CHAPTER 3

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The influence of a class F fly ash / sewage sludge mixture and class F fly ash on the physical and biological properties of degraded agricultural soils

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ABSTRACT

Prime agricultural land is a limited resource in South Africa. It is, therefore, necessary to reclaim poor and disturbed soils to feed the burgeoning population. Using conventional methods is costly and not necessarily sustainable. The challenge is to use alternative materials in an economically, ecologically and socially acceptable manner.

Previous research has shown that sewage sludge can be pasteurized by mixing it with class F fly ash and a suitable source of quicklime. The **SL**udge**ASH** (SLASH) mixture has been extensively evaluated as a soil ameliorant and has proven to be viable for the reclamation of poor and marginal soils. Many studies previously conducted and reported on, have focused on the effect of class F fly ash and SLASH on soil chemical properties and consequently plant production of various plant species.

This paper reports on subsequent research conducted to determine the effect of both class F fly ash and SLASH on soil physical and microbiological properties. SLASH and class F fly ash treatments were compared with the conventional soil ameliorant of agricultural dolomitic lime with fertilizer and an untreated control. The results obtained illustrate improvements in soil physical properties such as soil texture, bulk density, water infiltration rate and hydraulic conductivity by class F fly ash based soil ameliorants. In addition to the beneficial effect obtained on soil physical properties, the microbial properties had also improved, as indicated by the improved symbiotic relationship of the *Rhizobium* bacteria and the important host plant *Medicago sativa.* The results presented are encouraging and justify further research on the use of class F fly ash and it's co-utilization with other by-products to restore productivity to poor agricultural lands.

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INTRODUCTION

South Africa is a country with very little prime farmland. A large percentage of the land with a high agricultural capability is generally acidic and is situated in areas where large quantities of fly ash are disposed. To ensure healthy and productive vegetation, disturbed soils need to be ameliorated effectively. To date, conventional methods of liming and fertilization to improve productivity of impacted soils have been standard practices. This process can, however, be very expensive and is often not sustainable.

Soil physical and microbiological factors are also responsible for ensuring a healthy soil environment, which is necessary for seed germination, plant establishment and growth on any type of soil. Soil moisture retention affects the growth of all plants, especially in land rehabilitation. The ability of the soil to absorb water, however, is affected by soil characteristics such as texture, structure, organic matter and depth (Lyle, 1987). Soil texture is determined by the relative percentages of sand, silt and clay in a soil. Soils with a high sand content have a coarse texture and water will percolate easily through such a growth medium resulting in low water retention for plant use. A clayey soil can, however, reduce the movement of water through the profile resulting in waterlogged conditions. Different soil pore sizes (macro and micro) affect water infiltration and storage capacity of a soil. Without pores there would be no water or oxygen in the soil, which is essential for plant growth. Compacted soil reflects changes in bulk density, water holding capacity, hydraulic conductivity, and organic matter content and soil strength. Root growth is usually restricted when bulk density reaches approximately 1.25×10^{-3} kg m^{-3} in clay soils and about 1.75×10^{-3} kg m^{-3} in sandy soils (Hannan and Bell, 1986, Jackson, 1991), though some plants are able to grow in more highly compacted soils.

Fly ash and various organic materials have, however, been shown to improve soil bulk density, water holding capacity, hydraulic soil conductivity, organic content and soil strength, thereby creating a more favourable growth medium for plant roots to penetrate (Chang *et al*., 1977; Aitken and Bell, 1985; Eisenberg *et al*., 1986; Garg *et al*., 1996; Kalra *et al*., 1998). Soil characteristics, which affect hydraulic conductivity, are total porosity, the distribution of pore sizes and the pore geometry of the soil together with the fluid attributes such as fluid density and viscosity. (Hillel, 1982).

Another component, which is essential for a healthy soil environment, is soil organic matter. Organic matter in soils consists of the rotting or decomposing remains of plants and animals. The stage of decomposition varies from litter to humus (decomposed organic matter), which holds and absorbs water and nutrients for plant use. Soil depth is also regarded as another important aspect, which influences the soil environment. This may be defined as the distance from the soil surface to any layer, which prevents further root penetration and consequently affects the ability to absorb nutrients and water. Finally, microbial populations need to be present. If deficient they need to be re-established so that the decomposition of plant, animal and human residues and the mineralization of organically complexed nitrogen and phosphorus can be ensured.

Undisturbed and productive soils usually have the greatest diversity of species of soil organisms. The size of the microbial biomass is usually highly correlated with the amount of plant growth, soil organic matter content and the clay and silt content. The aggregation of soil is primarily responsible for controlling microbial activity. When microflora and roots produce fibrils, filaments, and polysaccharides that combine with clays to form organo-mineral complexes, aggregate formation is initiated. The quantity of micro-organisms decrease with depth in the soil, as do plant roots and soil organic matter. Factors such as tillage, micro-climate, and plant cover have considerable impacts on the microbial distribution within soil profiles. Soil organic matter is essential to provide a good soil structure and can have a great effect on the erosion resistance of a soil, the development of roots and the infiltration of water into the soil. Soil organic matter also stores nutrients such as N, S, P and many micronutrients and improves the cation absorption capacity of a soil. The amount of soil organic matter present is dependant on the balance between primary productivity and the rate of decomposition. Nitrogen (N) is the nutrient most often required by plants for growth and it is also the fourth most important element in plant composition, after carbon (C), hydrogen (H) and oxygen (O). Soil organisms commonly mediate shifts between these important plant constituents (Paul and Clark, 1996).

Many micro-organisms are responsible for processes that ensure the availability and loss of N in the soil. Various soil factors, including soil acidity, however, affect the functioning of these micro-organisms. Most micro-organisms responsible for mineralization, nitrification and denitrification, function best within an optimum pH range of 6-8. Organisms and associations involved in nitrogen fixation have been identified, and leguminous plants benefit from such beneficial effects. Nitrogen fixation in legumes is attributed to a group of bacteria consisting of a number of genera collectively known as rhizobia. Much is known about the use of rhizobia as inoculants, to establish a symbiotic relationship within the roots of host plants. Nodule development on the roots of host plants is the result of a successful inoculation, and can be affected by poor soil conditions, which needs to be ameliorated.

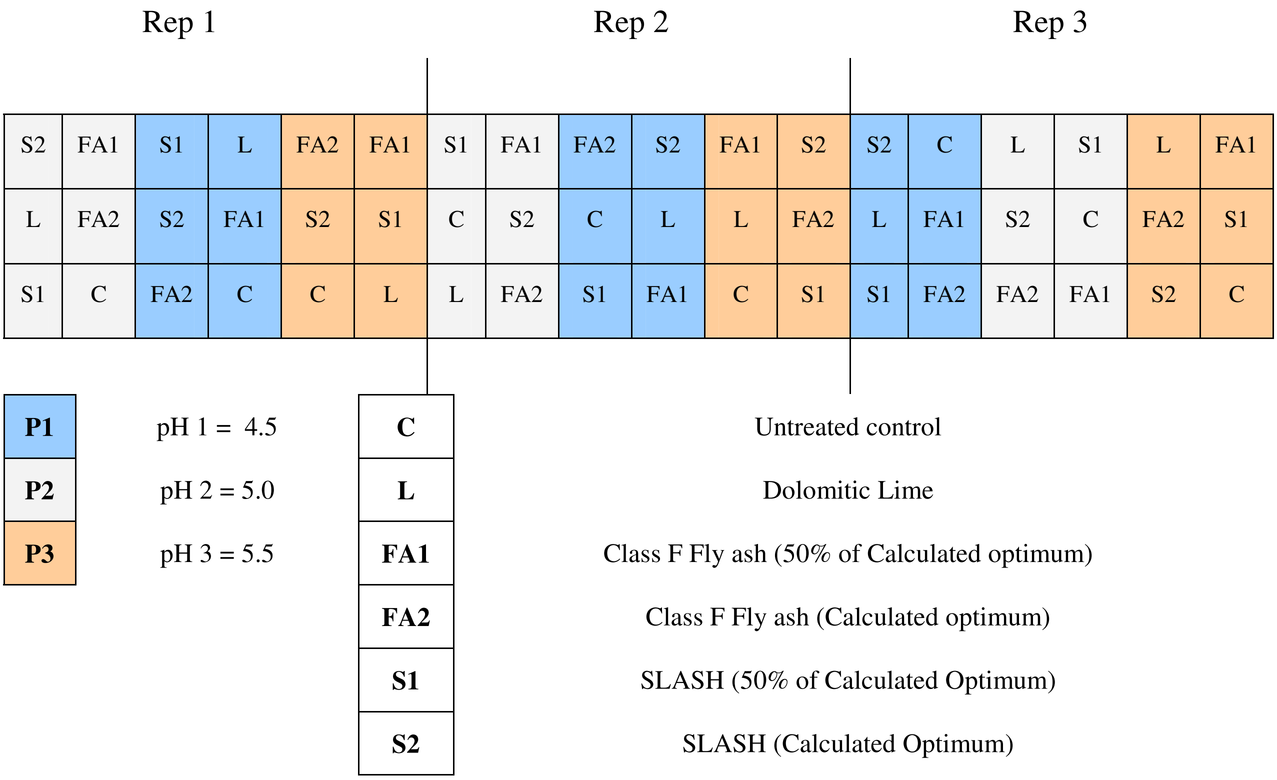
South Africa has an abundance of waste products, which might be used as alternative ameliorants. Fly ash is characterized as a good source of certain micronutrients; beneficial to plant growth, in addition to it's neutralizing qualities and other unique properties. This resource together with organic materials such as sewage sludge or animal manures (which are good sources of organic matter and macronutrients essential for plant growth), can serve as soil ameliorants in crop production systems (Norton *et al*., 1998; Truter, 2002). In future, conventional landfill and lagoon disposal of rapidly accumulating coal combustion byproducts, (especially fly ash), and organic biosolid wastes (such as sewage sludge and animal manures) is unlikely to comply with increasingly stringent environmental regulations (Sopper, 1992; Walker*, et. al*, 1997).

Previous work to determine the feasibility of converting waste disposal problems into a soil beneficiation strategy has proven true (Reynolds *et al*., 1999). The co-utilization of fly ash and sewage sludge with added lime (CaO) in a ratio of 6:3:1 on a wet basis, has delivered the product termed SLASH, which can be used as a soil ameliorant (Truter, 2002). This study entails an evaluation of SLASH and fly ash as alternative soil ameliorants to address the concern of poor soil physical and microbiological properties.

MATERIALS AND METHODS

A randomized field study with nett plots of 3.75m x 8.65m = $32.44m^2$, was conducted on the Hatfield Experimental Farm, Pretoria, South Africa ($25^{\circ}45$'S $28^{\circ}16$'E), 1327m above sea level (Figure 1). A uniform sandy loam Hutton soil was ameliorated with sewage sludge, class F fly ash and reactive lime (CaO) in combination (SLASH) at different levels and compared with fly ash and lime treatments.

Figure 1: The application of ameliorants to the Hatfield Field trial



Rep 1						Rep 2						Rep 3					
S2	FA1	S1	L	FA2	FA1	S1	FA1	FA2	S2	FA1	S2	S2	C	L	S1	L	FA1
L	FA2	S2	FA1	S2	S1	C	S2	C	L	L	FA2	L	FA1	S2	C	FA2	S1
S1	C	FA2	C	C	L	L	FA2	S1	FA1	C	S1	S1	FA2	FA2	FA1	S2	C

P1	pH 1 = 4.5
P2	pH 2 = 5.0
P3	pH 3 = 5.5

C	Untreated control
L	Dolomitic Lime
FA1	Class F Fly ash (50% of Calculated optimum)
FA2	Class F Fly ash (Calculated optimum)
S1	SLASH (50% of Calculated Optimum)
S2	SLASH (Calculated Optimum)

Figure 2: The experimental layout (Randomized Block Design) of the Hatfield Field Trial planted to *Medicago sativa* on soils with three different pH levels.

The primary objective of this study was to determine the influence of SLASH and class F fly ash treatments on the production of *Medicago sativa* (Lucerne or alfalfa) over a 24-month period on soils with different levels of acidity. The field consisted of three levels of acidity **[P1]** $pH_{(H_2O)} = 4.5$, **[P2]** $pH_{(H_2O)} = 5.0$ and **[P3]** $pH_{(H_2O)} = 5.5$. Lime application rates were based on the buffering capacity of the soil which was determined by using a $Ca(OH)_2$ titration solution. It was calculated from the buffer curve which was based on the initial soil $pH_{(H_2O)}$ of the Hatfield soil, and it required 4.0 tons ha^{-1} of dolomitic lime **[L]** to raise the pH of the soil to $pH_{(H_2O)}$ of 6.5 which is optimum for lucerne growth. The control **[C]** treatment was untreated (receiving no soil ameliorants). The other treatments were compared to the aforementioned control and lime treatment. These treatments included two levels (optimum level and 50% of the optimum level) of class F fly ash and SLASH. The optimum level of fly ash **[FA2]** was based on the assumption (from literature) that class F fly ash had a $CaCO_3$ equivalent of 20% (Truter, 2002). This resulted in a fly ash requirement of approximately five fold the amount of dolomitic lime required to raise the $pH_{(H_2O)}$ to 6.5, thus the optimum class F fly ash level **[FA2]** was calculated as 19 tons ha^{-1}**.** Level two **[FA1]** was 50 % of this, namely 9.5 tons ha^{-1}. The 50% of the optimum treatment was included to determine whether the $CaCO_3$ equivalent of South African class F fly ash was higher than the 20% guideline presented in international literature. The optimum SLASH **[S2]** of 64 tons ha^{-1} was calculated from the ratio of fly ash, sewage sludge and lime (6:3:1 on a wet basis) used in the process of making SLASH (Reynolds *et al*., 1999). The second level, 50% of the optimum, **[S1],** was 32 tons ha^{-1}. These treatments were replicated three times and were only applied at the beginning of the trial, prior to the establishment of the lucerne, to determine the long-term residual effect on sustainability.

In addition to the soil ameliorants being applied at the onset of the experimental trial, a basal application of 250 kg of K (potassium) ha^{-1} $year^{-1}$ was given to compensate for the relatively low K status and K removal, which resulted from the multiple harvesting of plant material each growing season.

The field was sown to *Medicago sativa* cv SA Standard (lucerne or alfalfa) in 20 cm rows using a seeding rate of 25 kg ha^{-1} and the seed was inoculated with a multi-strain inoculant of *Rhizobium* bacteria.

Figure 3: The Hatfield field trial planted to *Medicago sativa* on a soil with three different pH levels, shortly after planting.

During the growing season, irrigation was supplied to ensure that water was not a limiting factor. Two seasons of production data were collected over a period of 24 months. At the end of the 24-month period a root biomass study was conducted to determine the effect of the different soil ameliorants on root development and/or the symbiotic relationship of the *Rhizobium* bacteria. Three healthy plants were selected randomly in each soil treatment and soil cores of 30cm x 30cm x 30cm deep (representing the most active root zone) were excavated with each plant, to obtain the root sample. A root sample enclosed by soil was removed for microbial analysis and the rest of the soil was washed from the root sample using a sieve. Finally the washed roots were dried at 65°C for 24 hours to obtain the root dry mass.

Subsequently, a basic microbiological laboratory study was conducted using soil collected from the aforementioned field trial, to determine the effect of the applied soil ameliorants on *Rhizobium* nodulation and the total microbial activity in treatments applied to the most acidic soil, with an initial $\mathrm{pH}_{(H2O)}$ *of 4.5*. Microbial activity was determined according to the protocol of Inbar *et al*. (1991). All *Rhizobium* nodules on the plant roots were counted and also separated into single nodules and branched nodules.

Concurrent with this field trial, a study was conducted on the most acid soil from the Hatfield experimental site. Treatments ameliorated with optimum levels of SLASH, Class F fly ash, dolomitic lime were compared to the control (no treatment). This study was to determine the influence of SLASH and fly ash treatments on the physical properties of the most acidic soil. The following methodology was used to determine bulk density. A 100 mL graduated cylinder was weighed, and filled with soil that was sieved to 2mm. The first addition of soil to the cylinder was compacted by tapping the bottom of the cylinder ten times. Soil was added gradually and cylinder tapped repeatedly until 100ml soil was obtained. The filled cylinder was then weighed. Each ameliorated soil was replicated five times. The moisture content of the soil was determined separately and the oven dry weight of the 100 ml soil above was calculated (Tan, 2005). Equation (2.1) was used to calculate bulk density.

$$\text{Bulk Density} = \frac{\text{oven dry weight of 100mL soil}}{100} \qquad = \mathbf{10^{-3}\ kg\ m^{-3}} \qquad (2.1)$$

The measurement of hydraulic conductivity of a saturated soil was determined using the laboratory method of Klute (1965). The lower end of the soil cylinder (core) was covered with a filter paper to retain the soil. The soil was allowed to soak water slowly through the capillary rise and the saturated core was used for the K_s measurement. A constant head was maintained across the core and the volume of water coming out of the core was measured at specific time intervals. The flow rate along with the hydraulic head difference, length and cross section of the core are recorded and transferred into Eq. (2.2) (Lal and Shukla, 2004). This method equates to the following

$$\text{Hydraulic conductivity } (\boldsymbol{K}) = VL / tA\,\Delta H \qquad = \mathbf{10^{-3}\ cm\ sec^{-1}} \qquad (2.2)$$

Where $\mathbf{V}$ *= volume of water*

$\mathbf{L}$ *= length of the column*

$\mathbf{t}$ *= time*

$\mathbf{A}$ *= cross sectional area of flow through the soil column*

$\Delta\mathbf{H}$ *=hydraulic head difference*

Downward infiltration into an initially unsaturated soil generally occurs under the combined influence of suction and gravity gradients (Hillel, 1982). Darcy's equation for vertical flow Eq. (2.3) was used to determine the infiltration rate of the ameliorated soils.

$$\textit{Infiltration rate} \quad (\boldsymbol{q}) \;=\; K\,\Delta H/L \;=\; \mathbf{mm\ hr^{-1}} \qquad (2.3)$$

Statistical analyses

All the data was statistically analyzed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS software. A Bonferroni test was conducted where LSD's were taken at $P \leq 0.05$. (SAS, 1998).

RESULTS AND DISCUSSION

The legume crop (*M. sativa*), used as the test crop in this soil amelioration study, is the most common legume grown for grazing and hay production in South Africa. This legume is widely adapted, but prefers deep, well-drained soils with a neutral pH.

Soil physical analyses

Soil texture analysis

In Tables 1-3 it is clear that the soil ameliorants based on class F fly ash (S1, S2, FA1, FA2) had significant effects on the different fractions of the experimental soil. The coarse sand fraction (Table 1) was significantly lower in both the fly ash and SLASH treated soil, as a result of higher silt fraction (Table 2) while the clay fraction was slightly lower (Table 3). With the higher silt fraction prevalent in the class F fly ash and SLASH treated soils, it can be expected (as reviewed in previous research) that the altered soil texture would affect the movement and storage of water in the profile, which is available for plant use.

The data, obtained from the texture analyses, supports the conclusion, that soil ameliorants based on class F fly ash, contribute to a higher silt fraction in the soil. This can be ascribed to the fine texture of the fly ash. At high application rates it will consequently change the texture of a soil being ameliorated.

Table 1: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the coarse sand fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Coarse Sand						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	*SE (+/-)*
Control	75.4	74.4	70.9	72.5	65.8	**71.8**$_{a}$	(2.2)
SLASH	67.8	70.9	69.3	72.9	65.3	**69.2**$_{b}$	(2.6)
Fly ash	67.2	65.8	65.2	63.2	59.4	**64.2**$_{c}$	(2.3)
Lime	75.3	65.7	69.2	71.1	75.1	**71.3**$_{a}$	(2.9)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 2 indicates that class F fly ash increased the silt fraction of the Hutton soil from 8.28% to 20.1%, which is a highly significant improvement. This change in the silt fraction of soil is responsible for the changes noted in other soil physical properties.

Table 2: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the silt fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Silt						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	*SE (+/-)*
Control	8.3	10.1	9.1	12.0	1.9	**8.28**$_{d}$	(1.3)
SLASH	13.8	15.7	14.5	15.1	16.5	**15.1**$_{b}$	(0.6)
Fly ash	18.6	21.1	19.8	23	22.4	**20.1**$_{a}$	(1.4)
Lime	9.2	12.9	10.8	11.6	9.9	**10.8**$_{c}$	(1.1)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 3: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the clay fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Clay						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE (+/-)***
Control	16.4	19.6	20.0	20.2	16.7	**18.6** $_a$	(1.6)
SLASH	16.4	19.6	18.1	19.6	17.6	**16.3** $_b$	(1.1)
Fly ash	14.2	16.1	15.0	16.0	18.2	**15.9** $_b$	(1.0)
Lime	15.5	11.4	12.0	17.3	16.0	**18.4** $_a$	(2.6)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Bulk density

Bulk density is an important parameter used to determine the degree of compaction. Different textured soils can experience different degrees of compaction. Clayey soils generally compact the most. Table 4 shows that soil treated with class F fly ash or SLASH had a significantly lower bulk density than the untreated control or the lime treatment.

Table 4: The comparative influence of soil ameliorants on the bulk density of an acidic Hutton soil with an original pH$_{(H_2O)}$ *of 4.5*

	Bulk Density (x 10^{-3} kg m^{-3})						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	1.56	1.47	1.49	1.60	1.55	**1.53** $_a$	(0.04)
SLASH	1.48	1.39	1.49	1.46	1.45	**1.45** $_b$	(0.07)
Fly ash	1.34	1.27	1.39	1.32	1.35	**1.33** $_c$	(0.08)
Lime	1.58	1.38	1.45	1.49	1.59	**1.50** $_a$	(0.07)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Soil with a good organic matter content can theoretically have a lower bulk density. It was expected that the combination of sewage sludge (which contains organic matter) and fly ash, would lower the bulk density of the soil more than fly ash alone. This, however, was not the case; with fly ash reducing the bulk density the most significantly followed by SLASH. The possible reason for this result is that the soil used in this study had a high percentage of clay, and that the SLASH which has a coarser texture, did not have as significant an effect on the bulk density as it would have had on a sandier soil. The fly ash, however, with its fine texture and high silt fraction had a more significant effect on the clayey soils texture and bulk density.

These data demonstrate that class F fly ash, at high application rates, based on the neutralizing requirement of the soil, can have a beneficial effect on the bulk density, thereby ensuring a better plant root development.

Infiltration rate (q)

Sandy soils are known to have a high infiltration rate. This can often be a disadvantage if water is limiting plant growth, because the soil can dry out quickly. On the other hand if the infiltration rate increases, this causes more water to enter the soil profile and less is lost to runoff. A very low infiltration rate can be a disadvantage as it can lead to high runoff, resulting in erosion of the soil surface.

The data presented in Table 5 demonstrate that class F fly ash and SLASH treatments significantly increased the infiltration rate by 60% and 42% over the control, respectively. These results can be linked to the improved bulk density (Table 4) as well as the increased silt fraction of soil (Table 2) when class F fly ash was used as a soil ameliorant.

Table 5: The comparative influence of soil ameliorants on the infiltration rate of an acidic Hutton soil.

	Infiltration Rate (mm hr^{-1})						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	5.0	5.2	4.8	4.9	5.5	**5.1** $_{\mathrm{b}}$	(0.3)
SLASH	8.1	7.9	7.6	7.6	6.5	**7.5** $_{\mathrm{a}}$	(0.3)
Fly ash	8.3	7.3	7.9	9.0	8.6	**8.2** $_{\mathrm{a}}$	(0.5)
Lime	6.0	6.1	5.7	5.9	6.4	**6.0** $_{\mathrm{b}}$	(0.8)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

Hydraulic conductivity (K_s)

It is clear from Table 6 that the soil ameliorants based on class F fly ash (SLASH and FA) significantly reduced the hydraulic conductivity by changing the distribution of pore sizes, total porosity and soil geometry of the soil, with the assumption that the fluid density and viscosity used in the experiment remained constant.

These results illustrate that both SLASH and class F fly ash reduce the hydraulic conductivity by, 20% and 26% respectively, as compared to the 5% reduction by dolomitic lime. The implication of a lower hydraulic conductivity is that the rate at which water percolates through the soil profile, will be reduced, which will result in a higher water retention capacity. A higher water retention capacity will enhance crop production by improving nutrient uptake by plants.

Table 6: The comparative influence of soil ameliorants on the hydraulic conductivity (K_s) of an acidic Hutton soil

	Hydraulic conductivity (K_s) **(x 10^{-3} cm / sec)**						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	1.90	1.81	1.74	1.84	2.02	**1.86** $_{a}$	(0.08)
SLASH	1.50	1.38	1.51	1.6	1.43	**1.48** $_{c}$	(0.06)
Fly ash	1.40	1.21	1.36	1.52	1.45	**1.38** $_{d}$	(0.12)
Lime	1.84	1.72	1.78	1.86	1.74	**1.77** $_{b}$	(0.07)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Root biomass evaluation

A well-developed root system is an indication of the condition of the soil environment or growth medium. A healthy root system ensures a healthy and productive plant. The root biomass parameter is a good measure used to determine whether a plant's root system is well developed and whether sufficient nutrients and moisture are available, or whether the plant has been subjected to some form of stress. Acid soil environments restrict root development, which eventually affects the growth of the plant. *M. sativa,* is a species which is sensitive to an acidic environment and prefers a more neutral soil pH.

In Table 7 it can be seen that the untreated control had a comparatively low root biomass. Class F fly ash which is known to contain relatively little macro-nutrients produced a 74% higher root biomass of lucerne, by correcting the soil pH to 6.5 and by supplying additional micro-nutrients to the plant roots. The SLASH soil ameliorant, however, which contains the organic component of sewage sludge, and contains more macronutrients, increased the root biomass by 82%. The dolomitic lime treatment, which is devoid of macronutrients, such as N, P and K, increased the root biomass by only 14%.

Table 7: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 4.5*

	$pH_{(H2O)} = 4.5$						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	6.03	6.25	5.69	4.51	5.10	$\mathbf{5.52}_{\mathbf{d}}$	(0.43)
L	6.35	6.91	5.54	6.87	5.81	$\mathbf{6.30}_{\mathbf{c}}$	(0.54)
FA1	7.12	7.51	7.35	8.35	9.60	$\mathbf{7.99}_{\mathbf{b}}$	(0.79)
FA2	9.73	8.96	10.15	9.92	9.29	$\mathbf{9.59}_{\mathbf{a}}$	(0.39)
S1	6.78	7.22	9.26	8.80	10.80	$\mathbf{8.57}_{\mathbf{b}}$	(1.19)
S2	11.75	10.90	8.70	9.35	9.60	$\mathbf{10.06}_{\mathbf{a}}$	(1.01)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

It should be noted that the soils with originally higher pH levels (Table 8 & 9) exhibited the same trend in root biomass values, with the class F fly ash ameliorant and SLASH ameliorant on the higher soil pH value of 5.5, increasing the root biomass by 28% and 49%, respectively. The magnitude of the response to the soil ameliorants was, however, much smaller. This suggests that the soil ameliorants, based on class F fly ash, react better with the soil at a lower pH.

It is evident that the root biomass was much lower for the untreated control than the other soil pH levels. Nevertheless, the addition of both class F fly ash and SLASH increased the root biomass substantially, and these values were higher than on the other soils, with slightly higher pH levels, which had been ameliorated with the same amount of class F fly ash and SLASH.

Table 8: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 5.0*

	$pH_{(H2O)} = 5.0$						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	6.23	7.34	6.12	7.28	6.54	**6.70** $_{d}$	(0.49)
L	6.98	7.27	6.89	7.23	6.41	**6.95** $_{d}$	(0.25)
FA1	8.02	7.65	8.34	7.96	8.37	**8.06** $_{c}$	(0.23)
FA2	9.63	9.45	8.94	9.51	8.86	**9.27** $_{b}$	(0.30)
S1	9.95	9.56	9.37	10.14	9.28	**9.66** $_{b}$	(0.33)
S2	10.72	9.93	11.52	11.67	11.31	**11.03** $_{a}$	(0.56)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

Table 9: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 5.5*

	$pH_{(H2O)} = 5.5$						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	7.56	7.02	6.57	6.33	7.60	**7.02** $_{d}$	(0.45)
L	8.12	6.87	7.12	7.65	7.23	**7.39** $_{d}$	(0.39)
FA1	8.12	8.56	7.67	8.76	7.83	**8.18** $_{c}$	(0.38)
FA2	8.42	9.43	8.29	9.11	9.83	**9.01** $_{b}$	(0.49)
S1	9.54	9.32	9.97	8.98	9.53	**9.47** $_{b}$	(0.25)
S2	9.87	11.23	10.61	9.95	10.52	**10.44** $_{a}$	(0.42)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

Soil Microbiological Analyses

Microbial activity

Soil micro-organisms ensure the life of a soil. Disturbed soils, however, often need a replenishment of such organisms, either by the addition of organic matter or by creating a better soil environment through amelioration. Soil acidity is a major factor responsible for the destruction of soil microbial populations. By raising the soil's pH with the addition of an alkaline material, higher microbial activity can be obtained. As can be seen in Figure 4 it is evident that of the soil ameliorants evaluated, SLASH ameliorants improved the microbial activity by 100%. This can possibly be ascribed to a rise in soil pH, together with the addition of organic matter, via the sewage sludge component of SLASH. Class F fly ash, however, also resulted in a remarkable increase in the activity by 26% as compared to the untreated control, while the lime treatment had an insignificant effect on microbial activity.

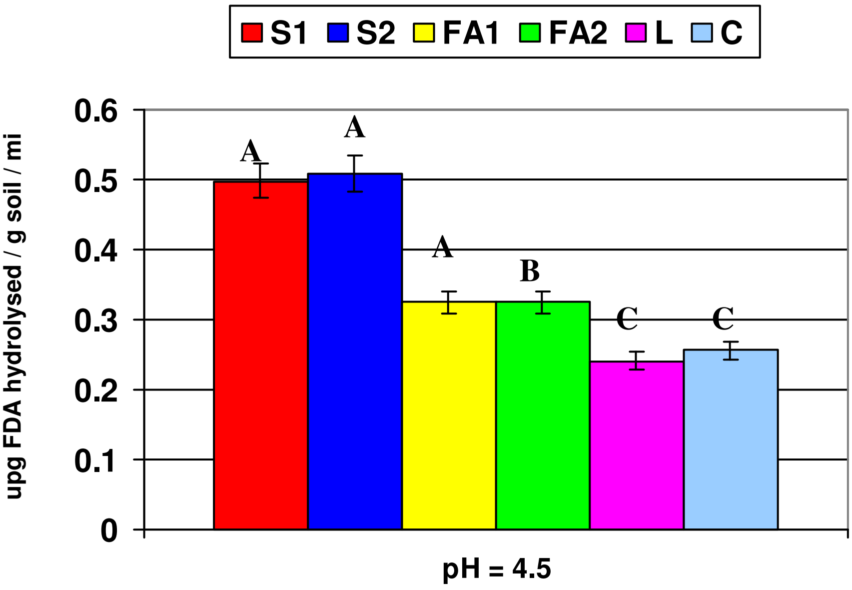


Figure 4: Mean microbial activity of the ameliorated soil with the lowest pH$_{(H2O)}$ *of 4.5.*

Rhizobium nodulation

With respect to nodule development on *M. sativa* roots, (Figure 5) higher nodule counts (total) were observed for both the SLASH treatments [S1 and S2] and the optimum class F fly ash treatment [FA1], as compared to the untreated control [C] and the conventional lime treatment [L] (Figure 5). This method was used as an assessment of whether soil conditions had improved enough to ensure successful inoculation.

It is interesting to note from Figure 6 that a higher *Rhizobium* nodulation was observed for the SLASH and class F fly ash ameliorated soils and that these results were related to the higher root mass produced on these ameliorated soils. It is evident from the data that the lower application of both fly ash and SLASH tended to have a depressing effect on the *Rhizobium* nodulation.

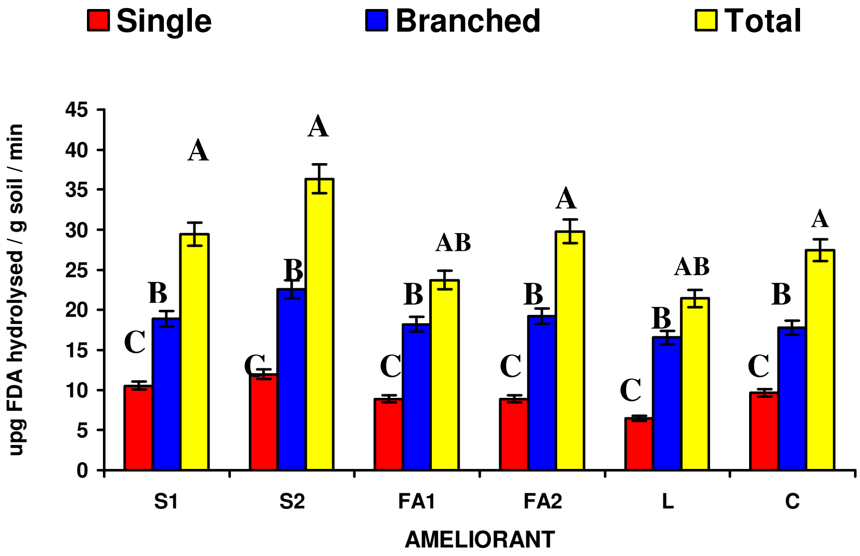


Figure 5: The mean quantity of *Rhizobium* nodulation in soils treated with different soil ameliorants.

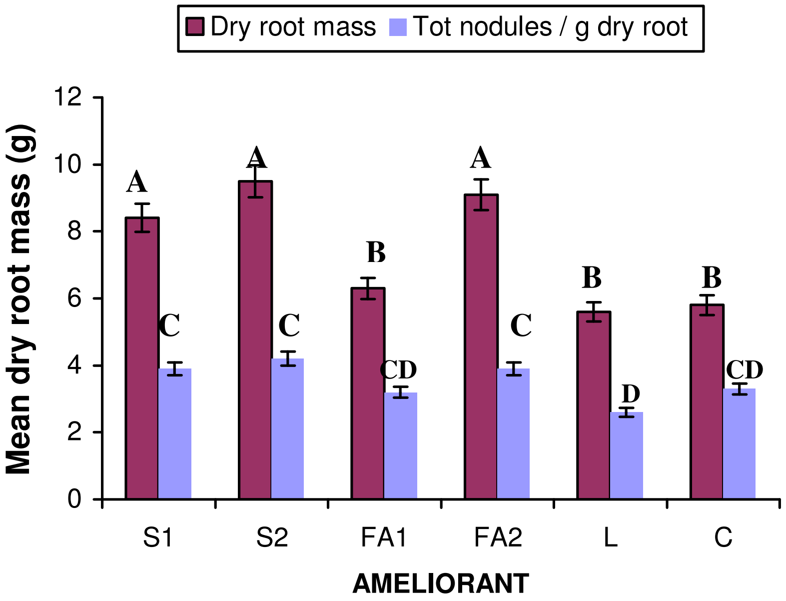


Figure 6: *Rhizobium* nodulation in relation to root biomass for ameliorated soils

With respect to the analyses, which were conducted, it is evident that the soil ameliorants based on class F fly ash resulted in significant changes in soil physical properties, such as texture, bulk density, hydraulic conductivity and water infiltration rate as well as, plant growth properties, such as root biomass, and, finally, relevant soil microbiological properties.

CONCLUSION

SLASH and class F fly ash have the potential to improve soil physical and microbiological properties. Soil texture was one of the characteristics that were modified significantly by these ameliorants, by increasing the silt fraction of the soil by as much as 143%. The increased silt fraction obtained by the addition of soil ameliorants based on class F fly ash, also improved the bulk density of the soil. The class F fly ash ameliorant was overall the best ameliorant with respect to its most significant affect on the rate of water infiltration into the experimental soil, increasing this by as much as 60%. This can possibly be ascribed to a 26% lower soil hydraulic conductivity, caused by the class F fly ash. For optimal crop production good soil conditions are required to ensure a healthy and well-developed root system.

Root biomass data were correlated with improved soil physical parameters, with an improved root biomass (of up to 74 – 82 %) where the class F fly ash based soil ameliorants were used. This was true of the SLASH ameliorant, which had the additional benefit of macronutrients in the organic component (sewage sludge). The effect that SLASH had on biomass enhancement emphasizes the importance of including organic materials, to provide the essential nutrients required for plant growth. By improving soil conditions, both chemically and physically, it was also possible to ensure an improvement in microbiological activity. The change in soil pH and soil texture, mainly as a result of the addition of class F fly ash, can - together with the organic matter introduced by the sewage sludge - help create a better soil environment for an increase in microbial activity. To date, conventional liming and fertilization has been the preferred method of ameliorating degraded soils, but this often necessitates annual applications and is not necessarily sustainable, because it's effect is mainly chemical in nature.

Agricultural, municipal and industrial by-products are often rich sources of nutrients or organic matter, that can be beneficially, utilized for crop production and to improve the physical, chemical or microbiological properties of relatively inert soils. These materials can be co-utilized, or combined, so that the materials are more easily applied, to provide a more complete/balanced nutrition, or to enhance soil condition, as well as the economic, or environmental value of these individual by-products.

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