LOW-COST SELF-CLADDING OF COAL DUMPS. THE FUNGCOAL PROCESS

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ABSTRACT

The cladding of waste and production coal dumps to prevent combustion and rainfall infiltration, with attendant acidic seepage, has long presented challenges with the high-cost of clay and soil liner systems. The associated environmental damage in sourcing cladding materials can also be severe. Here, we report the development of a biotechnological self-cladding process in which fungal inocula are used to degrade coal and establish a humic soil-like layer on the coal dump surface. The layer supports the growth of grass plantations and the sealing of the dump in this way controls ingress of oxygen and rainfall penetration. This form of cladding is self-generating and thus is not easily prone to permanent erosion damage and loss of the dump cover characteristic of soil/clay liners. Initial fundamental studies on the biodegradation of hard bituminous coals by mycorrhizal fungal strains is described and also how the development of the process has been scaled up from laboratory through piloting to field scale applications. The paper reports economic modeling of the Fungcoal Process which has shown a favourable potential cost benefit in comparison to conventional clay and soil liners.

KEY WORDS

Weathered coal, arbuscular miccorhizal fungi, discard coal dump cladding, coal degradation, coal mine rehabilitation, mine reclamation costs.

INTRODUCTION

Long-term surface storage of production and discard coal stockpiles can be associated with severe environmental impacts including combustion, rainfall infiltration and acid seepage. Current best practice for managing such storage dumps includes shaping and grading to control rainfall runoff and then cladding with a range of clay and soil liner designs, depending on availability of materials (Morgenthal 2003).

Garner et al. (1999) reported on the rehabilitation of discard dumps utilizing a three layered cladding system:

Layer 1: 30 t/ha lime spread evenly on the compacted discard to neutralise and control acidity.
Layer 2: 250 mm of compacted subsoil material to minimize air and water ingress
Layer 3: 300 mm of good quality topsoil with minimum compaction to sustain plant cover.

Topsoil is prepared for re-vegetation by tillage and fertilization with agricultural lime (3t/ha) and super-phosphate fertiliser (1t/ha), and a fine mist irrigation system is used to assist establishment of a range of grass types.

One of the challenges to these conventional approaches to coal dump cladding is the prevention of erosion of the topsoil and clay liners, which affects long-term sustainability of the intervention. Limpitlaw et al. (2005) have noted that the thickness of top soil cladding on coal dumps is not necessarily a guarantee for future dump stability. They have highlighted cases were rehabilitated dumps have experienced extensive soil erosion and loss of cladding over time, with the exposure of the underlying coal. Another challenge is the availability of suitable topsoil in volumes sufficient for the cladding operation and may require the excavation of undisturbed land with attendant environmental degradation. The costs involved in clay/soil dump cladding rehabilitation operations are generally high.

Here we report the development of a self-cladding operation in which the coal layer on the surface of the dump is converted to a humic soil-like material in a biotechnological process mediated by fungal action. The degradation of the coal provides a medium suitable for plant growth, and, with the establishment of grass cover, effects a cladding of the dump which is self-generating, continuously replaces erosion losses and regulates oxygen and rainfall penetration.

Results of process development field-scale studies are reported here, in what has been termed the Fungcoal Process (Rose et al 2010), and a techno-economic evaluation of the self-cladding operation has been undertaken comparing costs with conventional soil/clay liners. A discard coal dump at Kleinkopje Colliery (South Africa) provided the site for the field-scale studies.

BACKGROUND

This study followed observation of the random appearance of Bermuda grass (*Cynodon dactylon*) growth on old hard bituminous coal dumps many years after their establishment. Preliminary site studies at Navigation Colliery (South Africa), involved the sampling of such areas (Figure 1) and showed the formation of humic soil-like layers up to 1.5 m in depth with grass root penetration up to 2.2 m into the coal.

In the screening of over 2000 fungal samples from such sites, Igbinigie et al. (2008) described the newly reported isolate, *Neosartorya fischeri*, and its capacity to degrade hard bituminous coal with the formation of humic acids. Oxidation and nitration of condensed aromatic structures of the coal macromolecule provided a probable mechanism for the biodegradation function. Simulation of the process in column reactors in controlled laboratory studies showed that coal degradation within the system was dependent on the interaction of a plant/fungal consortium in which a mycorrhizal association was demonstrated to be an important component (Mukasa-Mugerwa et al. 2011). Igbinigie et al. (2010) have described the phyto-bioconversion of hard coal in the *C.dactylon*/coal rhizosphere microenvironment and that a soil-like substrate containing up to 40% humic acid compounds may be generated within 40 weeks of plant growth together with fungal inoculum. It was also shown that the addition of weathered coal accelerated the establishment of *C. dactylon* in this system.

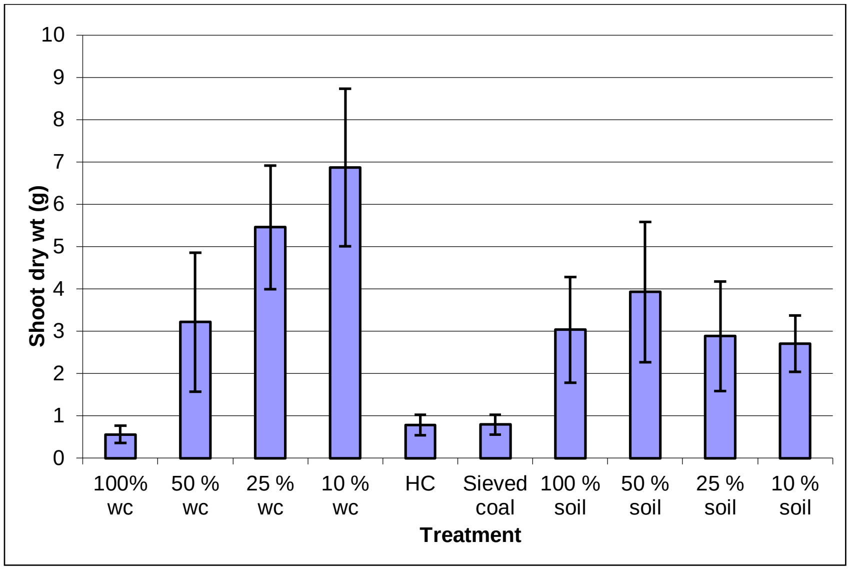
Figure 1 - Transect trench at Navigation Colliery hard coal dump showing grass growth and initial sampling by one of us (Peter Rose).

EXPERIMENTAL

Based on the preliminary laboratory-based studies described above, first pot trials and then small-scale and larger-scale field trials were set up to evaluate the performance of *C. dactylon* growth in hard coal in the presence of fungal inoculum and weathered coal amendments.

Pot Trials

Pots (1litre volume) were set up with a range of hard coal treatments and including fungal inoculum as shown in Figures 2a &b. These were each planted with one C. dactylon runner of the same length and were incubated in a controlled environment chamber at 25 ^{0}C with light regime of 16 hours light and 8 hours dark. Pots were harvested at 20 weeks and shoot and root dry weights determined gravimetrically. Results in Figure 2a show best shoot production with a 10% weathered coal amendment and significantly better performance than soil amendments of hard coal. Root production in the 10% - 50% treatments for both weathered coal and soil amendments were broadly comparable without significant differences between treatments, but significantly better than hard coal on its own.



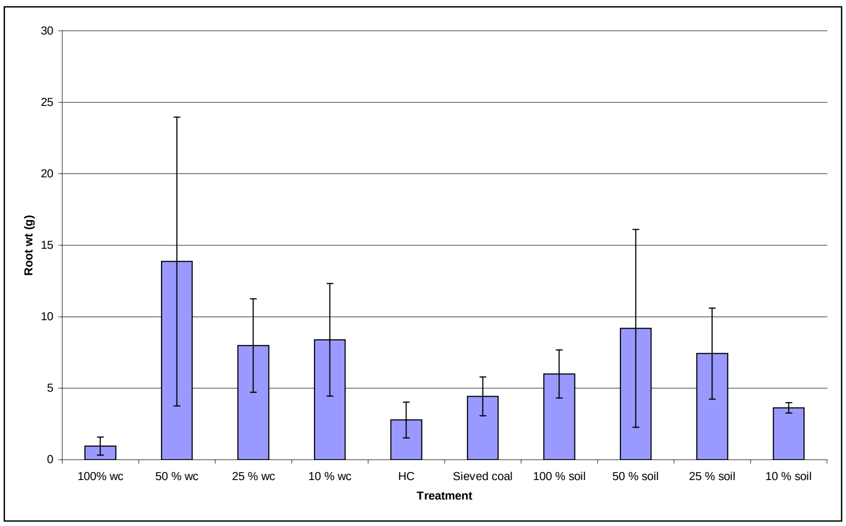


Figure 2. Pot trials showing shoot dry weight (a) and root dry weight (b) for growth in hard coal with a range of amendments (wc = weathered coal; HC = hard coal).

Small-scale Field Trials

Small-scale field trials were set up on the surface of a discard coal dump at Klein Kopje Colliery (South Africa). Plots of 1 m^2 were seeded with *C. dactylon* and combinations of treatments including fungal inoculum, weathered coal at various application rates, top soil and untreated control plots (hard coal alone) were applied. Results of the small-scale field trials showed that weathered coal treatments together with fungal inoculum performed comparably to top soil placed on the surface of hard coal in supporting plant growth. Hard coal control plots showed complete failure or very poor growth as may be expected. Figure 3 shows *C. dactylon* growth on amended hard coal.

Figure 3. Growth of *Cynodon dactylon* after one growth season on hard coal amended with fungal inoculum and weathered coal (a) compared to the hard coal control (b).

<u>Larger scale Field Trials</u>

Following the above results, larger-scale trials were established on 20 m^2 plots adjacent to the small-scale trials on the same discard coal dump for comparative purposes. Treatments were applied by disc plow and incorporated in the upper 200 mm hard coal layer as shown in Table 1. Fungal inoculum was composed of the *N. fischeri* inoculum and arbuscular mycorrhizal fungal (AMF) strains. *C. dactylon* production was measured by shoot dry mass harvested in square meter quadrant areas for each treatment as shown in Figures 4 & 5.

Table 1. Treatment regime applied to 20 m^2 plots on hard coal. (AMF = arbuscular mycorrhizal fungi; N.f = *Neosartorya fischeri*.

Plot No.	**Weathered coal** 20%top200 mm	**Lime** 25 tonnes/ ha	**Planting** 18kg/ha seed Sprigs15cm apart	**Inoculum**	**Fertilizer** Superphosphate 30g/m2
1	X	X	Sprigs	AMF	X
2		X	None	AMF	
3	X	X	Seed	AMF/ N.f	X
4		X	Seed	AMF	X
5	X		Seed	AMF	X

Figure 4. Harvesting of *Cynodon dactylon* biomass in 20 m^2 trials. Total foliage was cut to ground level within a square meter quadrant and dried and weighed.

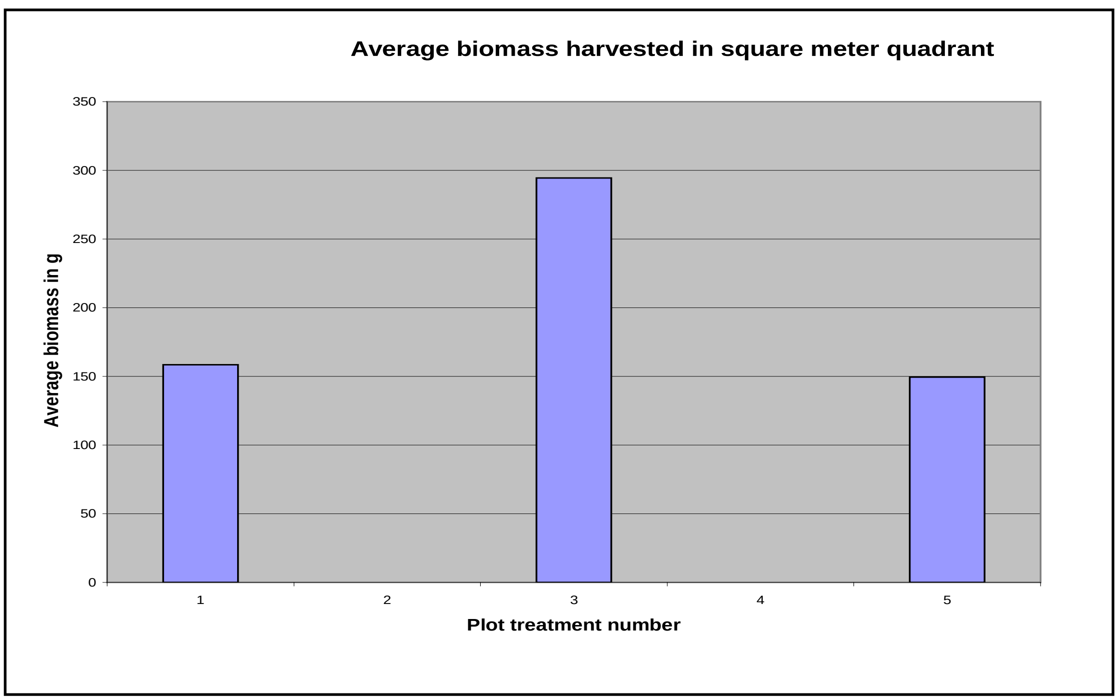


Figure 5. *Cynodon dactylon* bimass harvested from each of 20 m^2 plots with treatments as described in Table 1.

Results of this study after the first growth season indicated that the largest biomass production occurred in the treatment combination of liming and weathered coal together with combined fungal inoculum and fertilizer addition. It also shows that seeding (a less labour-intensive operation) gives a better take than sprigging of the plots.

The root zone was evaluated in profile holes dug into the trial plots and Figure 6 compares the results of root growth in untreated hard coal (a) and in the Plot 3 treatment (b). Hard coal in the root zone was degraded into a humic soil-like material as noted in previous studies.

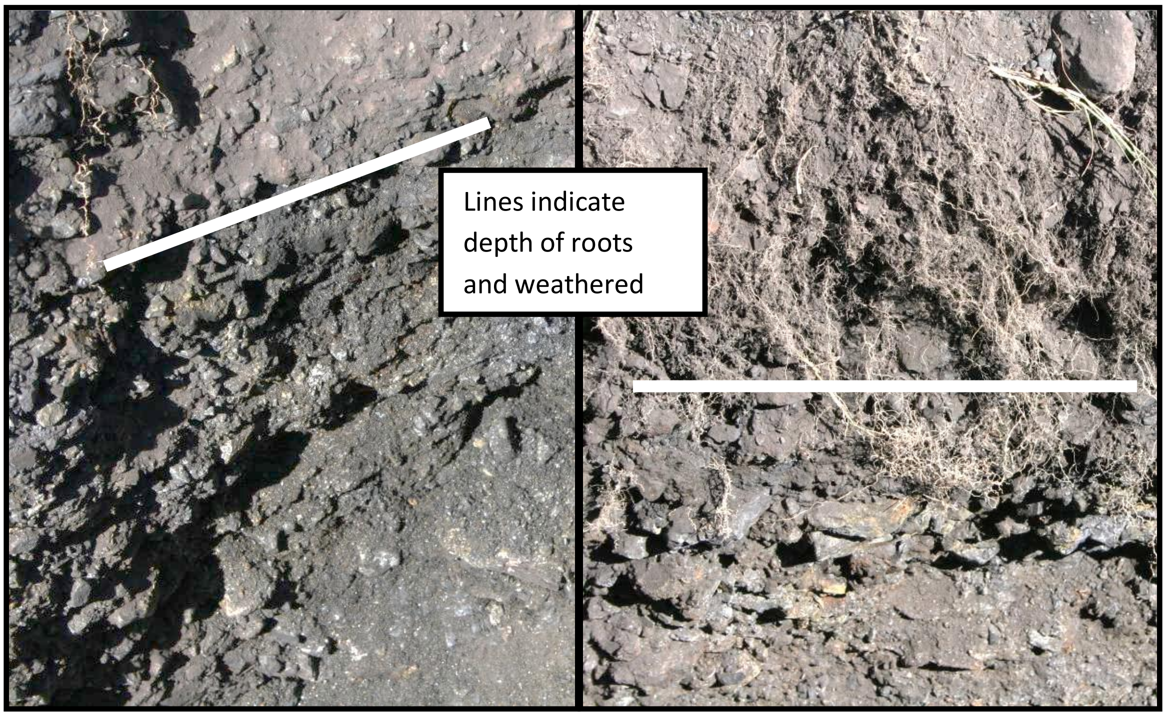


Figure 6. Photograph of profile holes dug into the discard coal comparing untreated coal (a) and the Plot 3 treatment (b).

The 20 m^2 field trial plots have been monitored for five years following establishment and results show continuous plant growth and the ongoing formation and replacement of the humic soil-like layer as measured by auger to a depth of first resistance (Table 3). Measurement after 5 years showed an augered depth of 380 mm in Treatment 3 (humic soil-like material without hard coal lumps) compared to 90 mm and 50 mm in control hard coal plots. Cation exchange capacity, an indicator of soil functionality, and humic acid formation was also measured in the soil-like layer after five years (Figure 7) and again showed best performance in the Plot 3 treatment.

Table 3. Formation of humic soil-like material comparing treatments in 20 m^2 trial plots as measured by auger sampling five years after establishment.

Treatment	Depth (mm)
1	180
2	90
3	380
4	50
5	15

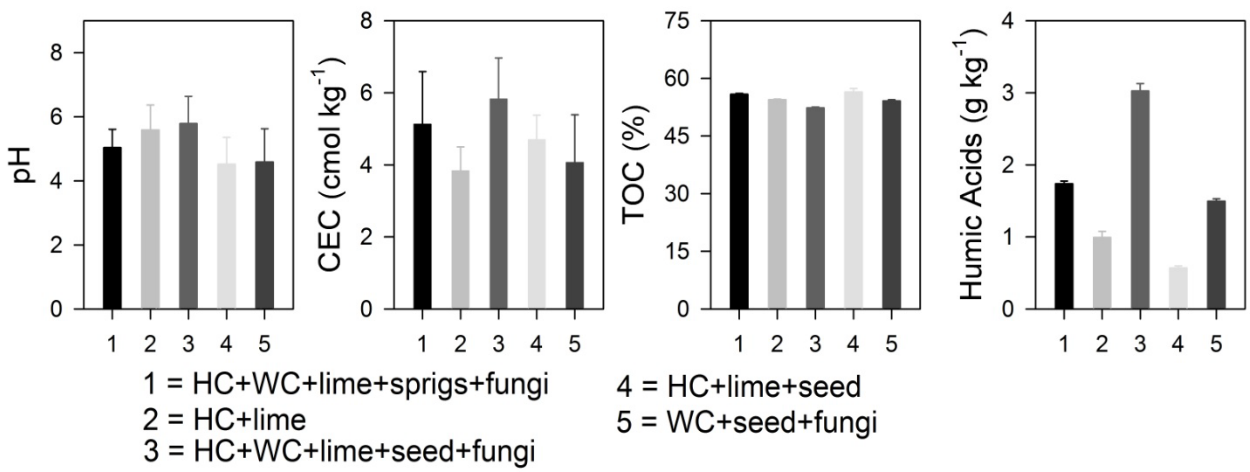


Figure 7. Measurement of pH, cation exchange capacity (CEC), total organic carbon (TOC) and humic acid in 20 m^2 field trial plots five years after establishment.

TECHNO-ECONOMIC MODEL

Based on the above results, hectare-scale plantations of the Fungcoal Process have been established in an investigation preparatory to using the process for the complete rehabilitation of legacy coal dumps. While these trials are currently ongoing, an attempt has been made to determine the costs of the process and to compare this to the implementation of conventional clay/soil liner systems. Operational procedures and costs are outlined in Table 4.

Table 4. Comparison of operational procedures and estimated costs for Funcoal and conventional clay/soil liner cladding systems.

Fungcoal process	**Estimated cost US$**	**Clay/soil cladding process**	**Estimated cost US$**
Planning of the dump cladding process including selection of machinery, sourcing of weathered coal, fungal inoculum (Fungcoal), and sourcing of irrigation water and preparation of fungal inoculum	$773	Planning of the dump cladding process including selection of machinery, sourcing of top and sub soil, sourcing of irrigation water.	$773
Division of the dump to be cladded into blocks to create manageable sized areas that can be rehabilitated in a scheduled and planned manner	$28	Division of the dump to be cladded into blocks to create manageable sized areas that can be rehabilitated in a scheduled and planned manner	$28
Placement of weathered coal into windrows by haul truck prior to spreading over the discard coal surface	$4,121	Placement of subsoil into windrows	$9,193
The use of either, tracked bull dozers, wheel loaders or front end loaders to spread the weathered coal evenly over the block to be cladded	$134	The use of either, tracked bull dozers, wheel loaders or front end loaders to spread the soil evenly over the block to be cladded	$403
Application of lime and fertilizer	$2,085	Application of lime and fertilizer	$2,085
Ripping or tilling of the area to be cladded	$62	Ripping or tilling of the soil for planting	$62
Application of grass seed	$182	Application of grass seed	$182
Light tilling to cover the grass seed	$34	Light tilling to cover the grass seed	$34
Installation of the irrigation system	$263	Installation of the irrigation system for dump and soil harvest area	$263
Ongoing monitoring and investigation to confirm soil formation, and overall adequacy of cover	$53	Ongoing monitoring and investigation to confirm soil formation, and overall adequacy of cover	$53
Operations particular to Fungcoal		**Operations particular to clay/soil cladding**	
Establishment of an initial block on the discard dump to generate inoculum for the remaining dump	$243	Purchase of land for sourcing of top soil and sub soil	$4,500
Addition of acclimatized arbuscular miccorhizal fungi and *N. fischeri* inoculum	$100	Rehabilitation of the area where soil is harvested from	$1,782

Fungcoal process	Estimated cost US$	Clay/soil cladding process	Estimated cost US$
Ploughing in using disc ploughing with the ability to have deep and vigorous mixing of the weathered coal into the upper 200 mm of the hard discard coal	$62	Applying seed to area from where soil is harvested	$268
Excavation of shallow pits to confirm thorough mixing of weathered coal into the upper 200 mm of discard coal	$6		
Total cost per hectare	**$8,146**	**Total cost per hectare**	**$19,726**

CONCLUSION

This study has shown that fundamental studies in the biodegradation of hard bituminous coal by fungal strains may be scaled up to provide a self-cladding operation in which a humic soil-like material is formed up to 380 mm on the dump surface. This material supports the active growth of grass plantations and, being self-generating, regulates erosion losses and exposure of underlying coal that occurs with clay/soil liner systems. Cost-benefit studies show substantial cost advantages in the use of what has been termed the Fungcoal Process. In follow-up studies hectare-scale plots now under investigation show results comparable to those reported here for the $20m^2$ plots and these results will be reported elsewhere.

In possible large-scale implementation of the technology in the cladding of legacy coal dumps, further studies will be required to determine long term performance and stability of the system under emergency impacts of flooding and fire.

ACKNOWLEGEMENTS

The authors wish to thank Anglo Coal and Bielie van Zyl, Mark Aken, and Henk Lodewijks for generous support for the Fungcoal Project. Also Keith Cowan and staff at the Institute for Environmental Biotechnology at Rhodes University for current data on the five year performance of trial plots.

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