these can be recommended. However, in such crusted soil which has been barren for 40-50 years, no seed bank is left and grass seed has to be sown together with application of an ameliorant. It is very important to take climate and weather conditions into account when implementing such a strategy.

6.2.2 Future actions

Looking forward, these well-planned and executed crusting trials should be repeated with the application of ameliorants, in combination with sowing of seeds to further support and confirm the recommendations made. The trials should be repeated on similar thin crust and should preferably also be done in an area with thicker crusts. The above research should include other methods of crust strength measurements in combination with the shear vane apparatus used in this study. This to refine the measurement of crust strength of very thin, dense and hard crusts. Very important for such a study is to plan according to the weather and longer time rainfall predictions.

APPENDICES

Appendix A: Turnitin Digital Receipt

M

by Anelle Human

Submission date: 02-May-2023 11:29AM (UTC+0200)
Submission ID: 2081903386
File name: Apr_2023_Ane_lle_Human_MSc_Dissertation-corrected_version.pdf (5.06M)
Word count: 25740
Character count: 126160

Figure A.1: Turnitin digital receipt

Appendix B: Ethical clearance

UNISA university of south africa

UNISA-CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 05/07/2021

NHREC Registration # : REC-170616-051
REC Reference # : 2021/CAES_HREC/104
Name : Ms A Human
Student #: 33072809

Dear Ms Human

Decision: Ethics Approval from 01/07/2021 to 30/06/2024

Researcher(s): Ms A Human
nelhuman@gmail.com

Supervisor (s): Dr GP Nortje
nortjgp@unisa.ac.za; 011-471-2286

Prof MC Laker
Giel.Laker1@gmail.com; 082-785-5295

Working title of research:

Evaluation of the efficacy of selected ameliorants to alleviate soil crusting, with a view to reclamation of degraded land, in Dinokeng game reserve

Qualification: MSc Environmental Science

Thank you for the application for research ethics clearance by the Unisa-CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is granted for three years, **subject to submission of yearly progress reports. Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report has been submitted.**

The researcher is cautioned to adhere to the Unisa protocols for research during Covid-19.

Due date for progress report: 30 June 2022

Please note the points below for further action:

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PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za

Figure B.1a: Ethical clearance, first page

1. The researcher is cautioned to adhere to Covid-19 regulations during field visits, where the researcher may come into contact with other people.
2. More detail is required on the statistical analysis – please specify the type of Anova that will be applied, and identify the model and the variables. The researcher is requested to indicate how the data for each objective will be analysed.

The ***low risk application*** *was* ***reviewed*** *by the UNISA-CAES Health Research Ethics Committee on 01 July 2021 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher will ensure that the research project adheres to the relevant guidelines set out in the Unisa Covid-19 position statement on research ethics attached.
2. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
3. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
4. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
5. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
6. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
7. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
8. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

URERC 25.04.17 - Decision template (V2) - Approve

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Figure B.1b: Ethical clearance, second page

> *Note:*
> *The reference number* ***2021/CAES_HREC/104*** *should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

Prof MA Antwi
Chair of UNISA-CAES Health REC
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Tel: (011) 670-9391

Prof SR Magano
Acting Executive Dean : CAES
E-mail: magansr@unisa.ac.za
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URERC 25.04.17 - Decision template (V2) - Approve

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Figure B.1c: Ethical clearance, third page

Appendix B: Ethical clearance (renewal)

UNISA university of south africa

UNISA-CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 21/07/2022

NHREC Registration # : REC-170616-051
REC Reference # : 2021/CAES_HREC/104
Name : Ms A Human
Student #: 33072809

Dear Ms Human

Decision: Ethics Approval Confirmation after First Review from 01/07/2021 to 30/06/2024

Researcher(s): Ms A Human
nelhuman@gmail.com

Supervisor (s): Dr GP Nortje
nortjgp@unisa.ac.za; 011-471-2286

Prof MC Laker
Giel.Laker1@gmail.com; 082-785-5295

Working title of research:

Evaluation of the efficacy of selected ameliorants to alleviate soil crusting, with a view to reclamation of degraded land, in Dinokeng game reserve

Qualification: MSc Environmental Science

Thank you for the submission of your yearly progress report to the Unisa-CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is confirmed to continue for the originally approved period, subject to submission of yearly progress reports. **Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report has been submitted.**

The researcher is cautioned to adhere to the Unisa protocols for research during Covid-19.

Due date for next progress report: 30 June 2023

The progress report form can be downloaded from the college ethics webpage:

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Figure B.2a: Ethical clearance (renewal), first page

> *Note:*
> *The reference number* ***2021/CAES_HREC/104*** *should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

Prof MA Antwi
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E-mail: antwima@unisa.ac.za
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Prof SR Magano
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URERC 25.04.17 - Decision template (V2) - Approve

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Figure B.2b: Ethical clearance (renewal), second page https://www.unisa.ac.za/sites/corporate/default/Colleges/Agriculture-&-Environmental-Sciences/Research/Research-Ethics

*The **low risk application** was originally **reviewed** by the UNISA-CAES Health Research Ethics Committee on 01 July 2021 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher will ensure that the research project adheres to the relevant guidelines set out in the Unisa Covid-19 position statement on research ethics attached.
2. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
3. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
4. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
5. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
6. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
7. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
8. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:

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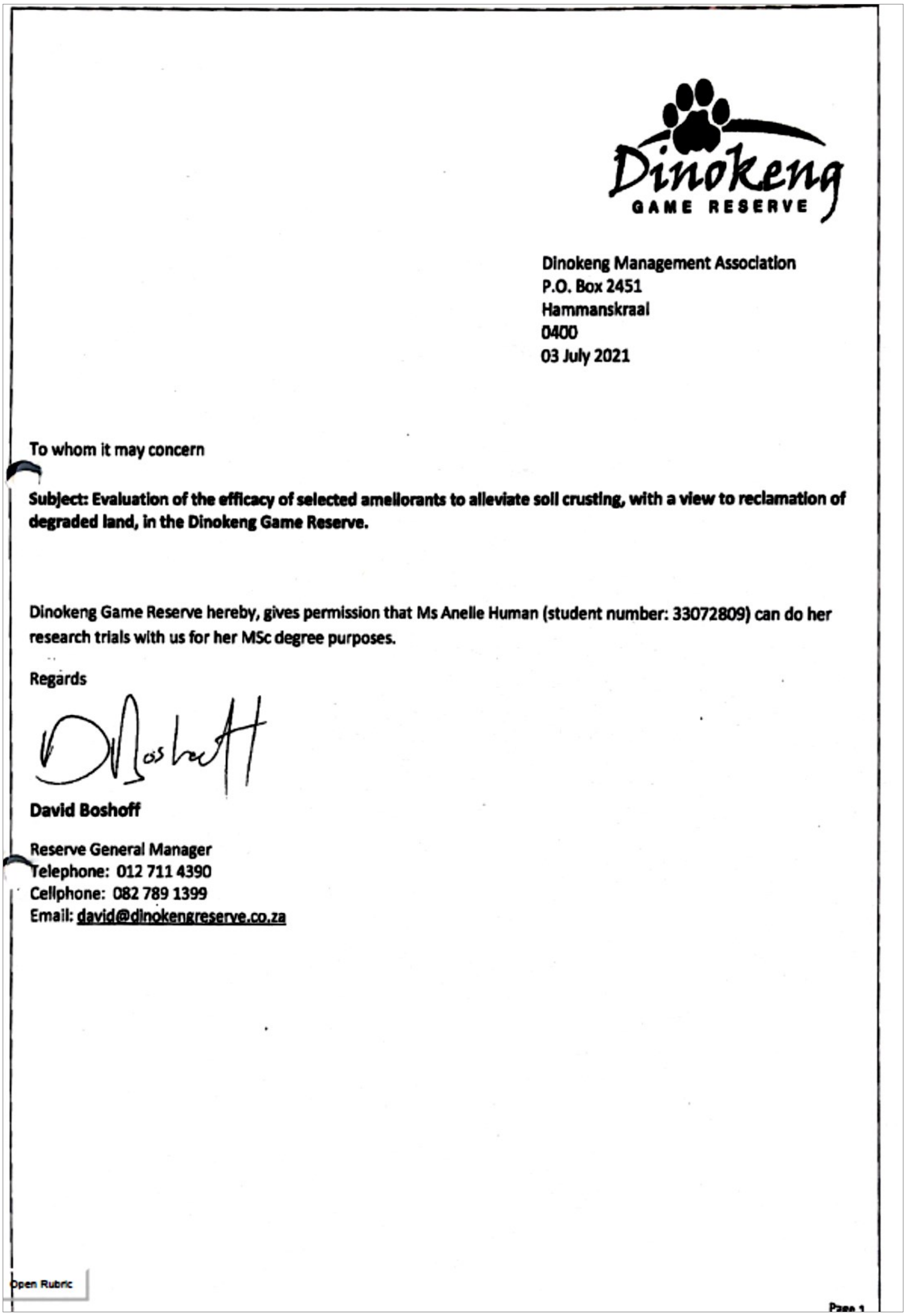
Figure B.2c: Ethical clearance (renewal), third page

Appendix C: Letter of Consent from Dinokeng Game Reserve



Dinokeng
GAME RESERVE

Dinokeng Management Association
P.O. Box 2451
Hammanskraal
0400
03 July 2021

To whom it may concern

Subject: Evaluation of the efficacy of selected ameliorants to alleviate soil crusting, with a view to reclamation of degraded land, in the Dinokeng Game Reserve.

Dinokeng Game Reserve hereby, gives permission that Ms Anelle Human (student number: 33072809) can do her research trials with us for her MSc degree purposes.

Regards

David Boshoff

Reserve General Manager
Telephone: 012 711 4390
Cellphone: 082 789 1399
Email: david@dinokengreserve.co.za

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Page 1

Figure C.1: Letter of Consent from Dinokeng Game Reserve

Appendix D: Soil physical and chemical analysis

FRM 168 version: 01, 2018-06-29 WO 93387:115256 **PAGE: 1 of 2**

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Grond / Soil

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Datum Ontvang/Date Received:	2021-07-28	**Verslag nr./Report no.:**	WO 93387:115256
Datum Begin/Date Commenced:	2021-07-28	**Datum Gerapporteer/Date Reported:**	2021-08-11

To/Aan:	NORTJE GP P.O. BOX 53606 CENTURION 0149	**Representative/Verteenwoordiger:**	GP NORTJE
		Farm Name/Plaas Naam:	
		Order/Bestel#:	Dinokeng Soils
		Email:	gerhard@solovivo.co.za

Lab Nommer	Sample Reference	pH KCl *	P Bray1	K AmAc *	Na AmAc	Ca AmAc	Mg AmAc *	EXCH ACID KCl	Ca% AmAc	Mg% AmAc	K% AmAc	Na% AmAc	ACID SAT. AmAc	Ca:Mg AmAc	(Ca+Mg)/K AmAc	Mg:K AmAc	S-VALUE AmAc	Na:K AmAc	T-VALUE AmAc *	Dens. *	S AmAc
Lab Number	Monsterverwysing	-	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	cmol(+)/kg	%	%	%	%	%				cmol(+)/kg	cmol(+)/kg	cmol(+)/kg	g/ml	mg/kg
G27-23638	Prismakutaniese B (Rooi sterkspruit)	5.2	2	116	75	1276	593	0.00	53.76	40.97	2.50	2.76	0.00	1.31	37.82	16.36	11.87	1.10	11.87	1.11	65.54
G27-23639	Kalklaag	7.3	2	172	175	2771	1163	0.00	56.35	38.77	1.79	3.09	0.00	1.45	53.27	21.71	24.59	1.73	24.59	1.10	7.58
G27-23640	Ortiese A (230 mm)	4.7	4	184	13	418	143	0.00	55.13	31.01	12.41	1.44	0.00	1.78	6.94	2.50	3.79	0.12	3.79	1.19	7.69
G27-23641	Ortiese A	5.6	2	513	16	657	271	0.00	47.67	32.28	19.04	1.01	0.00	1.48	4.20	1.70	6.89	0.05	6.89	1.05	18.85
G27-23642	Prismakutaniese B (26/7/2021)	5.4	2	187	89	1995	960	0.00	53.31	42.06	2.56	2.07	0.00	1.27	37.26	16.43	18.71	0.81	18.71	1.03	28.41

NOTAS / NOTES:

Verslag goedgekeur deur / Report approved by:

Leoni Erasmus
leoni.e@nvirotek.co.za
Data Administrator

Francois Reeders
francois.reeders@nviroteklabs.co.za
TS: ICP-OES & WIN 014

Figure D.1: Soil physical and chemical analysis, first page only

University of South Africa — Human, A (2023)