Reclaiming acidic, infertile and unstable soils with urban and industrial byproducts by improving chemical properties and enhancing plant growth.

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Abstract
Coal mining impacts large areas of agricultural land in South Africa. To mitigate such impacts, it is imperative to restore the once productive soils to the best possible condition. To achieve this, high costs are associated with conventional rehabilitation methods and these are, moreover, often not sustainable. The challenge is to find alternative amendments, which will ensure sustainable rehabilitation. The University of Pretoria, in cooperation with Eskom TSI, has conducted a series of trials over the past seven years, to demonstrate the feasibility of using class F fly ash and organic waste materials to amend acidic and infertile substrates. Pot and field trials have demonstrated that these amendments improve dry matter production, basal cover, botanical composition and soil chemical properties. To ensure a stable soil environment it is necessary to establish deep-rooted sustainable vegetation. Results have shown that fly ash / organic mixtures and fly ash improved root development substantially, which stabilized the soil and improved the nutrient and water use efficiency of plants, ensuring healthy and productive plants. The productive utilization of waste products is also important in ensuring a sustainable environment.

INTRODUCTION

Coal mining and agriculture are large industries in South Africa. They impact extensive land areas, and often compete for the same land. The surface mining of coal seriously damages the surface soil, local flora and fauna. Mining wastes viz. overburden, discards and mine effluents, have also created land degradation problems. To date, it has been common practice to lime and fertilize these soils to revegetate the area. This process is normally, very costly, because large amounts of lime and fertilizer are needed to create a sustainable system. The major problem in such a system is that when fertilization is stopped, the production and cover on more marginal sites declines .

South Africa also experiences problems with rehabilitating gold mine tailings. Many of these tailings are situated in close proximity to residential areas, and it remains a difficult task to stabilize these dumps with vegetation, to prevent dust pollution and erosion problems. Large amounts of lime and fertilizer are also used to rehabilitate these areas, but are often not sustainable. The challenge is thus to find alternative methods to which will be sustainable.

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). Land application of coal combustion wastes and biosolids, particularly fly ash either by itself or in a mixture with sewage sludge may offer a sensible alternative to current landfill or dump disposal and thereby serve as a source of micro and macro nutrients essential for plant growth. (Truter, 2002; Norton et al, 1998). The benefits are that these nutrients will be released over time. This could possibly improve sustainability. The University of Pretoria in cooperation with Eskom TSI has over the past seven years conducted a series of trials which have demonstrated the feasibility of using alkaline class F fly ash from the Lethabo coal fired power station to make sewage sludge safe for agricultural and land reclamation purposes. This mixture, known as SLASH, is characterized

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by the elimination of odor problems, the immobilization of possible metal contaminants, and the pasteurization of disease organisms. It has also been used successfully to improve soil acidity and fertility. (Rethman et al, 2000 a,b; Rethman and Truter, 2001; Truter and Rethman, 2001).

MATERIAL AND METHODS

Pot trial

A study was conducted to evaluate how *Cenchrus ciliaris* (a grass susceptible to acid soil conditions) would perform on different substrates treated with three different levels of fly ash, fly ash / sewage sludge mixture and dolomitic lime . This study also indicates the effect of treatments on chemical properties of the soil. All treatments were compared to a control, which received no treatment. Ten treatments were replicated six times and on three different substrates. The three levels were made up of an optimum level of each material, an optimum level plus 33% and optimum level less 33%. The three substrates used were a mine cover soil, a soil impacted by acid mine drainage (AMD) and gold mine tailings.

The pot trial commenced 24 months ago, with a period of 12 months for treatments to stabilize in the different substrates. *Cenchrus ciliaris* seedlings were then planted into the different substrates. During the growing season, four harvests were taken and the dry matter production determined. An initial soil analysis was taken before planting of the grass, and a final analysis was done after the last harvest. When the pot trial was complete, a root study was conducted to determine the effect of the treatment on the root development in the different substrates. The roots had been sieved and washed and the root mass was measured. Following the good results obtained in the pot trial, the study was expanded to a field trial on a surface mine in the Mpumulanga Province.

Field Trial

The field trial consisted of the same treatments used in the pot trial with five replications. The calculated optimum level of fly ash, sewage sludge/ fly ash mixture and lime for the field trial was 50 tons ha^{-1}, 166 tons ha^{-1} and 10 tons ha^{-1} respectively. The standard mine treatment (SMT) was four tons of agricultural lime, 65 kg N ha^{-1}, 203 kg P ha^{-1} and 134 kg N ha^{-1}. In the 2nd season the standard mine treatment only received 100 kg N ha^{-1}. All the treatments were applied to the mine cover soil placed on top of the leveled mine spoil during the rehabilitation process. The treated soil was planted to a grass / legume mixture used by the mine, consisting of an annual nurse crop *Eragrostis teff*, perennial grasses such as *Chloris gayana* (Rhodegrass), *Cynodon dactylon* (Bermuda grass) and *Digitaria erianthra* (Smutsfinger) grass and the perennial legume *Medicago sativa* (Alfalfa). In the first growing season the basal cover was measured using the point bridge method, counting each strike on a tuft. Subsequently, the first harvest was taken. In the second growing season basal cover was measured again and this was followed by a botanical composition survey and finally the second harvest. Soils were analyzed for pH, P, K, Ca and Mg before the area was planted to the seed mixture, and then after every harvest.

RESULTS AND DISCUSSION

POT TRIAL

Dry Matter Production

Table 1 indicates that the ameliorant SLASH gave the highest dry matter production on the AMD impacted soil and gold tailings, whereas on the mine cover soil it had only a slightly better yield than the other treatments. The strong response on the more degraded soils, may be partially ascribed to the organic carbon which SLASH provides, in addition to the supply of all the necessary macro-nutrients required for plant growth, as well as some micronutrients which are supplied by the fly ash component. 8888

It is interesting to note that the fly ash and lime gave very similar results (Table 1) and this can possibly be because these amendments have similar effects on the soil environment, which contributes to better plant growth.

The root study provided some significant results as it is shown in Fig.1. It is clear that the SLASH treatment had a strong influence on root development, which is imperative for stabilizing erodable substrates, and the increase of water and nutrient use efficiency. The fly ash treatments for the AMD polluted soils gave up to 90% better root mass than the control treatment. The SLASH treatment, however, gave 230% better yields. The SLASH and fly ash treatments on the gold tailings material, delivered extremely high root masses of 4250% and 1125% more than the control, respectively.

Soil analyses

A) Mine cover soil

The results in Table 2 clearly indicate that alternative amendment strategies do provide some of the nutrients required for plant growth. SLASH unfortunately is often devoid of the important macronutrient K. This aspect requires further investigation, to determine how an additional source of K, such as animal manures, can be incorporated into such a mixture. The SLASH treatments all contributed to a higher soil P level in the mine soil. It is clear that the SLASH ameliorant also supplied large amounts of Ca, which can explain why this amendment improves the pH of the soils so remarkably (Fig. 2). It can be seen from Fig. 2 that the both the fly ash and the lime have similar effect on the soil pH.

B) AMD impacted soils

These soils, which have been impacted by acid mine drainage, are normally very acidic and infertile. Table 3 indicates that both the fly ash and the SLASH contribute to the P status of the soil relative to the control. The K level of the soil, however, showed some improvement when treated with SLASH. When compared to the previous soil, it can be seen that the more degraded soil evidently causes a different chemical reaction, making the K, which is in the ameliorant more available. From Table 3 it is notable that while the fly ash and the SLASH treatments improved the Mg status by approximately 100%, the dolomitic lime improved the Mg much more dramatically. Fig. 2 shows clearly how the SLASH improved the pH significantly. This can, however, be a problem because the change to an alkaline condition, could have a negative effect on the germination of certain seeds planted in these amended soils. This dramatic increase in soil pH can possibly be the result of too high applications of SLASH to the soil. The neutralizing ability of the soil ameliorant SLASH has proven itself. Both the fly ash and the lime components of the SLASH are responsible for the increase in pH. Fly ash used in this experimental trial had a neutralizing value of 20%, but when combined with the CaO and sludge, it is estimated that the neutralizing value of the mixture was approximately 30-40% of that of lime.

C) Gold tailings

The results in Table 4 are very similar to those of the AMD polluted soil. It is clear that both the SLASH and fly ash improved the P status by 100% or more. These levels will not, however, necessarily support plant growth for too long. With respect to the K status, both fly ash and lime improved the levels, but not to the extent that SLASH did. The Ca levels of the tailings were initially very high and the increase of these levels in the SLASH amended soils indicated that the inclusion of CaO in the SLASH mixture contributed to the high Ca content because the fly ash treatment's Ca levels weren't different from the control. The pH of gold tailings is normally very low, and will often not sustain productive vegetation. It is noted from Fig. 2 that the SLASH undoubtedly improved the pH. This improvement in pH is also reflected in the growth enhancing effects of SLASH treatments. This pH stimulates the development of plant roots and ultimately improves the nutrient use efficiency as well as the water use efficiency of the plants.

FIELD TRIAL

Plant measurements

The field trial was an expansion of the pot trial to determine if the excellent results obtained in the pot trial would have application in a more practical situation. Good results in the field would supply the motivation to investigate the more serious situations which the mines encounter.

These mine soils although relatively fertile are normally very acidic. This stunts the growth of any plant susceptible to an acid soil environment, because the root cannot develop properly to support aboveground plant growth. From the results presented in Fig. 3, it can be seen that in the 1st season, which was dominated by the nurse crop *Eragrostis teff*, the SLASH treated soils had approximately 600% better cover than the control and the fly ash treated soil had a 200% higher basal cover than the control. The standard mine treatment also had a much lower cover than the SLASH and fly ash treated soils. In the second growing season better results were obtained. Although the SLASH treated soils still had the best cover, the fly ash and lime treatments had improved.

The dry matter production in both growing seasons, as shown in Table 5 illustrates that the fly ash treated soils produced slightly more dry material than some of the SLASH treated soils, lime treated soils, control and the standard mine treatment. In the second growing season more or less the same trend was evident with the fly ash treated soils still maintaining a better yield than the lime, control and standard mine treatments. The higher SLASH treatment gave an indication that the application rate could possibly have been too high, as it had a depressing effect on the plant production when it is compared to the lower SLASH treatments.

Soil Analyses

It is evident from the soil analyses, that both the SLASH and fly ash treatments improved the P and K status of the soils 12 months after the application of treatments. The P levels were close to the recommended amounts necessary for vigorous plant growth, whereas the K levels were still well below the recommended amount for most crops. In Fig. 4 it can be seen that the soil pH was dramatically improved by the SLASH treatments relative to the control, whereas the fly ash and lime treatments improved the soils pH by approximately one pH unit. This improvement in pH is a confirmation of the results obtained in the pot trials. The increased pH of the SLASH treated soils once again supports the hypothesis that the application rate of SLASH needn't be so high because it has a much higher neutralization value than 20-30% originally accepted.

Similar results were obtained 18 months after the initial treatment. It can be seen from Table 7 that both the P and K levels had increased slightly, indicating that both the fly ash and SLASH treatments have the ability to release nutrients slowly.

Fig. 4 shows that the pH of the mine soil had been improved by all fly ash and lime treatments by at least one pH unit relative to the control. The SLASH treated soils had, however, declined to a more favorable level, which can be beneficial to plant growth. Both the fly ash and lime maintained a good pH, and thereby creating a suitable soil environment for plants to utilize the elements present in the soil.

CONCLUSION

Mine soils and mining wastes are generally lower in fertility and are more acidic than natural top soils and will benefit from the addition of organic wastes and an amendment with neutralizing potential. A variety of organic waste materials are available for this purpose. In particular, municipal biosolids are freely available. Animal manures can also serve as a source of organic material and certain essential macro-nutrients, such as K, which is often lacking in biosolids. The fly ash treated soils have also given excellent results in terms of improved pH, indirectly stimulating the growth of plants. When considering the establishment of different land capability classes, the fly ash treatment could possibly be considered as a soil amendment rather than a plant growth enhancer.

These waste materials, unfortunately, vary greatly in nutrient content, trace metals and liming potential, and these factors can affect both revegetation success and the environmental impact of reclamation.

It is, therefore, imperative to combine careful analysis of both the organic material and the mine soil to which it is to be applied. The pH of the site must be controlled to limit heavy metal mobility and insure long-term plant community vigor, and site management. To reclaim a degraded soil is a major challenge, and is usually a very expensive process and it is difficult to establish a sustainable system. The problems that many countries face, in terms of waste disposal, could possibly become solutions for many of the problems experienced in reclaiming mined soils.

The pot and field trials discussed in this paper indicate that there is definitely a potential for using waste products, or mixtures thereof, such as SLASH and similar waste mixtures to reclaim degraded soils. From previous work done on acidic agricultural soils, the residual effect of SLASH has been measured for up to three years. It is expected that SLASH will have the same residual effect on the more acidic soils, and this will determine how sustainable a system will be when it is used in a rehabilitation programme.

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TABLES

Table 1: The influence of different soil amendments on the mean dry matter production for four harvests of *Cenchrus ciliaris* on different substrates.

Treatment	**Mine cover soil**	**AMD impacted soil**	**Gold tailings**
	g/plant	g/plant	g/plant
Fly ash (Opt - 33%)	9.07	7.06	0.00
Fly ash	9.21	6.74	0.23
Fly ash (Opt +33%)	9.84	7.19	4.84
SLASH (Opt –33%)	9.78	11.45	7.46
SLASH	11.05	13.06	7.77
SLASH (Opt +33%)	11.79	14.93	8.61
Lime (Opt –33%)	7.99	6.07	0.00
Lime	7.88	6.13	0.58
Lime (Opt +33%)	8.11	6.57	1.80
Control	7.52	5.60	0.00

Table 2: The influence of different soil amendments on the chemical properties of a mine cover soil

Treatment	P	Ca	K	Mg
	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}
Fly ash (Opt - 33%)	7.1	211.7	14.7	28.2
Fly ash	10.1	293.7	17.3	35.3
Fly ash (Opt +33%)	13	304.7	15.7	34.8
SLASH (Opt –33%)	13.1	1957.8	17.2	26.3
SLASH	35.8	2395.3	18.8	32
SLASH (Opt +33%)	15	3046.3	18.8	31.5
Lime (Opt –33%)	2.4	293.5	16	79.8
Lime	6.5	274.5	27.5	96.2
Lime (Opt +33%)	1.3	272.7	16.7	122.3
Control	2	149.7	18.2	20.8

Table 3: The influence of different amendments on the chemical properties of a AMD impacted soil

Treatment	P	Ca	K	Mg
	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}
Fly ash (Opt - 33%)	12.6	419.7	15	48.2
Fly ash	17.1	532.2	14.8	68.2
Fly ash (Opt +33%)	28.5	746.5	15.7	70
SLASH (Opt –33%)	13.7	3958.7	24.2	43.8
SLASH	10.6	4471.7	26.8	52
SLASH (Opt +33%)	4	4440.2	27.7	50
Lime (Opt –33%)	1.1	585.7	15.8	170.8
Lime	1	495.2	15.7	188.3
Lime (Opt +33%)	1.1	729	15.3	289.2
Control	5.3	259.8	14.8	25.3

Table 4: The influence of different amendments on the chemical properties of gold tailings

Treatment	P	Ca	K	Mg
	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}
Fly ash (Opt - 33%)	3.5	2574	2	368.7
Fly ash	2.9	2969.8	4.8	308.3
Fly ash (Opt +33%)	3.6	2313.7	3.2	292.2
SLASH (Opt –33%)	3.8	5368.2	61.2	196.8
SLASH	2.4	5157.7	100.2	153.8
SLASH (Opt +33%)	1.2	6155.5	151.8	110.5
Lime (Opt –33%)	0.5	1993.3	9.3	290.5
Lime	0.4	2297	7.2	326.5
Lime (Opt +33%)	0.5	2445	17.5	309.7
Control	0.7	2189.6	2.2	469.3

Table 5: The influence of different amendments on the dry matter production on the mine cover soil in the field

Treatment	1st Harvest	2nd Harvest
	Eragrostis teff	*Chloris gayana*
	tons ha^{-1}	tons ha^{-1}
Fly ash (Opt - 33%)	3.90	13.6
Fly ash	4.98	12.6
Fly ash (Opt +33%)	4.11	12.9
SLASH (Opt –33%)	4.24	12.3
SLASH	3.80	16.0
SLASH (Opt +33%)	3.19	10.6
Lime (Opt –33%)	3.31	8.5
Lime	4.02	8.4
Lime (Opt +33%)	3.65	8.4
Control	2.33	6.8
Standard mine treatment	2.48	8.7

Table 6: The influence of different amendments on the chemical properties of a mine cover soil 12 months after soils had been treated.

Treatment	P	K	Ca	Mg
	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}
Fly ash (Opt - 33%)	22.68	25.2	370.8	35
Fly ash	29.76	27.6	454.8	39.6
Fly ash (Opt +33%)	38.1	21	514.4	49
SLASH (Opt –33%)	31.44	35	3388.6	43.2
SLASH	24.6	32	4146.2	56.4
SLASH (Opt +33%)	25.58	33.6	4344.6	53.4
Lime (Opt –33%)	4.32	25	287.8	102.8
Lime	2.54	18.6	408.4	139
Lime (Opt +33%)	3.12	18.4	370.6	129.2
Control	3.64	20.2	123.6	12.2
Standard mine treatment	2.45	45.6	131.5	11.9

Table 7: The influence of different amendments on the chemical properties of a mine cover soil 18 months after treatment.

Treatment	P	K	Ca	Mg
	mgkg^{-1}	Mgkg^{-1}	mgkg^{-1}	mgkg^{-1}
Fly ash (Opt - 33%)	22.46	32.6	367.2	34
Fly ash	30.18	36.6	427.4	36.8
Fly ash (Opt +33%)	34.12	44	485	42.2
SLASH (Opt –33%)	37.54	48	3064	45.8
SLASH	38.22	43.2	3649.2	53
SLASH (Opt +33%)	37.94	47	4087.8	70.6
Lime (Opt –33%)	2.68	29.6	263.8	98.4
Lime	2.5	25.8	351.8	106.4
Lime (Opt +33%)	1.86	25	375	124.4
Control	2.42	31.8	125	14.8
SMT	1.02	73.4	128.6	11

FIGURES

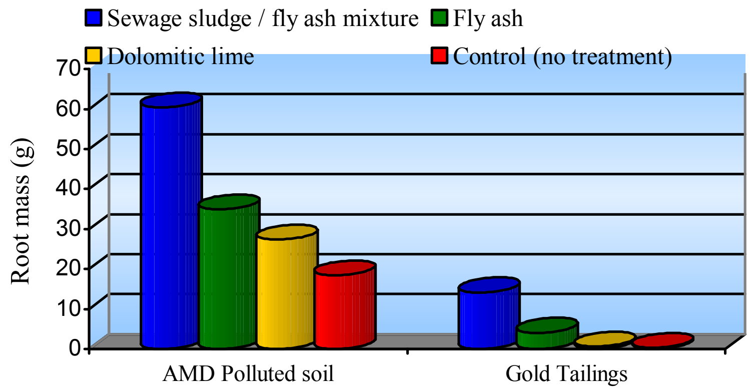

Figure 1: Ameliorating effect of waste products and lime on root mass of *Cenchrus ciliaris*

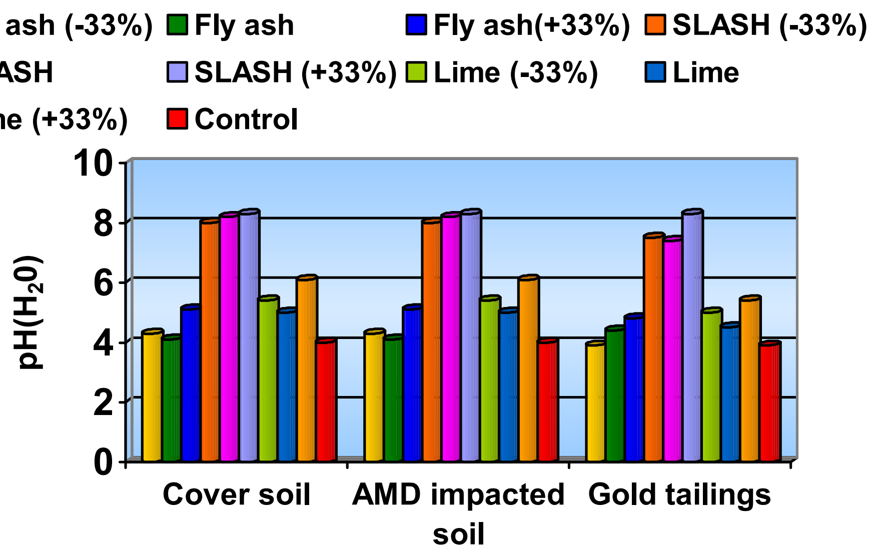

Figure 2: The effect of different treatments on the pH of three substrates

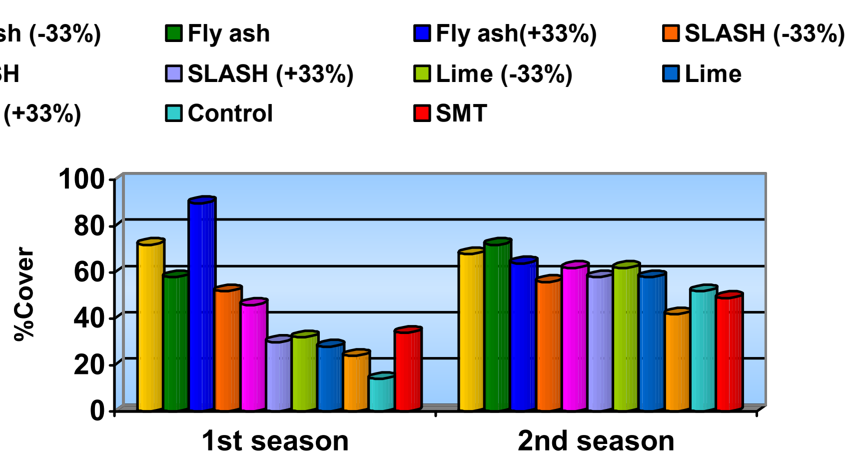

Figure 3: Basal cover measurement of two seasons after treatment application

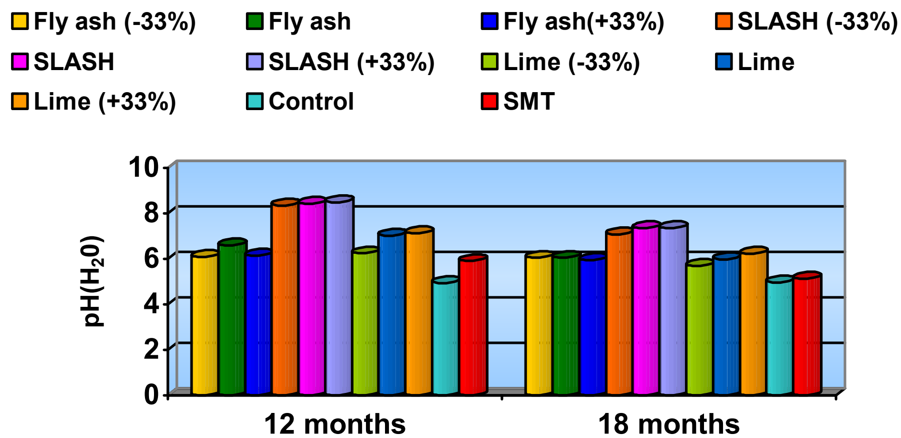

Figure 4: The effects of different treatments on the pH of mine cover soil in the field trial 12 and 18 months after treatment application.