The use of class F fly ash in reclaiming the agricultural potential of surface coal mine cover soils

Wayne Truter¹, Leushantha Mudaly¹, Du Toit Wilken² and Richard Kruger³

¹ Department of Plant Production and Soil Sciences, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa
² Centre of Environmental Studies, Faculty of Natural and Agricultural Sciences, University of Pretoria, South Africa
³ Richonne Consulting, Somerset West, Western Cape, South Africa

KEYWORDS: Reclamation, coal mine cover soils, agricultural potential, class F fly ash

ABSTRACT

The agricultural potential of surface coal mined soils is difficult to reclaim. It is possible to re-vegetate the covering topsoil, but the sustainability of many reclamation procedures is poor. This covering topsoil is exposed to chemical and physical degradation over time lowering the agricultural potential of these newly created “productive lands”. This is due to the unsustainable fertilizer practices used during re-vegetation, the management of these production systems and the additional acidity generated in the soils/substrates by contaminants of pyritic material or the shallow underlying pyritic spoil material. Roots are unable to grow properly in these substrates and vegetation is unable to become productive in these hostile growth mediums due to the changed chemical and physical properties. As a result, the covering topsoil becomes unstable, and susceptible to erosion. The experimental work is to identify amelioration strategies for the cover soil using the coal combustion by product - class F fly ash as a soil ameliorant.

The cover soil is planted to various grasses used in the reclamation process of South African agricultural land. Significant increases in yield were measured where class F fly ash had been incorporated into the soil as an ameliorant, relative to conventional mine treatments over specific growing seasons. The pH of the cover soil was the most strongly affected soil parameter during the experimental period. Therefore, the potential of class F fly ash as an ameliorant will facilitate effective reclamation of coal cover soils to reinstate the optimal agricultural potential of this pre-mined agricultural land.
INTRODUCTION

In South Africa, prime agricultural land is a limited commodity and a large amount of crops are grown on acidic and nutrient deficient soils in order to meet the demand for increased food production. There are several sources of soil acidity and these include the leaching of basic cations, acidity contributed by acid sulphate soils, acid rain, the removal or harvesting of crops, the use of fertilizers and the contribution from acidic mine spoil.

Opencast mining of coal is widespread in the grassland areas of Mpumalanga and KwaZulu-Natal and moving into the drier savannah regions of the Limpopo Province, of South Africa. These provinces are also home to many important agricultural production systems that contribute to the national objective to ensure food security. We can continue to debate whether mining is necessary and target the mining companies for their apparent destruction, or we can find ways to possibly integrate this land into our broader agricultural vision to achieve optimal food production for a growing nation.

Soil acidity has numerous detrimental effects, some of which include the contribution to soluble metal and micronutrient toxicity, the fixation of phosphorous and the inhibition of soil microorganism activity. When the pH of soil is below 7.0, the soil is considered to be acidic. In farming however, problems arise when the pH of the soil falls below 5.5. Most crops grow optimally in soils that have pH values between 5.5 and 7.0, which is the range in which the availability of most nutrients is at a maximum.

The re-vegetation of mined land presents a particular challenge because cover soils are often acidic and nutrient deficient. These conditions present major limiting factors in re-vegetation programs. It is current practice to amend such soils using lime and inorganic fertilizer. Research over the past 15 years into the use of a coal combustion by-product (CCB’s) - class F fly ash has demonstrated the feasibility of using such materials to amend acidic substrates. Soil pH is considered as a ‘master variable’ as it is the most diagnostic chemical measurement made on soil. Soil pH controls several chemical processes, including ion exchange reactions, dissolution or precipitation reactions, reduction or oxidation reactions, and the processes of adsorption and complexation.

Soil pH is the measure of acidity or alkalinity if the soil and most soils have values between 3.5 and 10. Soil pH influences the amount of nutrients that are soluble in soil water and therefore the availability of nutrients to plants. Most nutrients are readily available to plants when soil pH is near neutral.
Strongly acidic soils, which have a pH lower than 5.5, result in poor plant growth due to the low pH, aluminium and manganese toxicity, calcium deficiency and low levels of essential plant nutrients including phosphorus and molybdenum. The correct balance of nutrients is obtained at a soil pH between 5.5 and 7.5.\(^3\)

The objective of this research was to determine if alternative amendments could create a more sustainable system, in which the soil chemical properties, soil pH in particular and subsequently plant productivity can be improved. Coal mining impacts large areas in the grasslands of the Mpumalanga Province of South Africa. To mitigate such impacts, it is imperative to restore the once productive soils to the best possible condition.

There have been many investigations, which have studied re-vegetation and soil conditions on reclaimed mine land. Coal combustion by-products (CCB’s) have been widely used as cost effective amendments for acid soils. It is true that ashes have several advantages, and that their application is recommended\(^1,10,11\). The work conducted at the University of Pretoria has been successful in improving soil acidity\(^5,6,7,10,13,14\).

To ensure healthy and productive vegetation after the reclamation process, disturbed soils need to be ameliorated and initially re-vegetated with locally adapted grass species. The main objective of reclaiming surface coal mined soils is to reinstate the pre-mining agricultural potential. This is closely linked to the land capability of an area, which is determined by its own set of soil quality criteria.

The sustainability of these reclaimed environments largely depends on the improvement and maintenance of good quality soil that serves as a growth medium for established vegetation. It is evident from current research that planted pasture principles play an imperative role in the journey to achieve sustainable land reclamation, because to date the larger percentage of reclaimed surface mined land is returned to either planted pastures or artificial rangelands.

These provinces impacted on, provide good quality natural and planted pasture to support the cattle industry to meet the increasing protein demands of the growing population, but it is also home to a large proportion of South Africa’s arable farmland. Often the area classified as having grazing land capability post mining, makes up more than half of the reclaimed area. In some instances, it can even have better agricultural potential than the original pre-mined land. Nevertheless, the reinstatement of agricultural potential to support crop production on these reclaimed soils has been successful in certain areas where rehabilitation is regarded a core business, but is yet to be proven on a larger scale.
METHODOLOGY

A replicated field trial in a randomized block design, with five replications of an untreated control and six soil amendments of cover soil (consisting of a mixture of A and B horizons), with an average depth of 60 cm, was conducted over a six year period on a surface coal mine in the Mpumalanga Province of South Africa. The area is situated at 1500m above sea level and receives a summer rainfall of 600-700 mm and experiences dry frosty winters. The treatments consisted of three levels of fly ash (FA) and dolomitic agricultural lime (L). The optimum lime application rate was based on the buffering capacity of the substrate which was determined by using a Ca(OH)$_2$ titration solution. The mine cover soil had a pH$_{(H_2O)}$ of 4.3.

It was calculated, from the buffer curve, that the mine cover soil required 10 tons ha$^{-1}$ of dolomitic lime [L Opt.] to raise the pH of the soil to a pH$_{(H_2O)}$ of 6.5, ideal for plant growth. The calculated level of fly ash [FA Opt.], 50 tons ha$^{-1}$, was based on literature that class F fly ash had a CaCO$_3$ equivalent of 20% (Truter, 2002), and hence five times the amount of CaCO$_3$ required neutralizing acidity. The class F FA treatments were compared to the aforementioned control and three lime treatments. The other two levels of treatment were 33% above the optimum and 33% below the optimum. The untreated control (C) and a standard mine treatment (SMT) were included to serve as yardsticks. All treatments were applied once only in 1999 (the establishment season), at the beginning of the trial.

The quantities of fertilizer and lime used in the standard mine treatment in the establishment year were, 65 kg N ha$^{-1}$, 203 kg P ha$^{-1}$, 134 kg K ha$^{-1}$ in the form of limestone ammonium nitrate, super phosphate and potassium chloride and four tons of dolomitic lime per hectare. In subsequent years 100 kg N ha$^{-1}$ was applied each spring to SMT with applications of 2000 kg of lime and 250 kg K every two years.

Figure 1: Field trial on reclaimed surface coal mine (a) at establishment (b) 10 years later
After the initial soil analysis, pH(H₂O) measurements were conducted over 72 months after establishment. Soils were seeded with a mixture of Teff (Eragrostis tef), Rhodesgrass (Chloris gayana), Bermuda grass (Cynodon dactylon), Smutsfinger grass (Digitaria eriantha) and lucerne [alfalfa] (Medicago sativa) at a combined seeding rate of 40 kg ha⁻¹. Botanical composition and dry matter production (kg ha⁻¹) was monitored seasonally. Each season was measured by harvesting the material and drying it at 65 °C for 48 hours.

Statistical analyses

All dry matter production data and soil analyses were statistically analysed using PROC GLM. Statistical analyses were performed using SAS 9.2. LSD's were taken at P≤0.05. The standard deviation bars are from untransformed data.

RESULTS AND DISCUSSION

Soil Analyses

Soil pH

Soil analyses were conducted after every cropping cycle and the data presented includes the influence of the different treatments on the pH (H₂O) of the soil. The pH of the soil (Figure 3) was strongly affected by FA and lime. An improvement of up to 2 pH units was evident after 12 months (Figures 3 & 4) after treatment, and as cropping continued, and no further soil ameliorant applications were given in the 72-month period, soil pH gradually declined especially for the L treatments (Figure 5).

The FA treatments, however, as shown in Figure 4, maintained the soil pH, in the optimum range for good plant production (between 6 and 7). These data emphasize the residual alkalinity of FA, and supports the use of FA as a more sustainable soil ameliorant. This residual alkalinity of FA is present in the glass phase of the fly ash particle and with the dissolution of this phase through localized acidity; alkalinity is released to facilitate the neutralization of such soil acidity. With the correction of soil pH as initially calculated, plant nutrients in the soil are more soluble and available for plant uptake. It can, therefore, be concluded that class F fly ash definitely has a much higher CaCO₃ equivalent than was originally assumed. The stable pH noted for the SMT is due to the bi-annual application of a small amount of lime applied together with the limestone ammonium nitrate fertilizer given each year.
Figure 3: The influence of treatments, relative to C and SMT treatments, on the soil pH(H2O) over a 72-month period

Figure 4: The influence of FA treatments, relative to C and SMT treatments, on the soil pH(H2O) over a 72-month period
Vegetation analyses

Botanical composition

In Figure 6 there was a slight tendency for the productive grass numbers to decline on the “lower fertility treatments”, especially on the SMT, C and L treatments. A decrease in the vigor of one of the key species *C. gayana* occurred, which can be expected due to its relatively poor perenniality under local conditions. Nevertheless, the higher fertility treatments maintained a good population of productive grasses, especially after a high rainfall event. It is also noted in Figures 6 that as the conventional ameliorants become depleted, the species composition changes and a higher proportion of other annuals and perennial species become more abundant. The other “higher fertility treatments” such as the FA treatments, however, continued to provide a more favourable soil environment for the grasses in the mixture to produce well. These results support a high agricultural potential, through increasing the grazing capacity of the land for animal production.

The relatively small changes noticed in species composition on the FA ameliorated soils over the past 72 months, substantiates the conclusion that the
long term residual effect of these soil ameliorants are more sustainable than the traditional liming and fertilization.

Figure 6: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2005/2006 growing season.

# AB means differ significantly in botanical composition within treatments at P>0.05
# ab means differ significantly between treatments at P>0.05
(Tukey’s Studentized Range Test)
**Dry matter production**

Significant yield differences were evident in the 72 months. The trend clearly indicated that FA treatments significantly increased the dry matter production of the vegetation (Figures 7 & 8). In the initial growing season of the 72 month period the vegetation was predominantly *E. tef*. Yields of this species under normal agricultural conditions are approximately 5 tons ha\(^{-1}\). In Figure 7 it is noted that the FA+ yielded up to 6.5 tons ha\(^{-1}\), compared to the 2.8 and 1.25 tons ha\(^{-1}\) of the SMT and untreated control, respectively.

![Figure 7: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 1999/2000 growing season.](image)

The generally higher yields evident 72 months later on the FA treatments (Figure 8) were surprising, even after the first and only application that has conditioned the soil to make it favourable for plant growth over the past 72 months.

The lime treatments generally performed poorly, and the effects weren’t as pronounced as with the other soil ameliorants. The SMT had a significantly better yield, over the 72-month period, than the untreated control and some of the lime treatments. This can be ascribed to the additional nutrients provided initially together with the annual nitrogen applications.

These data clearly indicate that the FA soil ameliorants can improve the degraded soil environment on surface mines to the benefit of the plant production of plants established in the re-vegetation programmes.
Class F fly ash treatments showed a clear response to the level of application and this was significant in certain seasons. This poses the question whether the optimum level of application of these ameliorants has been achieved? Considering the effect these treatments have on soil pH at these application levels, a shift from an initially acidic soil condition towards a potentially saline condition is a potential concern. This observation, however, indicates that more frequent applications of these ameliorants at lower levels could be considered, but this aspect requires further investigation.

Figure 8: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2005/2006 growing season.

# Means with the same letter are not significantly different at P>0.05 (Tukey’s Studentized Range Test)

Figure 9: The dry matter production on re-vegetated soils, treated with FA ameliorants, relative to the C and SMT treatments over a 72-month period.
The regression analysis of these data sets (Figures 9), shows that the responses are not linear, and that the optimum level of ameliorants has been reached, and might in fact be too high already.

4. Conclusions

Results from this investigation indicate that alternative ameliorants such as class F fly ash, can have marked beneficial effects, which are still evident in the 6th year after establishment, despite no fertilizer being applied to all treatments, except the SMT, since the 1st season. This would indicate that such ameliorants produce more sustainable vegetation than current practice, and due to their chemical nature and reactivity, long-term residual soil effects are evident. It can be concluded from this experimental work, that this class F fly ash definitely has a much higher CaCO$_3$ equivalent than the 20%, which was originally assumed and is considered to be closer to 33%.

Fly ash treatments had significantly higher DM yields while the lower fertility treatments, such as the lime and the control, had a greater diversity of species. Excellent basal cover and yields were obtained when planted pastures on reclaimed soils were fertilized with some kind of nutrient source, organic or inorganic. The challenge, therefore, is to establish a sustainable system, when inorganic fertilization is either reduced or stopped. Industrial and urban by-products have unique properties and release both micro- and macro-nutrients slowly over time, to sustain productivity, and to effectively reclaim degraded soils and reclaim their agricultural potential. On the basis of these results, investigations of using alternative materials as ameliorants to reclaim degraded mine soils should be expanded.

5. References


