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CHAPTER 4

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Reclaiming degraded mine soils and substrates with domestic and industrial by-products by improving soil chemical properties and subsequently enhancing plant growth: A greenhouse study

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Abstract

The South African mining industry has been the backbone of the country's economy for much of the past century. Mining has, however, often caused the degradation of productive soils. The amendment of these soils is often very expensive and often not sustainable. The University of Pretoria in co-operation with Eskom TSI, has over the past ten years conducted a series of trials to determine the feasibility of using alkaline class F fly ash (from the coal-based Lethabo power generating facility) and organic materials to ameliorate acidic and infertile soils and substrates. In this investigation pot trials were conducted to measure and monitor the effect of different ameliorants on dry matter production and on the chemical properties of soils and substrates. Based on the results obtained in these pot trials, it was concluded that fly ash and fly ash/organic material mixtures improved dry matter production as well as the soil pH, ammonium acetate extractable K, Ca and Mg and Bray 1 extractable P levels. All parameters measured were significantly influenced by the fly ash and fly ash / organic material mixtures. Fly ash and fly ash / organic ameliorated soils delivered approximately 850%, 266% and 110% higher dry matter production on gold mine tailings, AMD impacted soil and acidic mine cover soil, respectively, relative to the control treatments. With respect to soil chemical properties, the pH of AMD impacted soils was dramatically improved by 240% by the fly ash / organic mixture. An industrial byproduct such as fly ash, either by itself, or together with organic waste, can serve, therefore, as a soil ameliorant for the reclamation of surface mine land.

Key Words: acidic soils, fly ash, infertile soils, organic materials, soil ameliorants

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1. Introduction

Coal mining and agriculture are both important industries in South Africa. They impact extensive land areas, and often compete for the same land. The surface mining of coal seriously degrades the surface soil and 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 such impacted areas. This process is normally very costly because large amounts of lime and fertilizer are needed. A 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 reclaim these areas, but reclamation is often not sustainable. The challenge is thus to find alternative amelioration methods, 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 [11; 15]. Land application of coal combustion wastes and biosolids, particularly class F fly ash, either by itself or in a mixture with sewage sludge, may offer a viable alternative to current landfill or dump disposal. It may, thereby, serve as a source of micro- and macro-nutrients essential for plant growth [3;13]. The benefits are that these nutrients will be released over time. This could possibly improve sustainability. The University of Pretoria in co-operation with Eskom TSI has over the past ten 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 (60 % fly ash, 30 % sewage sludge and 10% unslaked lime on a wet matter basis), is characterized by the elimination of odour 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 [5; 6; 7; 13].

2. Experimental procedures

A study was conducted at the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level, to evaluate how *Cenchrus ciliaris* (an indigenous grass species sensitive to acid soil conditions) would perform on different substrates treated with three different levels of class F fly ash, fly ash / sewage sludge mixture and dolomitic lime. This study was also used to assess the effect of treatments on the chemical properties of the substrates. The three substrates used were a mine cover soil, a soil impacted by acid mine drainage (AMD) and gold mine tailings. Lime application rates were based on the buffering capacity of the substrates which were determined by using a $Ca(OH)_2$ titration solution. The mine cover soil had a $pH_{(H2O)}$ of 4.3, the AMD impacted soil a $pH_{(H2O)}$ of 3.4 and the gold mine tailings a $pH_{(H2O)}$ of 4.5. It was calculated, from the buffer curve, that the different substrates required the following amounts of dolomitic lime **[L Opt.]** to raise the pH of the soil to a $pH_{(H2O)}$ of 6.5, suitable for plant growth. The mine cover soil required 10 tons ha^{-1}, AMD impacted soil required 23 tons ha^{-1}, and gold mine tailings required 19 tons ha^{-1} of dolomitic lime as shown in Tables 1-3. The class F fly ash and SLASH treatments were compared to the aforementioned control and three lime treatments. The three levels of class F fly ash, SLASH and dolomitic lime were made up of an optimum **(Opt.)** level of each material, an optimum level plus 33% **(Opt. +)** and optimum level less 33% **(Opt. -)** as shown in the Tables 1-3.

Table 1: Treatment levels applied to the mine cover soil with a basal $pH_{(H2O)}$ of 4.3

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	*Opt.*	*Opt. +*	*Opt. –*
Control	0	0	0
Dolomitic Lime	10	13	7
Class F fly ash	50	67	34
SLASH	167	217	117

Table 2: Treatment levels applied to the AMD impacted cover soil with a basal $pH_{(H2O)}$ of 3.4

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	*Optimum*	*Opt. +*	*Opt. –*
Control	0	0	0
Dolomitic Lime	23	31	16
Class F fly ash	116	154	78
SLASH	387	514	259

Table 3: Treatment levels applied to the gold mine tailings with a basal $pH_{(H2O)}$ of 4.5

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	***Optimum***	***Opt. +***	***Opt. –***
Control	0	0	0
Dolomitic Lime	19	25	13
Class F fly ash	93	124	62
SLASH	310	414	207

The optimum level of fly ash **[FA Opt.]** was based on reports in the literature that class F fly ash had a $CaCO_3$ equivalent of 20% [13]. This resulted in a fly ash requirement of approximately five times the amount of dolomitic lime required to raise the $pH_{(H2O)}$ to a level of 6.5. The optimum level plus 33% **(Opt. +)** and optimum level less 33% **(Opt. -)** treatments were included to determine if the $CaCO_3$ equivalent of South African class F fly ash differed from the 20% guideline suggested in the international literature. The optimum level of SLASH **[S Opt.]** was calculated using the ratio of fly ash, sewage sludge and lime (6:3:1 on a wet basis), which is used in the process of making SLASH [8]. All soil ameliorants were only applied once off at the beginning of the trial and monitored over time to establish the residual effects of ameliorants.

All treatments were compared to a control **[C]**, which received no treatment, to clearly illustrate positive or negative effects. The ten treatments were replicated six times on three different substrates in a completely randomized design.

The pot trial was conducted over a period of 24 months. After a period of 12 months for treatments to stabilize in the different substrates, five *C. ciliaris* cv. Molopo seedlings were planted into 10 L pots of the different substrates. The growth was harvested every 45 days during the growing season of September 2001 – June 2002 (Figure 1).

Figure 1: *Cenchrus ciliaris* plants on three different substrates

During the growing season, four harvests were taken and the dry plant biomass was determined, by drying the material at 65 ^{o} C for 48 hours. Initial soil analyses were conducted before treatment application, then 12 months later, after the stabilization period (before the planting of the grass) with final analyses done after the last harvest, 24 months after the onset of the trial. The soil chemical analyses entailed, $pH_{(H2O)}$, P (Bray 1 Method) and K, Ca, and Mg (1:10 Ammonium Acetate Extraction Method). When the pot trial was complete, a destructive root study was conducted to determine the effect of treatments on the root development in the different substrates. The roots were sieved and washed and the dry root mass determined.

2.1 Statistical analyses

All dry matter production data and soil analyses were statistically analysed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS [9]. LSD's were taken at $P \leq 0.05$.

3. Results and discussion

This study entailed the measurement of both plant and soil parameters. Plant dry matter production data served as an indication of the benefits of alternative ameliorants on plant growth. Root biomass data was measured to obtain what affect alternative ameliorants had on root development, ultimately ensuring enhanced plant growth. Basic soil chemical analyses were conducted to try and explain the basic causes of changes in root development and ultimately plant production.

3.1 Dry Matter Production

Tables 4-6 clearly show that the ameliorant SLASH resulted in the most significant increases in dry matter production on all three substrates. 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 macro-nutrients required for plant growth, as well as some micronutrients, which are supplied by the fly ash component. It is interesting to note that the lime treatments did not have as significant an effect on the dry matter production. This can possibly be because dolomitic lime has a relatively slow reaction period and after an initial effect the reactivity of the lime decreased over time.

Table 4: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* planted on cover soil.

Treatment	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	Mean
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	9.4 $_b$ (+/-3.8)	15.0 $_a$ (+/-3.6)	13.0 $_a$ (+/-3.4)	7.0 $_{cd}$ (+/-2.7)	**11.1** $_b$
S Opt. +	13.9 $_a$ (+/2.5)	16.2 $_a$ (+/-3.5)	13.8 $_a$ (+/-3.4)	15.6 $_a$ (+/-3.9)	**14.9** $_a$
S Opt. -	11.2 $_a$ (+/- 2.2)	10.6 $_b$ (+/-1.1)	8.4 $_b$ (+/-2.0)	9.6 $_b$ (+/-1.1)	**10.0** $_b$
FA Opt.	8.3 $_b$ (+/- 2.4)	9.1 $_b$ (+/- 1.4)	10.2 $_b$ (+/-1.0)	9.3 $_b$ (+/-2.9)	**9.2** $_b$
FA Opt. +	11.0 $_a$ (+/- 2.4)	9.4 $_b$ (+/- 1.7)	8.7 $_b$ (+/- 1.7)	10.3 $_b$ (+/-1.8)	**9.9** $_b$
FA Opt. -	7.7 $_c$ (+/- 1.7)	10.8 $_b$ (+/- 1.9)	8.3 $_b$ (+/- 1.5)	9.1 $_b$ (+/-1.8)	**9.0** $_b$
L Opt.	8.5 $_b$ (+/- 1.6)	7.8 $_c$ (+/- 1.0)	6.5 $_c$ (+/- 1.2)	8.3 $_c$ (+/-1.1)	**7.8** $_c$
L Opt. +	8.9 $_b$ (+/- 2.0)	7.9 $_c$ (+/- 1.2)	7.1 $_c$ (+/- 0.9)	8.4 $_c$ (+/-1.5)	**8.1** $_c$
L Opt. -	6.9 $_c$ (+/- 0.6)	8.5 $_c$ (+/- 1.2)	7.2 $_c$ (+/- 1.3)	7.9 $_c$ (+/-1.7)	**7.6** $_c$
C	6.0 $_c$ (+/- 4.17)	8.1 $_c$ (+/- 5.4)	7.1 $_c$ (+/- 4.8)	6.8 $_d$ (+/-3.7)	**7.0** $_c$

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

The AMD impacted soil, which is the soil with the lowest soil pH of all the substrates evaluated, probably has the greatest limitation with respect to the availability of nutrients. With the significant increase in pH as a result of the class F fly ash and SLASH treatments, as shown in Figure 6, a higher availability of nutrients in soil can result, apart from the added benefit of nutrients supplied by the ameliorant itself. The high organic matter content of the SLASH ameliorant, due to the sewage sludge component, and the higher amounts of macro-nutrients in this ameliorant, are probably responsible for the significant increase in dry matter yield (Table 5) on this substrate.

Table 5: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* planted on AMD impacted soil.

Treatment	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	Mean
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	14.9 $_a$ (+/-2.7)	13.5 $_a$ (+/-1.8)	12.7 $_a$ (+/-1.5)	11.3 $_a$ (+/-1.9)	**13.1** $_a$
S Opt. +	17.9 $_a$ (+/-1.2)	15.2 $_a$ (+/-1.3)	13.7 $_a$ (+/-2.5)	12.9 $_a$ (+/-3.2)	**14.9** $_a$
S Opt. -	15.3 $_a$ (+/-3.9)	12.9 $_a$ (+/-1.3)	9.6 $_b$ (+/-2.5)	8.2 $_b$ (+/-3.2)	**11.5** $_b$
FA Opt.	9.2 $_b$ (+/-1.1)	7.9 $_b$ (+/-0.3)	7.4 $_b$ (+/-0.7)	6.1 $_c$ (+/-0.9)	**7.7** $_c$
FA Opt. +	10.1 $_b$ (+/-1.1)	8.2 $_b$ (+/-1.2)	7.5 $_b$ (+/-0.9)	7.1 $_{bc}$ (+/-0.9)	**8.2** $_c$
FA Opt. -	9.3 $_b$ (+/-2.1)	8.5 $_b$ (+/-1.7)	7.1 $_{bc}$ (+/-1.6)	7.2 $_b$ (+/-1.5)	**8.0** $_c$
L Opt.	7.1 $_c$ (+/-1.4)	6.4 $_c$ (+/-1.6)	5.9 $_c$ (+/-1.2)	5.1 $_c$ (+/-1.2)	**6.1** $_{de}$
L Opt. +	7.4 $_c$ (+/-1.5)	6.9 $_{bc}$ (+/-1.1)	6.1 $_c$ (+/-0.8)	6.0 $_c$ (+/-0.8)	**6.6** $_d$
L Opt. -	7.7 $_c$ (+/-1.6)	6.3 $_c$ (+/-1.2)	5.3 $_{cd}$ (+/-0.7)	4.9 $_d$ (+/-0.8)	**6.1** $_{de}$
C	6.3 $_c$ (+/-4.4)	5.5 $_c$ (+/-3.8)	5.0 $_d$ (+/-3.6)	4.6 $_d$ (+/-3.3)	**5.4** $_e$

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

The gold mine tailings material, which had a similar substrate pH to the mine cover soil, was, however, a more inert material. This material had very low levels of certain macronutrients, which has a significant affect on the growth of plants. The dry matter production on the gold mine tailings increased by 697% on the SLASH treated soils (Table 6).

The gold tailings were chemically unbalanced and they lacked organic matter, which could have improved physical and microbiological characteristics, which would provide a friendlier soil environment for plant roots to develop and then ultimately have a beneficial affect on plant growth. It is once again noted that the SLASH ameliorant with its sewage sludge organic component, had a remarkable affect on the plant growth in this material (Table 6). The different SLASH treatments did not, however, differ significantly.

Although there was a trend for improved yields with increased levels of SLASH (7.5, 7.8 and 8.6 respectively) this result did not justify the higher levels of SLASH.

Table 6: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* on gold mine tailings.

Treatment	**1st Harvest**	**2nd Harvest**	**3rd Harvest**	**4th Harvest**	**Mean**
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	10.7 $_{a}$ **(+/-1.7)**	8.7 $_{a}$ **(+/-0.6)**	6.6 $_{a}$ **(+/-0.6)**	5.3 $_{a}$ **(+/-0.8)**	**7.8** $_{a}$
S Opt. +	11.2 $_{a}$ **(+/-1.6)**	9.3 $_{a}$ **(+/-1.6)**	7.3 $_{a}$ **(+/-1.0)**	6.4 $_{a}$ **(+/-0.9)**	**8.6** $_{a}$
S Opt. -	9.5 $_{a}$ **(+/-3.7)**	7.8 $_{a}$ **(+/-2.9)**	6.8 $_{a}$ **(+/-2.7)**	5.8 $_{a}$ **(+/-2.3)**	**7.5** $_{a}$
FA Opt.	4.7 $_{b}$ **(+/-1.3)**	3.8 $_{c}$ **(+/-1.0)**	2.9 $_{c}$ **(+/-1.4)**	2.4 $_{c}$ **(+/-1.4)**	**3.5** $_{bc}$
FA Opt. +	6.2 $_{b}$ **(+/-1.5)**	4.8 $_{b}$ **(+/-1.1)**	4.4 $_{b}$ **(+/-1.5)**	3.6 $_{b}$ **(+/-1.5)**	**4.8** $_{b}$
FA Opt. -	3.5 $_{c}$ **(+/-0.8)**	2.8 $_{c}$ **(+/-0.7)**	2.1 $_{c}$ **(+/-0.5)**	1.3 $_{cd}$ **(+/-0.4)**	**2.4** $_{c}$
L Opt.	2.3 $_{c}$ **(+/-0.7)**	1.5 $_{d}$ **(+/-0.7)**	1.1 $_{d}$ **(+/-0.7)**	0.7 $_{d}$ **(+/-0.3)**	**1.4** $_{de}$
L Opt. +	3.1 $_{c}$ **(+/-0.9)**	1.9 $_{cd}$ **(+/-0.6)**	1.6 $_{cd}$ **(+/-0.6)**	0.9 $_{d}$ **(+/-0.4)**	**1.9** $_{d}$
L Opt. -	2.1 $_{cd}$ **(+/-0.8)**	1.1 $_{d}$ **(+/-0.6)**	0.9 $_{d}$ **(+/-0.4)**	0.5 $_{d}$ **(+/-0.2)**	**1.2** $_{e}$
C	1.5 $_{d}$ **(+/-1.0)**	1.2 $_{d}$ **(+/-0.8)**	0.6 $_{d}$ **(+/-0.5)**	0.5 $_{d}$ **(+/-0.4)**	**1.0** $_{e}$

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

The class F fly ash, although not having as beneficial an effect as SLASH, did provide additional essential micro-nutrients for plant growth and had beneficial affects on soil physical and microbiological characteristics, as has been reported by Truter (2007) [14]. This can be seen in Table 6 where the dry matter production was increased by a maximum of 370% by class F fly ash.

3.2 Root biomass study

The root study also provided significant results as it is shown in Tables 7-9. It is clear that although the SLASH treatment had the strongest influence it was only marginally better than FA. Root development is vital for stabilizing erodable substrates, and for increasing the efficiency of water and nutrient use.

Table 7: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the mine cover soil

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	**Mean**	*SE(+/-)*
S Opt.	64.8	37.5	43.6	29	51.3	50.8	**46.2**$_a$	(9.5)
S Opt. +	54.5	49.1	56.8	29.1	40	37.9	**44.6** $_a$	(8.9)
S Opt. -	37.9	40.7	38.6	39.2	35.8	22.3	**35.8** $_b$	(4.5)
FA Opt.	43.5	39.9	53.1	34.3	24.1	37.8	**38.8** $_a$	(5.9)
FA Opt. +	72.9	34.9	36.3	38.2	34.8	27.9	**40.8** $_a$	(12.4)
FA Opt. -	63.3	41.9	58.7	26.1	39	43.6	**45.4** $_a$	(10.4)
L Opt.	44	22.1	30	35.2	40.6	32.5	**34.1** $_b$	(5.9)
L Opt. +	40	31.8	37.3	28.1	36.4	32.4	**34.3** $_b$	(3.6)
L Opt. -	37.9	22.1	25.3	35.9	34.1	30.3	**30.9** $_{bc}$	(5.0)
C	37.1	21.4	28	16.6	22.9	34.6	**26.8** $_c$	(6.46)

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

The class F fly ash treatments applied to AMD impacted soils gave up to 40% better root mass than the control treatment. The SLASH treatment, however, had 185 % better root development. This strongly significant increase can definitely be ascribed to the combined function of improving the soil pH with the class F fly ash component, and providing the plant roots with the heightened ability to utilize the abundant macronutrients provided by the sewage sludge component and the micronutrients from the class F fly ash component. The possible improvement of a microbial population by improving the soil or substrate environment by changing the soil pH, or just the addition of organic matter may, however, have had additive effects [14].

Table 8: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the AMD Impacted soil

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***Mean***	***SE(+/-)***
S Opt.	54.4	43	55.8	64.8	52.7	81.2	**58.7** $_{a}$	(9.6)
S Opt. +	56.9	50.4	87.7	50.2	81.4	92.3	**69.8** $_{a}$	(7.31)
S Opt. -	81.1	53.2	40.4	36	53.7	52.8	**52.9** $_{b}$	(9.8)
FA Opt.	44.3	36	19.4	27.6	32.7	17	**29.5** $_{c}$	(8.18)
FA Opt. +	45.1	37.6	29.7	36.6	31.8	26	**34.5** $_{c}$	(5.3)
FA Opt. -	54	18	38.6	14.4	25.6	23	**28.9** $_{cd}$	(11.6)
L Opt.	36	24.8	23.6	22.9	19.4	19.8	**24.4** $_{d}$	(6.65)
L Opt. +	52	24	18.6	24.7	31.3	21.5	**28.7** $_{cd}$	(8.65)
L Opt. -	30.4	31.4	34.2	13.6	30.8	31.8	**28.7** $_{cd}$	(5.03)
C	32	23.6	25.4	23.3	24.4	19	**24.6** $_{d}$	(2.7)

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

While the SLASH and fly ash treatments applied to gold tailings, delivered extremely high root mass differences, of up to (S Opt +) 6133% and (FA Opt +) 833% more than the control, respectively, the lime treatment improved root biomass by only 167%. These improvements justify any addition of material that contains either some nutrients or organic matter, or even a different textured ameliorant, which can change the soil conditions, chemically, physically or microbiologically.

Table 9: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the gold mine tailings

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***Mean***	*SE(+/-)*
S Opt.	15.8	11.7	10.3	17	13	10.9	**13.1** $_b$	(2.18)
S Opt. +	22.4	29.5	11.1	11.2	13.4	23.8	**18.7** $_a$	(6.7)
S Opt. -	20.1	12.2	3.1	9.6	12.3	7.6	**10.8** $_b$	(4.0)
FA Opt.	1.5	2.4	1.6	1.6	1.8	1.3	**1.7** $_c$	(0.37)
FA Opt. +	3.6	1.9	3.1	1.8	3.4	2.8	**2.8** $_c$	(0.56)
FA Opt. -	0.5	0.6	0.4	0.7	1.1	0.4	**1.5** $_{cd}$	(0.3)
L Opt.	0.5	0.7	0.7	0.4	0.5	0.4	**0.5** $_d$	(0.1)
L Opt. +	0.9	1	0.4	0.8	0.9	0.6	**0.8** $_d$	(0.2)
L Opt. -	0.7	1.0	0.5	0.8	0.9	0.6	**0.7** $_d$	(0.2)
C	0.3	0.3	0.3	0.2	0.4	0.4	**0.3** $_d$	(0.1)

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

To explain the significant response of plants, on these degraded soils and substrates, to the ameliorants, it is essential that soils be analysed chemically, physically and microbiologically. In this investigation emphasis was on, chemical analyses, which are presented and discussed, to illustrate the benefits of applying alternative soil ameliorants to degraded soils as compared to conventionally used ameliorants, or no amelioration (C).

3.3 Soil analyses

The beneficial effects of FA on plants are at least partly as a result of the adjustment of soil pH of an acidic soil or substrate, hence supplying deficient nutrients, resulting in improved crop growth [13]. Each substrate under investigation had a different nature and condition, and hence soil ameliorants reacted differently in different substrates. The trends evident from amelioration effects are, however, similar for most degraded soils as will be noted in the following section.

3.3.1 Mine Cover Soil

The mine cover soil, with an initial soil $pH_{(H2O)}$ of 4.3, was a mixture of approximately 10cm of topsoil, with organic matter and a viable seed bank, and an underlying B horizon soil layer deficient in certain nutrients. The topsoil is often diluted and acidic due to the acid generated in the coal-mining environment.

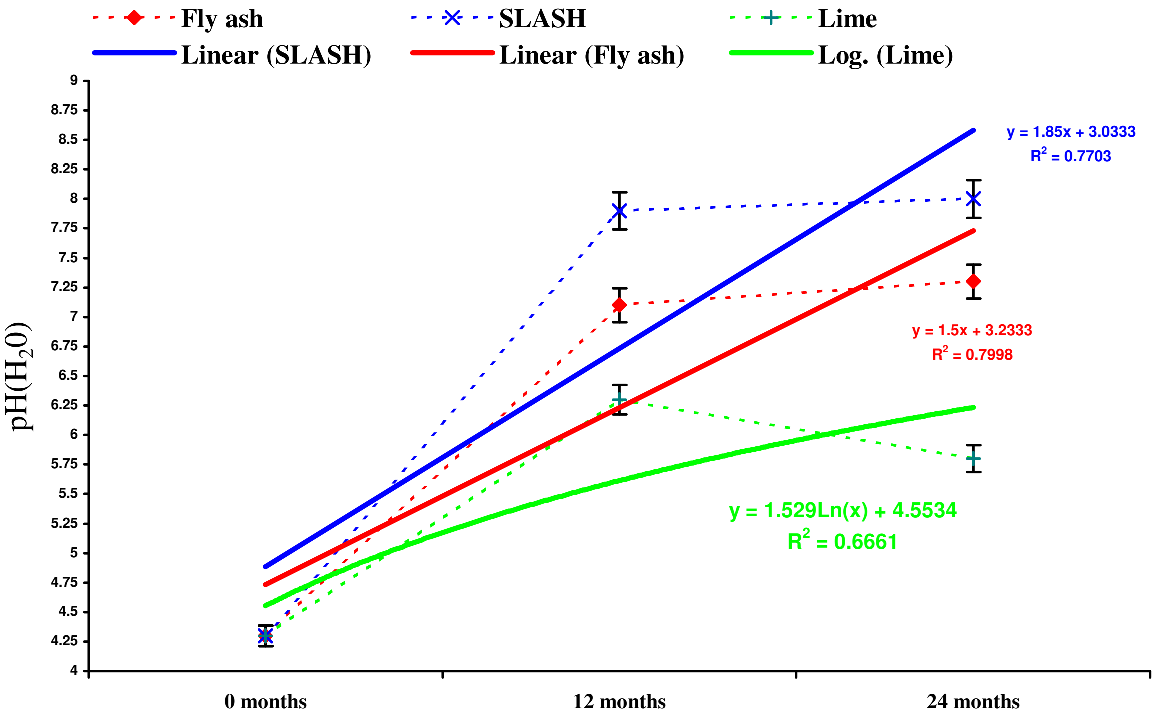

Figure 2: The comparative effect of three ameliorants (optimum levels) on the pH of a degraded mine cover soil over time.

In Figure 2, it is evident that both the SLASH and class F fly ash treatments had a strongly significant effect on the soil pH, raising it too much higher levels than was originally calculated. The calculation was based on the assumption that class F fly ash had only a 20% $CaCO_3$ equivalent, which would be sufficient to raise the soil pH to 6.5. The corrected pH of the soil, from 4.3 to approximately 7 for class F fly ash, indicates that class F fly ash may have a higher $CaCO_3$ equivalent than the 20%. The effect that SLASH had on the soil pH raising it to pH of 8.0 can be ascribed to the class F fly ash in addition to the CaO included in the SLASH mixture during processing. It is noted from

Figure 2 that the pH levels were at least maintained for 12 - 24 months by the class F fly ash and SLASH treatments and tended to increase, whereas, the pH of the lime treatment declined from 12 to 24 months. These results confirm the sustainability of such alternative ameliorants.

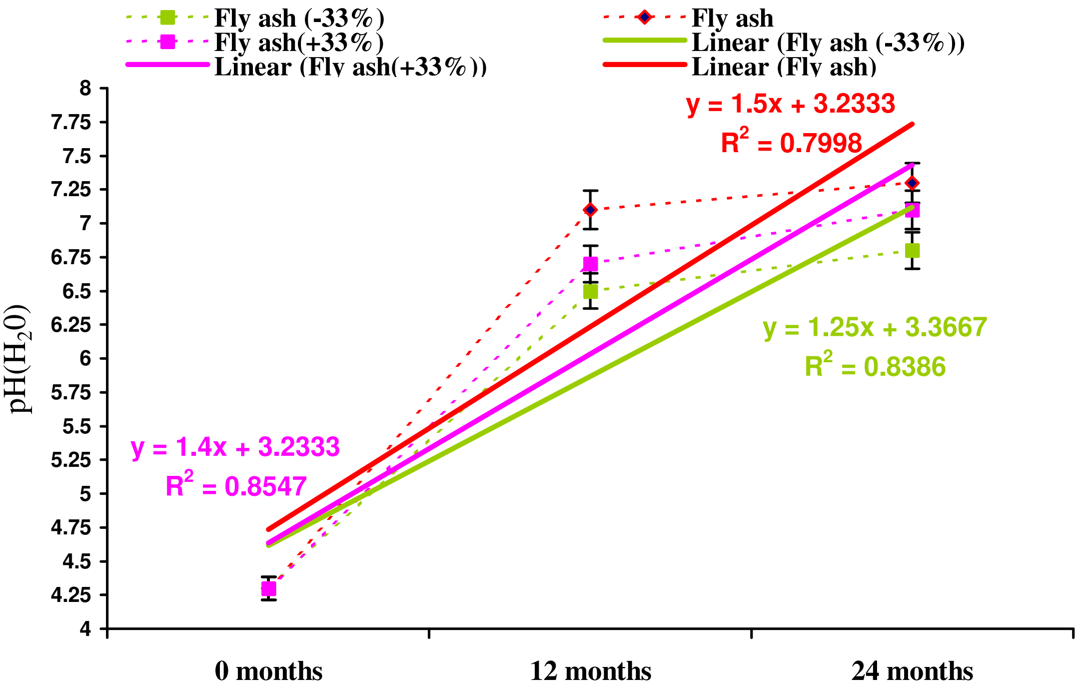

Figure 3: The effect of three different levels of class F fly ash on the pH of a degraded mine cover soil.

In Figures 3-5 the effect of different levels of fly ash, SLASH and dolomitic lime on the pH of the three substrates, is illustrated. It should be noted in Figure 3, that in the mine cover soil, the optimum level of fly ash had a more significant effect on soil pH, than the higher class F fly ash level, as had been expected. The assumption can possibly be made, as discussed in literature, that the reactive response of the soil ameliorant is also influenced by the cation exchange capacity (CEC). Soils with different cation exchange capacities will hence have a different reactive response to different soil ameliorants. This aspect requires further investigation, however, to substantiate this conclusion.

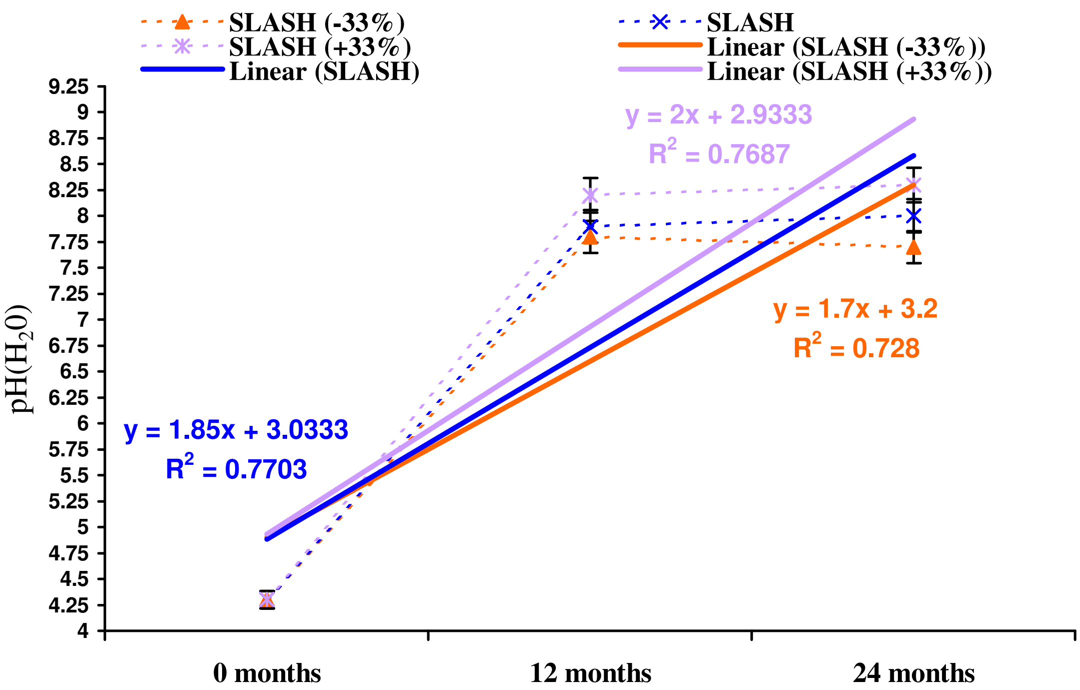

Figure 4: The effect of three different levels of SLASH on the pH of a degraded mine cover soil.

The significant affects of soil ameliorants on soil pH, as illustrated in many line graphs in this paper, clearly shows that this is not a short-term effect. Note that in the results presented, the affect that soil ameliorants have, has often decreased slightly over the period of 12 - 24 months. The dolomitic lime treatment has been the ameliorant with the highest drop in soil pH over the 12 – 24 month period. Previous research conducted by Truter (2002) [13], illustrated a similar long-term residual effect of the class F fly ash based treatments, which highlights the sustainability of using such ameliorants.

Figure 4 demonstrates that the different levels of SLASH had similar affects on the pH of the cover soil, with the increases correlated with the increase in the level of SLASH applied. The highest increase in soil pH of approximately 4 units is most significant, although, the optimum level of SLASH increased the soil pH by almost as much. This small difference between SLASH treatments, poses the question of whether the higher levels of SLASH can be economically justified.

The addition of lime to acidic degraded soils is the conventional method, and is very effective. The effect of lime, however, is limited to its affect on soil pH, with the addition of macro-nutrients being limited to Ca or Mg. Figure 5 illustrates that lime had a significant affect on the soil pH, raising it approximately 2 units. This affect, however, was not as prolonged, or as sustainable, as the other ameliorants. After a period of 12 months under cropping, the effect of lime declined markedly (Figure 5).

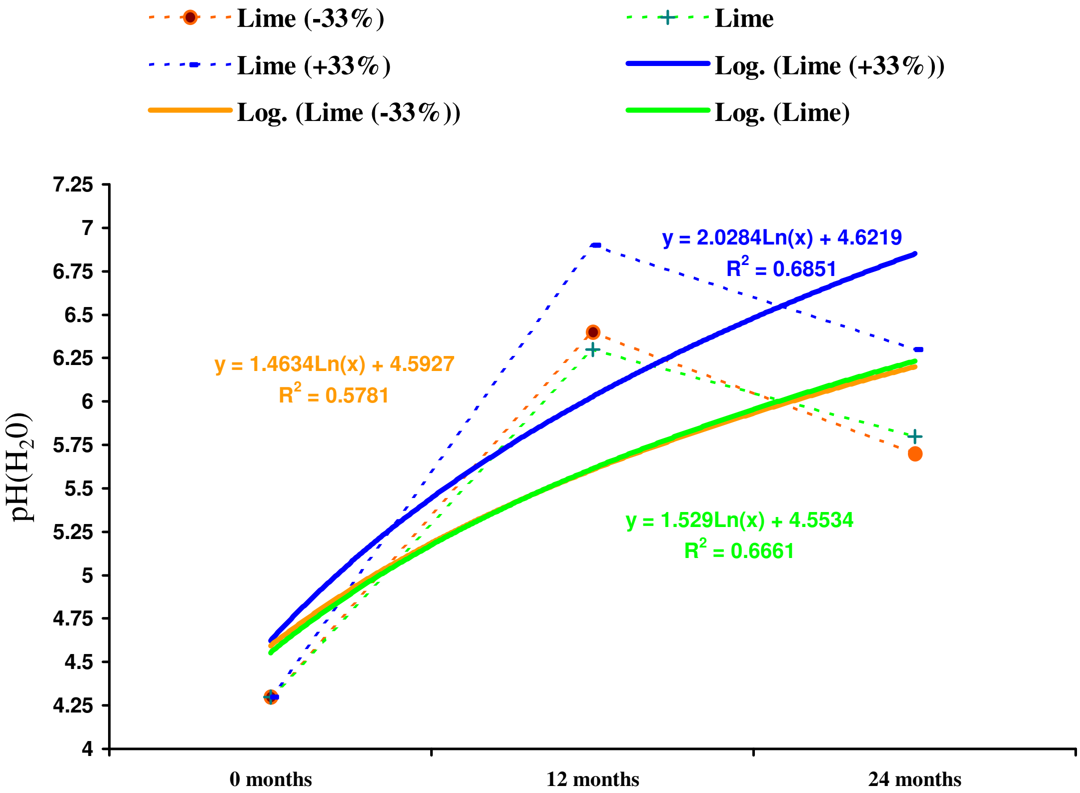

Figure 5: The effect of three different levels of agricultural dolomitic lime on the soil pH of a degraded mine cover soil.

With respect to important macronutrients (P, K, Ca and Mg) required for optimum plant growth, Tables 10-13 clearly indicates that the alternative ameliorant strategies can provide some of these nutrients. SLASH unfortunately is often devoid of the important macro-nutrient K (Table 11). This aspect, therefore, 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 higher levels of P in the mine soil. It is clear that the SLASH ameliorant also supplied large amounts of Ca, which could explain why this amendment improved the pH of the soils so markedly (Figure 4). The calcium levels of the mine cover soil were relatively low (Table 12), but with the addition of the different soil ameliorants these levels were raised significantly, especially by the SLASH treatments. The high amounts of Ca provided by the SLASH treatments are at least partly as a result of the CaO used in making SLASH.

Table 10: The influence of soil ameliorants on the phosphorus (P) content of a mine cover soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	27.4 $^{A}_{a}$ **(+/-2.7)**	19.7 $^{B}_{b}$ **(+/-3.4)**
S Opt. +	36.7 $^{A}_{a}$ **(+/-8.0)**	27.7 $^{B}_{a}$ **(+/-5.4)**
S Opt. -	21.0 $^{A}_{b}$ **(+/-5.8)**	14.6 $^{B}_{b}$ **(+/-4.3)**
FA Opt.	10.1 $^{A}_{bc}$ **(+/-1.2)**	7.2 $^{B}_{c}$ **(+/-1/0)**
FA Opt. +	13.0 $^{A}_{b}$ **(+/-1.9)**	8.7 $^{B}_{c}$ **(+/-1.6)**
FA Opt. -	7.1 $^{A}_{c}$ **(+/-0.8)**	5.3 $^{A}_{cd}$ **(+/-0.7)**
L Opt.	7.0 $^{A}_{c}$ **(+/-0.6)**	4.9 $^{A}_{cd}$ **(+/-0.4)**
L Opt. +	6.6 $^{A}_{c}$ **(+/-2.2)**	4.2 $^{A}_{d}$ **(+/-1.7)**
L Opt. -	3.0 $^{A}_{d}$ **(+/-1.0)**	2.0 $^{A}_{e}$ **(+/-0.6)**
C	2.5 $^{A}_{d}$ **(+/-0.9)**	1.8 $^{A}_{e}$ **(+/-0.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

Table 11: The influences of soil ameliorants on the potassium (K) content of a mine cover soil.

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	18.8 $^{A}_{b}$ **(+/-1.6)**	9.8 $^{B}_{b}$ **(+/-5.1)**
S Opt. +	18.8 $^{A}_{b}$ **(+/-2.1)**	11.5 $^{B}_{b}$ **(+/-2.2)**
S Opt. -	17.2 $^{A}_{b}$ **(+/-1.9)**	9.9 $^{B}_{b}$ **(+/-1.2)**
FA Opt.	17.3 $^{A}_{b}$ **(+/-5.0)**	11.8 $^{B}_{b}$ **(+/-2.7)**
FA Opt. +	15.7 $^{A}_{bc}$ **(+/-4.0)**	12.5 $^{A}_{b}$ **(+/-2.9)**
FA Opt. -	14.7 $^{A}_{c}$ **(+/-1.9)**	9.2 $^{A}_{b}$ **(+/-3.5)**
L Opt.	24.2 $^{A}_{a}$**(+/-11.6)**	19.1 $^{A}_{a}$ **(+/-4.7)**
L Opt. +	16.7 $^{A}_{b}$ **(+/-4.6)**	12.4 $^{A}_{b}$ **(+/-3.1)**
L Opt. -	16.0 $^{A}_{b}$ **(+/-4.3)**	11.3 $^{A}_{b}$ **(+/-4.0)**
C	18.2 $^{A}_{b}$ **(+/-6.9)**	13.5 $^{A}_{b}$ **(+/-4.0)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

It is evident that in some instances a significant amount of Ca was either used or lost from the system, indicating a decreased amount of Ca over the 12 month in which cropping of the soils took place. In this respect *Cenchrus sp.* is known to have, a preference for soils with a high Ca content. Nevertheless, there is a significant amount of Ca remaining in the soils/substrate as seen in Tables (12, 16 and 20), and it is suggested that it be investigated whether such high levels of Ca can have a negative effect on plant growth or whether it can inhibit the utilization of other elements by the plants, which is not evident at this stage considering the strong plant growth on the SLASH treated soils.

Table 12: The influence of soil ameliorants on the calcium (Ca) content of a mine cover soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	2395.2 $^{A}{}_{a}$ **(+/-539.1)**	2203.0 $^{A}{}_{a}$ **(+/-430.1)**
S Opt. +	3046.3 $^{A}{}_{a}$ **(+/-599.0)**	2635.5 $^{B}{}_{a}$ **(+/-326.7)**
S Opt. -	1957.8 $^{A}{}_{b}$ **(+/-231.4)**	1771.8 $^{A}{}_{b}$ **(+/-299.3)**
FA Opt.	293.7 $^{A}{}_{c}$ **(+/-74.9)**	266.4 $^{A}{}_{c}$ **(+/-33.23)**
FA Opt. +	304.7 $^{A}{}_{c}$ **(+/-19.8)**	276.0 $^{A}{}_{c}$ **(+/-21.3)**
FA Opt. -	211.7 $^{A}{}_{c}$ **(+/-28.1)**	194.5 $^{A}{}_{c}$ **(+/-29.8)**
L Opt.	274.5 $^{A}{}_{c}$ **(+/-38.9)**	195.3 $^{A}{}_{c}$ **(+/-29.1)**
L Opt. +	272.7 $^{A}{}_{c}$ **(+/-92.2)**	216.8 $^{B}{}_{c}$ **(+/-45.8)**
L Opt. -	293.5 $^{A}{}_{c}$ **(+/-26.3)**	204 $^{B}{}_{cd}$ **(+/-71.1)**
C	149.7 $^{A}{}_{d}$ **(+/-24.7)**	129.0 $^{A}{}_{d}$ **(+/-50.3)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

In Table 11 it is noted that none of the soil ameliorants, used in this trial, contributed significantly to the K status of the mine cover soil. It may, therefore, be concluded that it will be essential to provide sufficient potassium if such soils are to be re-vegetated and the plant material utilized. With the removal of plant material, potassium levels became further depleted, although under grazing there would be an excellent re-cycling of K.

Table 13: The influence of soil ameliorants on the magnesium (Mg) content of a mine cover soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	32.1$^{A}_{b}$ **(+/-5.6)**	23.1 $^{B}_{c}$ **(+/-4.3)**
S Opt. +	31.5 $^{A}_{b}$ **(+/-10.0)**	23.3 $^{B}_{c}$ **(+/-8.7)**
S Opt. -	26.3 $^{A}_{bc}$ **(+/-6.6)**	16.5 $^{B}_{c}$ **(+/-5.3)**
FA Opt.	35.3 $^{A}_{b}$ **(+/-7.1)**	26.1 $^{B}_{c}$ **(+/-7.1)**
FA Opt. +	34.8 $^{A}_{b}$ **(+/-9.2)**	24.4 $^{B}_{c}$ **(+/-7.3)**
FA Opt. -	28.2 $^{A}_{b}$ **(+/-5.2)**	21.1 $^{B}_{c}$ **(+/-2.9)**
L Opt.	96.2 $^{A}_{a}$ **(+/-10.8)**	80.3 $^{B}_{a}$ **(+/-8.1)**
L Opt. +	122.3 $^{A}_{a}$ **(+/-20.6)**	103.2 $^{B}_{a}$ **(+/- 15.8)**
L Opt. -	79.8 $^{A}_{a}$ **(+/-7.5)**	61.5 $^{B}_{b}$ **(+/-7.2)**
C	20.8 $^{A}_{c}$ **(+/-3.5)**	17.5 $^{B}_{c}$ **(+/-5.6)**

***AB** Row means with common alphabetical superscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

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

3.3.2 AMD Impacted Soil

The AMD impacted soil was much more degraded, and due to the water being contaminated by oxidized pyrite, the soil had a pH of only 3.4. It is evident from Figure 6 that SLASH had the most significant affect on the pH, raising it from 3.4 to just above 8.0. This significant response can be attributed to the effect the class F fly ash and the highly reactive lime (CaO), which were included in the SLASH.

All levels of class F fly ash (in Figure 7) had a significant affect on the soil pH. In comparison SLASH treatments (Figure 8), (which had additional CaO in its composition) increased the pH even further (8.2 vs 6.7). These data, demonstrate that class F fly ash can counteract acidity, especially in very acidic environments.

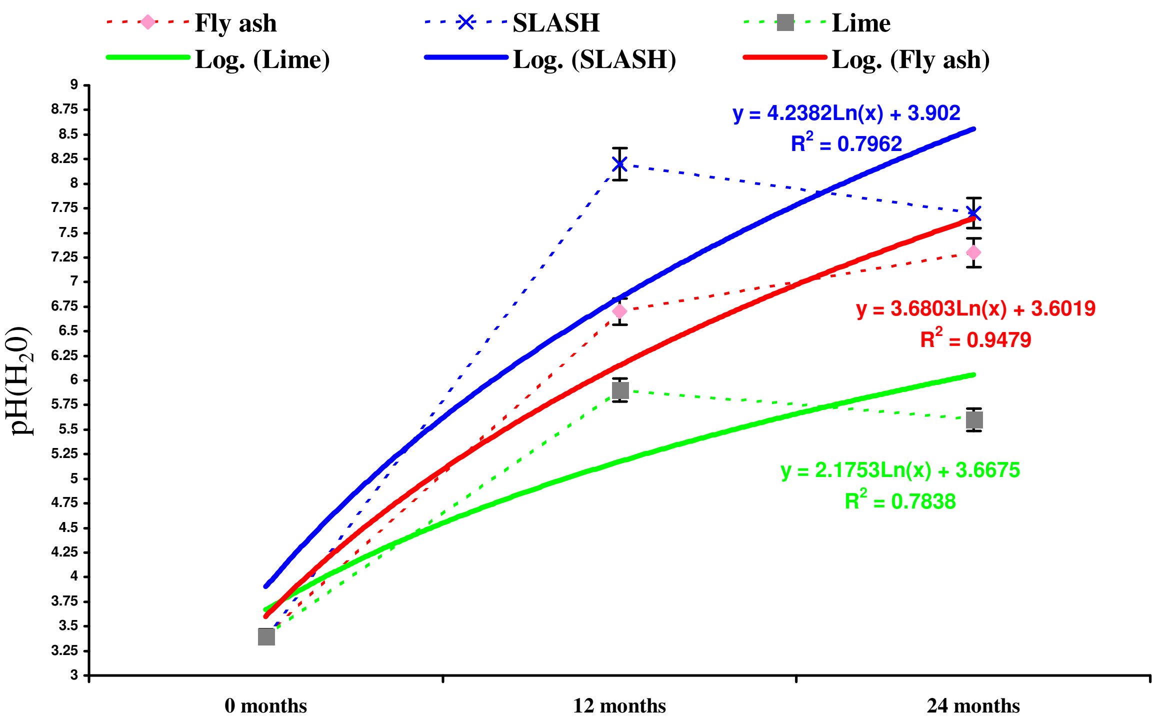

Figure 6: The comparative effect of three ameliorants on the pH of an AMD impacted soil

It can be assumed that the calcium silicates present in class F fly ash play a significant role in neutralizing the acidity (H^+) within the soil complex. The detailed soil chemistry required to establish the chemical functionality of class F fly ash within the acidic soil complex is required to better understand what the exact mechanism of acid neutralization is. This is currently being investigated in continuing research.

The SLASH treatments (Figure 8) resulted in highly significant increases in soil pH. This could, however, be a problem because the change to an alkaline condition could have a negative effect on the germination of certain seeds planted in such amended soils. This dramatic increase in soil pH can possibly be the result of too high applications of SLASH to the soil (because of an under-estimation of the neutralizing value of class F fly ash).

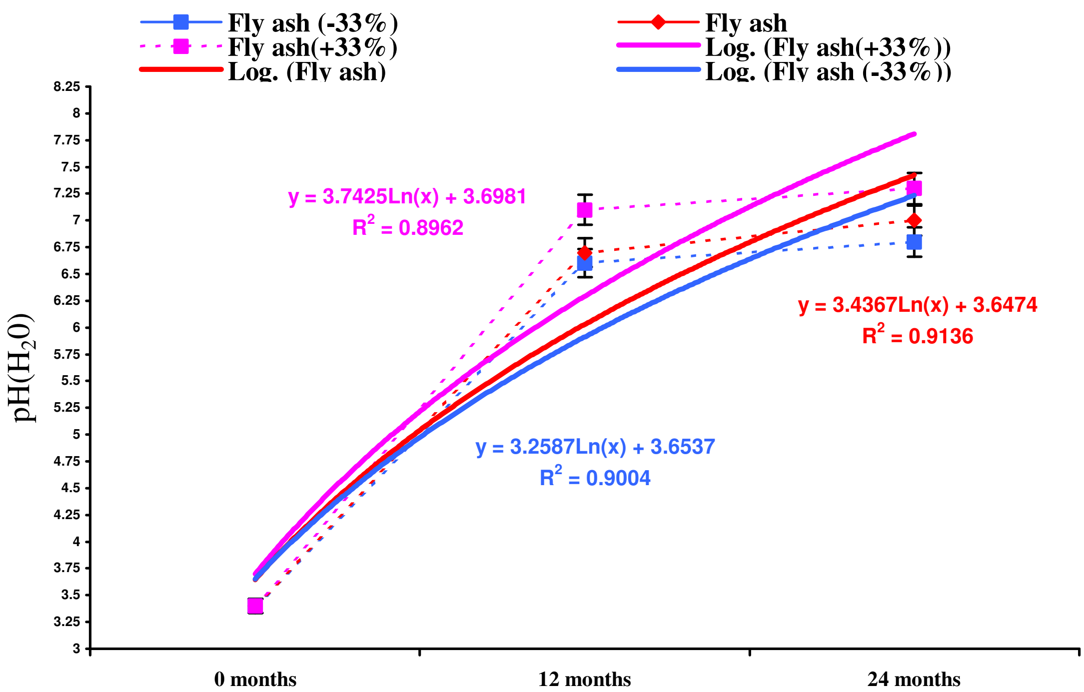

Figure 7: The effect of three different levels of class F fly ash on the soil pH of an AMD impacted soil

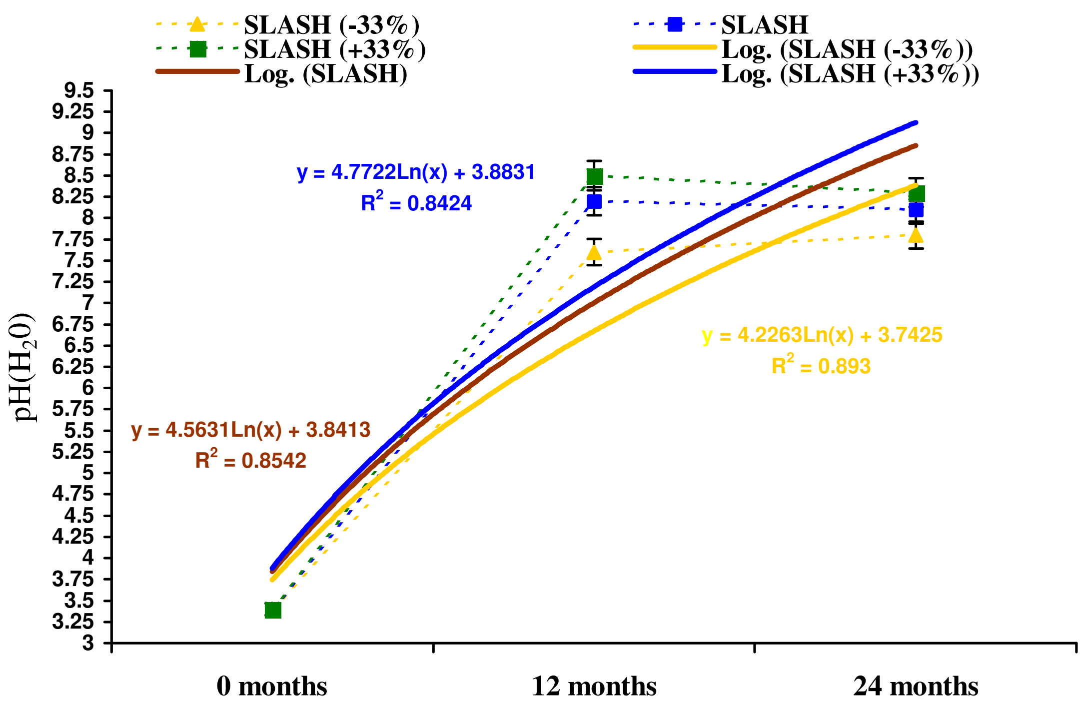

Figure 8: The effect of three different levels of SLASH on the pH of an AMD impacted soil

The lime treatment affects, as observed in Figure 9, illustrated the significant effect on the pH of AMD impacted soil. The highest level of lime (L Opt+), however, only raised the soil pH to just below 6.5 as was originally calculated for the optimum level lime required to raise the soils pH to 6.5. These slightly disappointing data may be ascribed to the poor reactivity of the lime as a result of either variability in lime quality or to an ineffective method of incorporation. In Table 13, however, it is noted that the dolomitic lime had a significant effect on the Mg content of the soil.

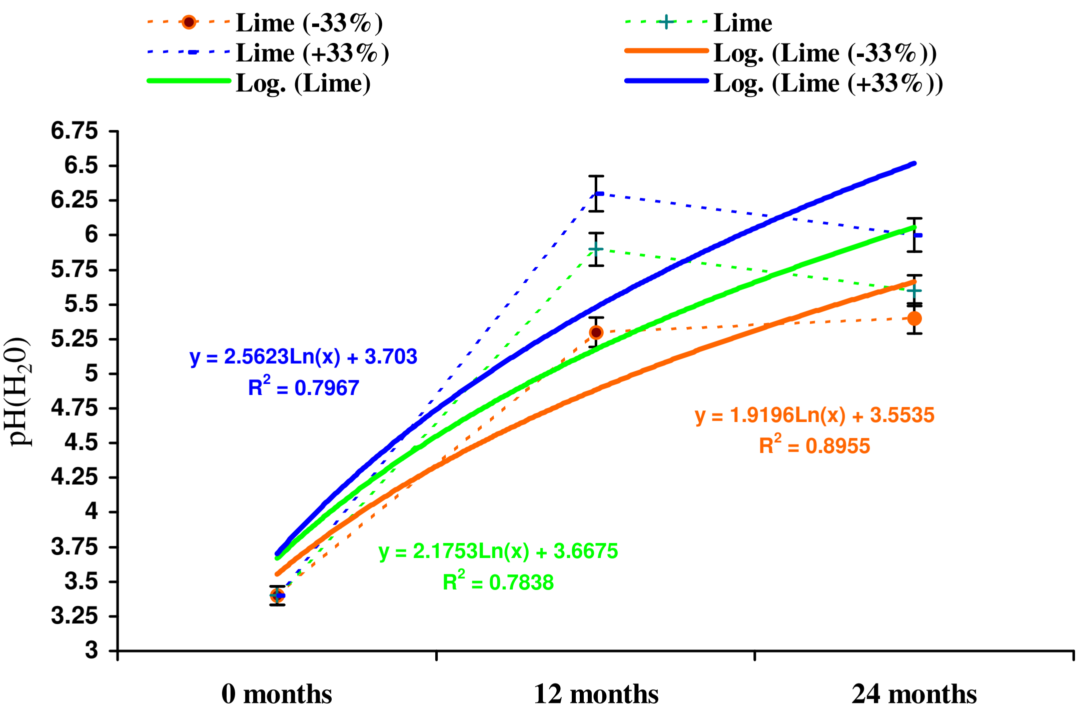

Figure 9: The effect of three levels of dolomitic lime on the pH of an AMD impacted soil

The neutralizing capacity of the ameliorant SLASH has proven itself. Both the fly ash and the lime components of the SLASH are responsible for this effect. Fly ash used in this trial had a neutralizing value in excess of 20%, and when combined with the CaO and sludge, it is estimated that the neutralizing value of the SLASH mixture was between 30 and 40% that of lime.

The soils, impacted by acid mine drainage, are normally very acidic and infertile. With respect to soil nutrient status, Table 14 indicates that both the fly ash and the SLASH contributed to the P status of the soil, relative to the control. The K level of the soil (Table 15), however, showed some improvement when treated with SLASH (Table 16). When compared to the previous mine cover soil, it can be seen that in the more degraded soil amelioration, evidently caused a different chemical reaction, making the small amount of K, which is in the ameliorant or in the soil, more available. The levels of K are, however, still very low and provision for extra K will have to be made. From Table 17 it is noted that while the fly ash and the SLASH treatments improved the Mg status by approximately 100%, the dolomitic lime had a much more dramatic effect because of the Mg in this lime source.

Table 14: The influence of soil ameliorants on the phosphorus (P) content of AMD impacted soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	10.6^{A}_{c} **(+/-2.3)**	8.0^{A}_{b} **(+/-3.8)**
S Opt. +	14.0^{A}_{bc} **(+/-3.8)**	9.8^{B}_{b} **(+/-2.0)**
S Opt. -	11.6^{A}_{c} **(+/-2.1)**	8.9^{A}_{b} **(+/-1.4)**
FA Opt.	17.1^{A}_{b} **(+/-3.0)**	13.4^{A}_{ab} **(+/-4.1)**
FA Opt. +	28.5^{A}_{a} **(+/-2.8)**	20.2^{B}_{a} **(+/-3.5)**
FA Opt. -	12.6^{A}_{c} **(+/-2.6)**	9.2^{A}_{b} **(+/-1.3)**
L Opt.	1.5^{A}_{d} **(+/-0.3)**	0.9^{A}_{c} **(+/-0.3)**
L Opt. +	1.9^{A}_{d} **(+/-0.3)**	1.3^{A}_{c} **(+/-0.1)**
L Opt. -	1.4^{A}_{d} **(+/-0.2)**	0.9^{A}_{c} **(+/-0.3)**
C	2.1^{A}_{d} **(+/-0.5)**	1.4^{A}_{c} **(+/-0.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

With respect to the Ca levels in the AMD impacted soil (Table 16), the significant contribution from the SLASH treatments was again noted. The significant level of Ca depletion over the cropping period was more evident in the AMD impacted soil than it had been in the cover soil. This leads to the possible conclusion that more Ca was involved in either the acid neutralization, or the plants, in the more degraded soil, utilized more calcium.

Table 15: The influence of soil ameliorants on the potassium (K) content of an AMD impacted soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	26.8 $^{A}{}_{a}$ **(+/-3.2)**	19.5 $^{A}{}_{a}$ **(+/-4.8)**
S Opt. +	27.7 $^{A}{}_{a}$ **(+/-4.7)**	19.7 $^{B}{}_{a}$ **(+/-4.3)**
S Opt. -	24.2 $^{A}{}_{a}$ **(+/-4.1)**	16.0 $^{B}{}_{ab}$ **(+/-3.6)**
FA Opt.	14.8 $^{A}{}_{b}$ **(+/-4.7)**	8.3 $^{A}{}_{c}$ **(+/-3.1)**
FA Opt. +	10.7 $^{B}{}_{c}$ **(+/-3.4)**	15.7 $^{A}{}_{b}$ **(+/-3.3)**
FA Opt. -	15.0 $^{A}{}_{b}$ **(+/-3.0)**	9.3 $^{A}{}_{c}$ **(+/-2.7)**
L Opt.	15.7 $^{A}{}_{b}$ **(+/-3.3)**	9.4 $^{A}{}_{c}$ **(+/-2.7)**
L Opt. +	15.3 $^{A}{}_{b}$ **(+/-4.1)**	9.8 $^{A}{}_{c}$ **(+/-3.7)**
L Opt. -	15.8 $^{A}{}_{b}$ **(+/-4.1)**	9.3 $^{A}{}_{c}$ **(+/-2.8)**
C	14.8 $^{A}{}_{b}$ **(+/-4.7)**	9.2 $^{A}{}_{c}$ **(+/-3.1)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

Table 16: The influence of soil ameliorants on the calcium (Ca) levels of an AMD impacted soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	4471.1 $^{A}{}_{a}$ **(+/-469.2)**	4029.0 $^{B}{}_{a}$ **(+/-322.2)**
S Opt. +	4440.2 $^{A}{}_{a}$ **(+/-312.8)**	4102.7 $^{B}{}_{a}$ **(+/-459.2)**
S Opt. -	3958.7 $^{A}{}_{a}$ **(+/-303.9)**	3614.7 $^{B}{}_{a}$ **(+/-483.4)**
FA Opt.	532.2 $^{A}{}_{b}$ **(+/-73.7)**	458.7 $^{A}{}_{bc}$ **(+/-41.7)**
FA Opt. +	746.5 $^{A}{}_{b}$ **(+/-125.2)**	657.0 $^{B}{}_{b}$ **(+/-123.6)**
FA Opt. -	419.7 $^{A}{}_{bc}$ **(+/-42.1)**	333.0 $^{B}{}_{d}$ **(+/-42.3)**
L Opt.	478.5 $^{A}{}_{b}$ **(+/-44.7)**	403.8 $^{B}{}_{cd}$ **(+/-42.5)**
L Opt. +	544.0 $^{A}{}_{b}$ **(+/-37.3)**	427.7 $^{B}{}_{c}$ **(+/-29.3)**
L Opt. -	485.7 $^{A}{}_{b}$ **(+/-50.2)**	388.7 $^{B}{}_{cd}$ **(+/-49.3)**
C	356.0 $^{A}{}_{c}$ **(+/-60.8)**	283.5 $^{B}{}_{d}$ **(+/-66.1)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

Table 17: The influence of soil ameliorants on the magnesium (Mg) content of an AMD impacted soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	52.0 $^{A}{}_{cd}$ **(+/-9.7)**	42.3 $^{B}{}_{cd}$ **(+/-9.8)**
S Opt. +	50.0 $^{A}{}_{cd}$ **(+/-9.5)**	43.5 $^{A}{}_{cd}$ **(+/-8.8)**
S Opt. -	43.8 $^{A}{}_{d}$ **(+/-7.8)**	34.8 $^{B}{}_{d}$ **(+/-11.3)**
FA Opt.	68.2 $^{A}{}_{c}$ **(+/-23.4)**	54.2 $^{B}{}_{c}$ **(+/-19.1)**
FA Opt. +	70.0 $^{A}{}_{c}$ **(+/-15.6)**	59.0 $^{B}{}_{c}$ **(+/-14.6)**
FA Opt. -	48.2 $^{A}{}_{cd}$ **(+/-10.8)**	36.3 $^{A}{}_{d}$ **(+/-10.3)**
L Opt.	188.3 $^{A}{}_{b}$ **(+/-38.0)**	165.5 $^{B}{}_{b}$ **(+/-29.8)**
L Opt. +	289.2 $^{A}{}_{a}$ **(+/-50.8)**	269.8 $^{A}{}_{a}$ **(+/-50.1)**
L Opt. -	170.8 $^{A}{}_{b}$ **(+/-54.8)**	155.5 $^{A}{}_{b}$ **(+/-48.5)**
C	25.3 $^{A}{}_{e}$ **(+/-9.6)**	18.0 $^{A}{}_{e}$ **(+/-7.7)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

3.3.3 Gold Mine Tailings

The gold mine tailings, although not classified as a soil, must serve as a growing medium for plants, during the reclamation process. This material is acidic in nature and can contain certain heavy metals, which can become available at low pH values [13]. Ideally the pH of this material should be raised to prevent any leaching of heavy metals or trace elements which are hazardous to the environment, and simultaneously create a more plant friendly environment, so as to reduce or prevent erosion. Figure 10, illustrates how SLASH, class F fly ash and dolomitic lime affected the pH of the material.

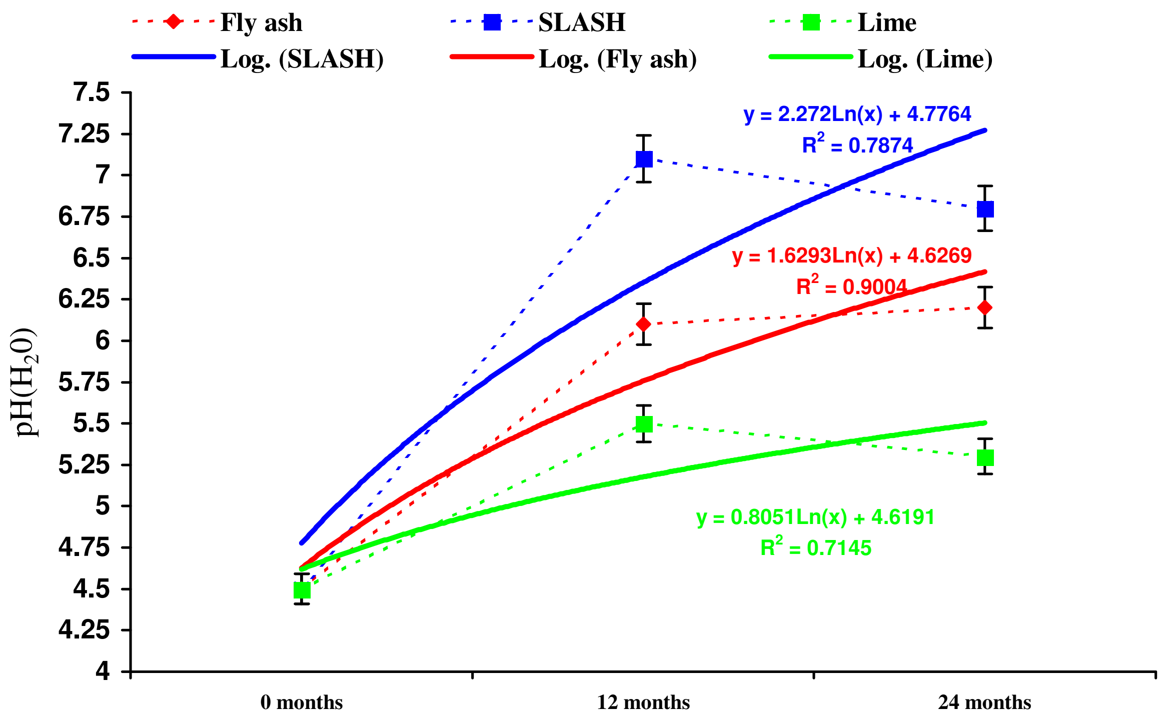

Figure 10: The comparative effect of three ameliorants on the pH of gold mine tailings

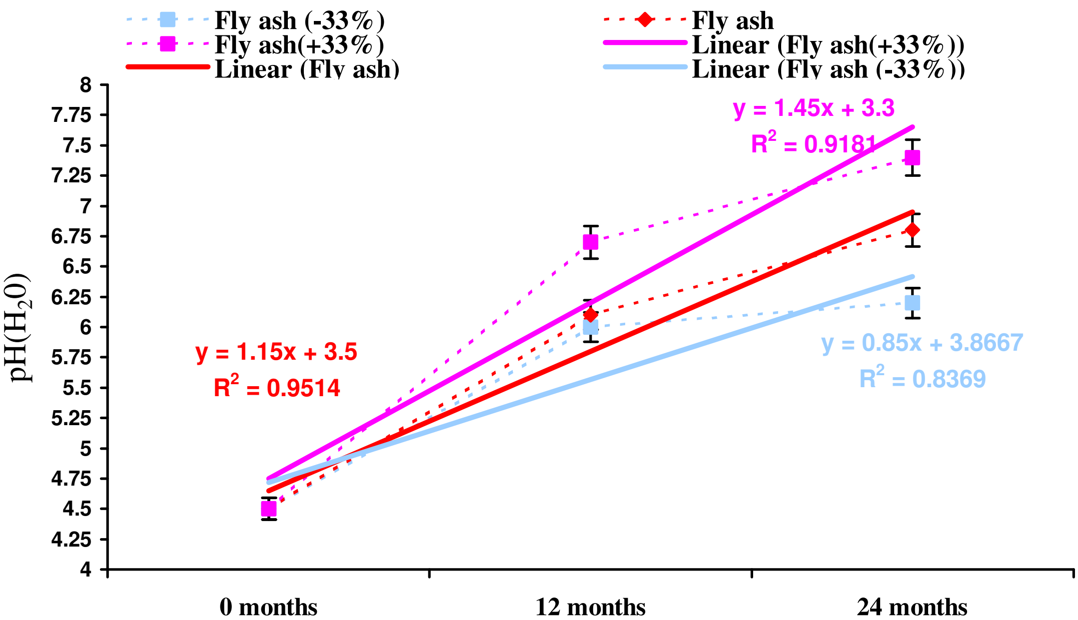

Figure 11: The effect of three different levels of class F fly ash on the soil pH of gold mine tailings

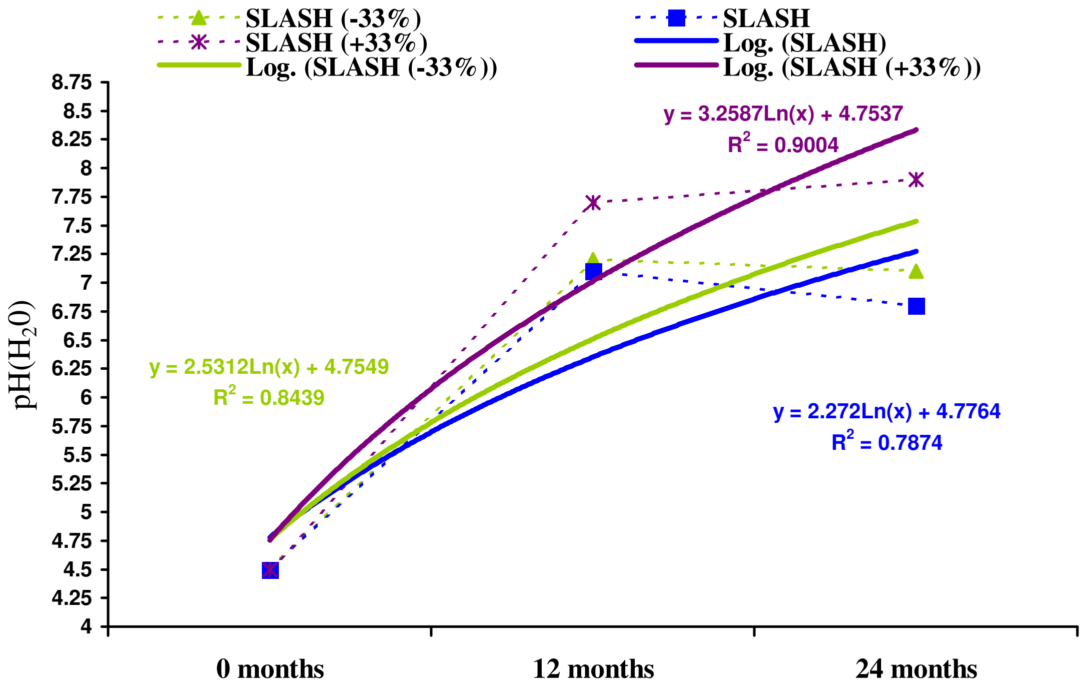

Figure 12: The effect of three different levels of SLASH on the pH of gold mine tailings

It was notable that the effect of the lime treatments, observed in Figure 13, decreased over the 12 month period during which the cropping took place, in comparison with an increased affect on the class F fly ash (Figure 12) treatments. These data illustrates the residual alkalinity present in the class F fly ash, resulting in more sustainable effects.

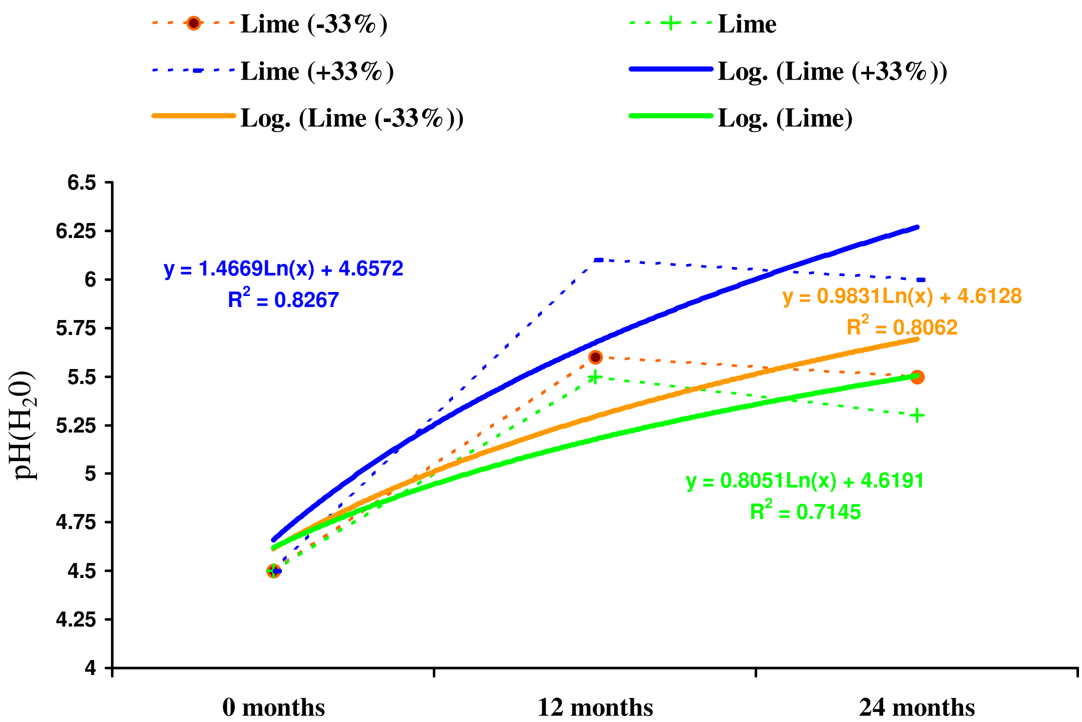

Figure 13: The effect of three levels of dolomitic lime on the pH of gold mine tailings

The pH of gold tailings is normally very low, and will often not sustain vegetation. It is noted from Figures 11 and 12 that the class F fly ash and SLASH undoubtedly improved the pH. This improvement in pH is also reflected in the growth enhancing effects of these ameliorants based on class F fly ash. Alkaline FA is most frequently used for its acid neutralizing potential, through hydrolysis of CaO and MgO [1] and the weathering of Al_2SiO_5 [10]. The degree of neutralization is dependent on the difference in pH between FA and soil, soil buffering capacity and FA neutralizing capacity, as determined by the amounts of CaO, MgO and Al_2SiO_5 present.

Numerous findings, in India, support the general findings of international literature, and conclude that fly ash on different occasions will improve soil pH, Ca, Mg and certain micronutrients levels in acidic soil [2; 4], as is the case in most of the data, presented in this paper. With respect to the effect of soil ameliorants on the nutrient status of the gold tailings, the results in Table 18 are very similar to those obtained with the AMD polluted soil. It is clear that both the SLASH and fly ash improved the P status by 100% or more. These levels are, however, still very low and will not necessarily sustain plant growth for extended periods, indicating a need for supplementary fertilization.

Table 18: The influence of different soil ameliorants on the phosphorus (P) content of gold tailings

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	2.4^{A}_{b} **(+/-1.8)**	1.5^{B}_{b} **(+/-1.1)**
S Opt. +	3.9^{A}_{a} **(+/0.7)**	2.6^{B}_{a} **(+/-0.6)**
S Opt. -	2.9^{A}_{b} **(+/-1.3)**	2.3^{A}_{a} **(+/-1.1)**
FA Opt.	3.1^{A}_{b} **(+/-0.8)**	1.9^{B}_{ab} **(+/-0.7)**
FA Opt. +	4.0^{A}_{a} **(+/-2.0)**	2.5^{B}_{a} **(+/-1.4)**
FA Opt. -	3.5^{A}_{ab} **(+/-2.1)**	2.4^{B}_{a} **(+/-1.8)**
L Opt.	0.8^{A}_{c} **(+/-0.2)**	0.4^{B}_{c} **(+/-0.1)**
L Opt. +	0.5^{A}_{c} **(+/-0.1)**	0.2^{B}_{c} **(+/-0.1)**
L Opt. -	0.5^{A}_{c} **(+/-0.1)**	0.3^{A}_{c} **(+/-0.1)**
C	0.7^{A}_{c} **(+/-0.9)**	0.6^{A}_{c} **(+/-)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

With respect to the K status (Table 19), both fly ash and lime improved the soil content, but not to the same extent as SLASH. These data illustrate how different substrates react differently to different ameliorants. The K present in either the gold tailings or SLASH ameliorant evidently became available, as a result of a chemical reaction that did not take place in the cover soil. This increase in available K, and to some extent P, substantiates the significant enhancement of plant growth by applications of SLASH observed in this study.

Table 19: The influence of different soil ameliorants on the potassium (K) content of gold tailings

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	100.2 $^{A}{}_{b}$ **(+/-37.2)**	77.8 $^{B}{}_{b}$ **(+/-34.5)**
S Opt. +	151.8 $^{A}{}_{a}$ **(+/-18.5)**	123.8 $^{B}{}_{a}$ **(+/-15.5)**
S Opt. -	61.2 $^{A}{}_{c}$ **(+/-19.2)**	43.7 $^{B}{}_{c}$ **(+/-16.9)**
FA Opt.	8.2 $^{A}{}_{d}$ **(+/-3.5)**	4.9 $^{A}{}_{d}$ **(+/-2.1)**
FA Opt. +	9.0 $^{A}{}_{d}$ **(+/-3.1)**	6.1 $^{A}{}_{d}$ **(+/-4.9)**
FA Opt. -	7.3 $^{A}{}_{d}$ **(+/-3.0)**	4.9 $^{A}{}_{d}$ **(+/-1.9)**
L Opt.	7.3 $^{A}{}_{d}$ **(+/3.0)**	4.9 $^{A}{}_{d}$ **(+/-1.9)**
L Opt. +	10.7 $^{A}{}_{d}$ **(+/-4.3)**	7.0 $^{A}{}_{d}$ **(+/-2.3)**
L Opt. -	7.7 $^{A}{}_{d}$ **(+/-3.7)**	4.9 $^{A}{}_{d}$ **(+/-2.8)**
C	3.6 $^{A}{}_{e}$ **(+/-1.3)**	1.9 $^{A}{}_{e}$ **(+/-0.9)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

The Ca levels of the tailings (Table 20) were initially very high, which is ascribed to the addition of Ca through the liming process of tailings material before disposal. The higher Ca levels of SLASH amended soils, are also attributed to inclusion of CaO in the SLASH mixture, because the Ca levels of the fly ash treatment's were not that different from the control.

Table 20: The influence of different soil ameliorants on the calcium (Ca) content of gold tailings

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	5033.3^{A}_{a} **(+/-653.4)**	4546.3^{B}_{b} **(+/-718.2)**
S Opt. +	6155.5^{A}_{a} **(+/-507.9)**	5413.5^{B}_{a} **(+/-686.2)**
S Opt. -	5368.5^{A}_{a} **(+/-795.2)**	4890.2^{B}_{ab} **(+/-830.1)**
FA Opt.	2969.8^{A}_{b} **(+/-574.1)**	2503.0^{B}_{c} **(+/-605.1)**
FA Opt. +	2313.7^{A}_{b} **(+/-541.5)**	1819.8^{B}_{cd} **(+/-450.4)**
FA Opt. -	2598.0^{A}_{b} **(+/-787.3)**	2093.2^{B}_{c} **(+/-643.9)**
L Opt.	2298.5^{A}_{b} **(+/-563.3)**	1832.8^{A}_{c} **(+/-511.47)**
L Opt. +	2445.0^{A}_{b} **(+/-799.0)**	2052.8^{B}_{c} **(+/-852.3)**
L Opt. -	2010.0^{A}_{b} **(+/-319.0)**	1530.5^{B}_{d} **(+/-301.1)**
C	2222.8^{A}_{b} **(+/-387.4)**	1679.8^{B}_{d} **(+/-405.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

Table 21: The influence of different soil ameliorants on the magnesium (Mg) content of gold tailings

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	153.8^{A}_{c} **(+/- 51.8)**	132.0^{A}_{b} **(+/-45.7)**
S Opt. +	184.2^{A}_{c} **(+/-30.2)**	149.0^{B}_{b} **(+/-38.8)**
S Opt. -	146.8^{A}_{c} **(+/-50.7)**	123.3^{A}_{b} **(+/-46.7)**
FA Opt.	291.7^{A}_{b} **(+/-77.1)**	243.0^{B}_{a} **(+/-74.7)**
FA Opt. +	292.2^{A}_{b} **(+/- 82.6)**	234.7^{B}_{a} **(+/-76.5)**
FA Opt. -	368.7^{A}_{a} **(+/-110.1)**	307.2^{B}_{a} **(+/-88.5)**
L Opt.	326.5^{A}_{a} **(+/-52.7)**	266.8^{B}_{a} **(+/-52.2)**
L Opt. +	293.0^{A}_{b} **(+/- 42.0**	235.0^{B}_{a} **(+/-40.1)**
L Opt. -	290.5^{A}_{b} **(+/-24.7)**	234.1^{B}_{a} **(+/-29.3)**
C	225.0^{A}_{b} **(+/-53.0)**	159.3^{B}_{b} **(+/-58.5)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

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

In Table 21, it is noted that the natural levels of Mg are relatively high, as a result of the Mg SO_4, which is used in the gold mining process. Generally it is expected that Mg levels rise with the addition of dolomitic lime, however, there was no significant change in the gold tailings Mg levels when lime or fly ash was applied. It was interesting to note that the SLASH treatments had a depressing effect on the Mg levels of the tailings material. This can possibly be as a result of Mg participating in the complex chemical interactions caused by the addition of organic matter via sewage sludge to the tailings material, however this remains to be investigated.

4. Conclusion

Mine soils and mining wastes are generally infertile and are more acidic than natural topsoils. They will, therefore, 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 are 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. These waste materials, unfortunately, vary greatly in nutrient content, trace metals and liming potential, and these factors can affect both re-vegetation success and the environmental impact of reclamation. It can be concluded, that the class F fly ash used in this experimental work does have a higher $CaCO_3$ equivalent than what is referenced in the literature. This conclusion is based on the significant increases in soil pH and soil root biomass resulting in enhanced plant growth.

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 soil or substrate must be controlled to limit heavy metal mobility and ensure long-term vigour of the plant community. To reclaim a degraded soil is a major challenge, and is usually a very expensive process and it is often 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 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 other work done on acidic agricultural soils, the residual effects of SLASH have been measured for up to seven years. It is expected that SLASH and class F fly ash will have the same residual effect on the more acidic soils, and this will determine how sustainable such ameliorants are in reclaiming degraded soils and substrates.

5. References

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