SOIL DEVELOPMENT IN A COAL WASTE, SLAG AND SLUDGE ARTIFICIAL TOPSOIL MIX[1]

by

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Abstract. Waste disposal has become a major concern for industries that create a large amount of by-products due to the cost of landfill and environmental responsibility. Beneficial re-use of these by-products which contain resources for other industries, will solve some of these problems. An artificial soil mix has been created out of ironmaking and sewage wastes, for use in a revegetation program to improve the BHP Steelworks site in Australia. Coal washery refuse, blast furnace slag and sewage sludge have been combined to form a topsoil which is placed on waste mounds and revegetated. Field trials were established to evaluate the soil forming characteristics of this artificial media. The fine fraction (<2mm) of the particle size distribution decreased from 71% to 64% in one year, showing evidence of weathering and particle breakdown. Bulk density remained the same (1.0 g/cm^3) in a two year comparison. The pH of the soil mix declined from 7.6 to 7.1 in one year. Native tree growth in the soil mix was very good, although comparisons could not be made with real soil . The long term viability of the soil mix in relation to nutrient cycling could not be extrapolated with only two years of data. The potential is promising for the use of this soil substitute in urban landscaping, land restoration and revegetation, and opportunities for further research are available.

Introduction

Beneficial Waste Re-use

Industrial waste material has been typically dumped, used as landfill or otherwise disposed of and generally regarded as a problem, but there is an increasing shift towards the beneficial use of these by-products. Waste management strategies currently seek to minimise costs of disposal by the consideration of other methods of use besides dumping. Recycling by-product materials has helped improve the environment by reducing the amount going to landfill, but these methods still regard industrial by-products as wastes. The majority of by-products should be viewed as potential resources. Many 'waste' materials possess beneficial attributes for alternate industries or processes, which should then be fully utilised (see Joost *et al.* 1987, Logan & Harrison 1995). The physical and chemical characterisation of by-products enable these factors to be uncovered.

BHP (the Broken Hill Proprietary Company Limited) in Wollongong, on the east coast of Australia, has an integrated steelworks producing 5 million tonnes of steel a year. Along with this, approximately 2.5 million tonnes of solid wastes are produced, mainly coal washery refuse (CWR), blast furnace slag (BFS) and basic oxygen steel (BOS) slag. Some slag is re-used for sand, cement and road production,

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and coal wash has been used as structural fill in vast quantities in the local area (Thompson & Makin 1990). Waste emplacements of these by-products on site has occurred over many years with several off site locations also utilised. This has meant space for future material disposal has become increasingly scarce.

Revegetation of Waste Emplacements

Due to the urban location, environmental awareness and the company's decision to improve the conditions of the 800 ha BHP site, research into the revegetation of waste emplacements was initiated. Waste stabilisation and site rehabilitation methods of topsoiling and seeding with grass or cover crop were not undertaken. This was because the aim of the large scale project was to establish native vegetation in the waste material, and to eventually create a sustainable "urban forest" (Thompson & Makin 1990). There is no soil on site and very large areas are involved, so the cost and environmental impact of transporting native soil to the site was considered to be excessive. A soil substitute was required to provide the nutrients and growing conditions necessary for plant growth and survival. The abundance and availability of coal washery refuse and slag provided an opportunity to utilise waste products which contained elements beneficial for this purpose.

The BHP Soil Mix

While the major steelworks wastes provide an adequate physical structure for the basis of an artificial soil medium, there is a lack of organic matter, essential nutrients and micro-organism activity. Sewage sludge (biosolids) is a waste product of the sewage treatment system, and seems capable of providing these requirements. It is high in organic matter, contains organic nitrogen (which becomes available slowly), phosphorous and provides a suite of decomposer bacteria and fungi. An artificial growth medium has been created out of coal washery refuse, granulated blast furnace slag and sewage sludge in a ratio of 2:1:1. The materials are blended together with a front end loader to form a substitute topsoil, and stockpiled for various times, depending on the rate of utilisation. Several other wastes have been examined for growth potential, such as fly-ash, foundry sand and BOS slag and dust (Whelan *et al.* 1993) but are not used in the soil mix.

Constituents

The characterisation of this artificial growth medium can be estimated using soil analyses. However, as the material is man-made, unique and not a "real" soil it may be difficult to interpret some results. The properties of each component will also aid in understanding the soil's potential.

Coal washery refuse is the by-product of washing coal from underground mines in the local area for coke making. The majority of the shale and clay minerals are quartz and kaolinite. In addition, the material contains residual coal particles. The black waste is dewatered by belt press to 2-20 mm size fragments and is generally quite alkaline (Table I). The pyrite content is very low in this type of coal.

Blast furnace slag is the by-product of the iron-making process and is created at extremely high temperatures. It is granulated by a high pressure jet of water to a texture similar to coarse silica sand, and consists of calcium and aluminium silicates (especially wollastonite and mullite) (Thompson & Makin 1990). The size fraction is generally 0.2-2 mm and is also quite alkaline (Table I).

The sewage sludge obtained from several Wollongong sewage treatment plants is anaerobically digested after sedimentation (Table I). It's dewatered by either centrifuge or belt press. As well as contributing organic nutrients, there are also some heavy metals at low concentrations. The soil mix project uses all of the local area's sludge, and the volume of soil mix produced is constrained by this supply.

Table I. Physical and chemical characteristics of the constituents of the soil mix (from Whelan and Liangzhong 1991).

	particle size distribution (mm)	**pH (H_2O) 1:1 w/v**	**Ec 1:5 w/v**	**N (%)**
coal wash refuse	0.2 - 20	9.4	0.15	
blast furnace slag	0.2 - 2	9.2	0.21	
sewage sludge		6.4	6.19	5.24

Soil Mix Characteristics

The soil mix is a black, granular, relatively homogeneous mixture with an initially alkaline pH due to the slag and coal wash. The use of salt water to granulate the BFS has meant that some soils made in 1994 are reasonably sodic (Thompson & Makin 1990). Also, due to the granular nature of the mix, the water infiltration rate is very high. Given these attributes from the constituents analyses, no amelioration was attempted. Instead, native species tolerant of these factors were initially chosen. The plant response to this growing medium was exceptional. Many types of native trees, shrubs and ground covers grew quickly even though site conditions are often harsh. The adequate rainfall of the region (approx. 1000 mm/yr with a summer and winter maxima) could also contribute to this effect.

On-Site Revegetation of Waste Mounds

There are currently many types of revegetated areas around the industrial site, with more than 300,000 native plants growing in the artificial soil. A typical garden is comprised of a mound of waste coal washery refuse which ranges considerably in size, from small strips for car parks to boundary, screening mounds sometimes exceeding 1km in length. Soil mix is placed on top of the coal wash base (usually to a depth of 150mm), and bark chip type mulch added. Tree, shrub and ground cover seedlings from local nurseries are planted by hand and watered until established. Over the past eight years 20% of the steelworks site has been revegetated, using over one hundred Australian and exotic plant species growing in the soil mix. Detailed records and site history are kept for future reference. Weed control is carried out by mulching, using woodwaste or woven plastic matting, and herbicides. Lawn is grown in several areas where trees/shrubs are unacceptable (e.g. around heavy industry).

Soil Mix Development

The aim of the greening program was to create a self-sustaining forested ecosystem which required no maintenance, such as nutrient input, weed control or soil additives. It was also to create a value-added soil mix product from wastes for eventual use in the urban landscaping industry. Restoration of degraded sites, revegetation projects and other land rehabilitation efforts may also benefit from this type of media in the future. The long term aim of the soil mix project is for the artificial growing medium to function as a true soil whereby soil forming processes occur. Bradshaw (1987) recognised the importance of the soil substrate as the basis for successful revegetation and restoration attempts. Once physical, chemical and biological barriers to plant growth are ameliorated, there is a much better (and quicker) chance for ecosystem development.

To create a self-sustaining ecosystem it is necessary once the plants (especially legumes) are established, for the litter layer to build up, decomposer organisms to be active and nutrient cycling to begin to operate. For the long term viability of the soil mix it is useful to assess the changes in the physical, chemical and biological characteristics over time which relate to soil development. Due to the nature of the material and the revegetation methods used, it is difficult to predict *a priori*, the rate and direction of these changes.

The factors that influence soil formation are: parent material, climate, slope (topography), organisms and time (Jenny 1941, Crocker 1952, Paton 1978). These universal forces would also act on the soil mix, changing its physical structure, chemical environment and biological activity with time. Many studies on the initial stages of soil development have identified important parameters of soil formation. These include particle weathering and horizon formation (Roberts *et al.* 1988), increases in nitrogen (especially), carbon, Cation Exchange Capacity and decreases in bulk density (Anderson 1977, Varela *et al.* 1993) and increased root biomass and microbial activity (Schafer *et al.* 1979). Revegetation of mine spoil with sewage sludge has shown that the organic source of nitrogen and phosphorous has dramatically improved the establishment of plants, due to the nutrients and the improvement in soil structure it provides (Topper & Sabey 1986, Seaker & Sopper 1988, Wong & Ho 1994).

The present study evaluates some physical, chemical and biological changes of the artificial soil mix in relation to soil formation over time. Several parameters were chosen to fully characterise the initial soil state and then to monitor the development of the mix in a field trial on a site at BHP Flat Products Division, Pt. Kembla for two years. Native tree/shrub species were used as indicator plants.

Methods

Field Trial Description

A very large coal washery refuse emplacement was the base of the trial site at the BHP Steelworks. This level area measuring approximately 60m x 20m, was situated on top of a hill overlooking a blast furnace. Twelve small plots (4m x 2m) were created for the control (no plants), oats and lucerne treatment (three replicates each) with four large plots (10m x 5m) created as the plots for native species. Each plot was lined with plastic sheeting to a depth of 1m of coal wash. The plastic surface sloped to direct leachate water into a sump of several 44 gallon drums welded together. Once backfilled and flattened, each coal wash surface was topsoiled with 300mm of BHP Soil Mix.

The four 'native' plots were planted with *Eucalyptus maculata* (Myrtaceae), *Acacia floribunda* (Mimosaceae) and *Callistemon salignus* (Myrtaceae). On each plot, fifteen individuals of each species were hand-planted (total 45). An irrigation system was established to water twice a week (sometimes three times in the first Summer), but this was stopped after the first year.

Soil Physical Parameters

Soil samples were taken approximately every three months for physical analysis. With a screw auger 20 cm long, ten random samples per plot were taken, and composited. Samples were spread thinly on newspaper then air dried for at least 48 hours. Pretreatment entailed light crushing to disperse the aggregates. Particle size distribution was measured by sieving the "soil" into fractions of: >16mm, 16-8, 8-4, 4-2, 2-1, 1-0.5, 0.5-0.25, 0.25-0.125, <0.125mm using a mechanical shaker. Not all samples were analysed, so only data collected over one year for the significant <2mm fraction is presented. Bulk density was determined at the end of the experiment for comparison with values examined by Whelan & Liangzhong (1991). This was measured by the core method, where a known volume (29.5 cm^3) of soil was sampled, dried and weighed. Ten replicates were sampled from each plot.

Soil Chemical Parameters

Soil was sampled as before, with ten random auger samples composited and sub-sampled for individual analyses. Available nitrogen (nitrate/nitrite and ammonium) and total phosphorous concentration were measured three monthly for twelve months for all plots. The leachate water from each plot was also sampled after six and twelve months, for nitrate, ammonia and phosphate concentration. Each water sample was comprised of five aliquots from individual samples. The pH of the soil mix was measured at the beginning of the experiment and after one year. Ten replicate individual soil samples per plot were air dried, sieved and the <2mm fraction used in a 1:5 soil : $CaCl_2$ solution. Composite samples from the soil mix were also analysed for ten heavy metals (Pb, Cd, Zn, Cr, Cu, Ni, Mo, As, Hg and Se) at the beginning of the experiment.

Soil Biological Parameters

Native plant growth was monitored monthly for a year, then three monthly for another year. Tree height, and diameter of the stem at 20 cm above the ground were measured. This bioassay of the soil mix provides an integrated analysis of the physical structure (relating to rooting environment and water use), nutrient availability, potential toxicities and microbiological decomposer activity. Two pathogen indicators were also measured; enumeration of fecal coliforms and the presence of *Salmonella*.

Results

In the particle size analysis, the initial mean proportion of < 2mm fraction in the soil mix was 71% (± 0.7% SE) and had significantly declined to 64% (± 0.7%) over one year (Fig 1). This meant that the soil mix had

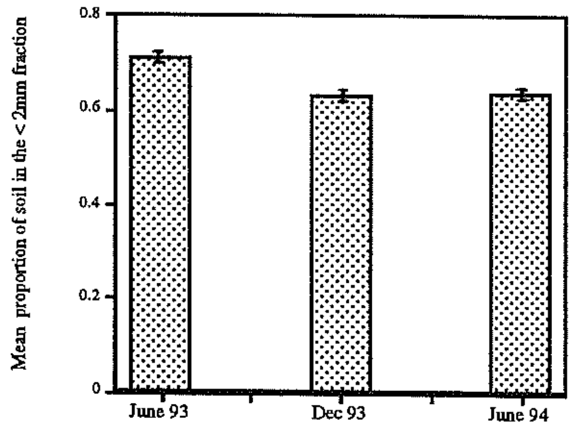

Figure 1. Mean proportion of soil in the <2mm fraction (after sieving) over one year. Standard error is shown.

undergone particle weathering and breakdown, and / or movement down the profile. This breakdown occurred quite rapidly after exposure to the environment, and the subsequent movement of particles has many consequences related to the leaching of ions into deeper layers. The bulk density of the soil mix initially was 1.0 g/cm^3, and after two years it had not changed with a mean value of 1.0 g/cm^3 (± 0.03).

The available nitrogen in the soil mix was initially high due to the sewage sludge, with a mean nitrate/nitrite content of 169 mg/kg (± 44) and ammonia of 50mg/kg (± 13). These values rapidly declined to a very low level in three months and remained there for another nine months (Fig 2). Total phosphorous concentration in the soil mix at the beginning of the experiment was variable with a mean of 740 mg/kg (± 115). Unfortunately there were some doubts about validity in all subsequent analyses, and so they are not reported. The nutrients in the leachate water were low. At six months, the mean nitrate concentration was 25.0 ug/ml (± 5.6), the phosphate

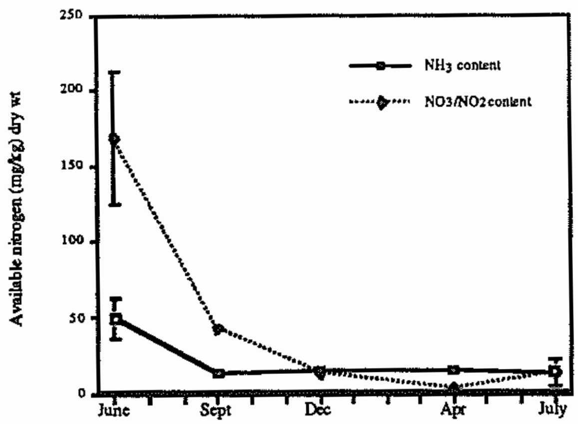

Figure 2. Mean available nitrogen (nitrate/nitrite and ammonia-N) content of the soil mix over one year (mg/kg dry weight).

concentration all <1mg/ml, and the ammonia concentration all <0.1 mg/L. After twelve months the mean nitrate concentration was a very low 0.95 mg/ml (± 0.23) with the phosphate and ammonia concentrations the same as before.

The initial mean pH ($CaCl_2$) of the soil material was 7.59 (± 0.04), and dropped to 7.10 (± 0.02) after one year. This meant that some acidification process had occurred. The heavy metal concentration of the soil mix are all quite low with mean values given in Table II. New draft guidelines on heavy metal concentrations of all biosolids products in Australia are presented for comparison (EPA 1995).

Plant growth was exceptionally good over the extent of the study duration. The native species grew rapidly after establishment and continued to develop. The *Eucalyptus* showed the most accelerated growth, and the *Acacia* also performed well (Fig 3). The *Callistemon* plants displayed relatively less growth which may be due to the advanced stages of the plants when the experiment began. Several plants of all three species died, with *Callistemon* most affected. Over the two years, weed invasion increased, but did not suppress native tree growth. This was mainly due to the delay in weed establishment, their annual life cycle and the large size of the trees when they eventually took hold. Insect attack was also noted. A number of *Acacia* plants flowered in the first spring, with most flowering in the second.

Table II. Heavy metal concentrations (mean and standard error) of the soil mix at the start of the field experiment (n=3), with the maximum metal concentration in any biosolids product from EPA Draft Environmental Management Guidelines (EPA 1995).

Heavy metal	Mean concentration in the initial soil mix (mg/kg)	Standard error	Max. conc. in unrestricted biosolids product (mg/kg)
Pb	4.77	0.19	150
Cd	1.30	0.06	3
Zn	31.0	1.20	200
Cr	7.60	0.50	100
Cu	24.67	2.33	100
Ni	5.50	0.21	60
Mo	2.77	0.32	-
As	0.22	0.12	20
Hg	0.99	0.13	1
Se	0.30	0.12	5

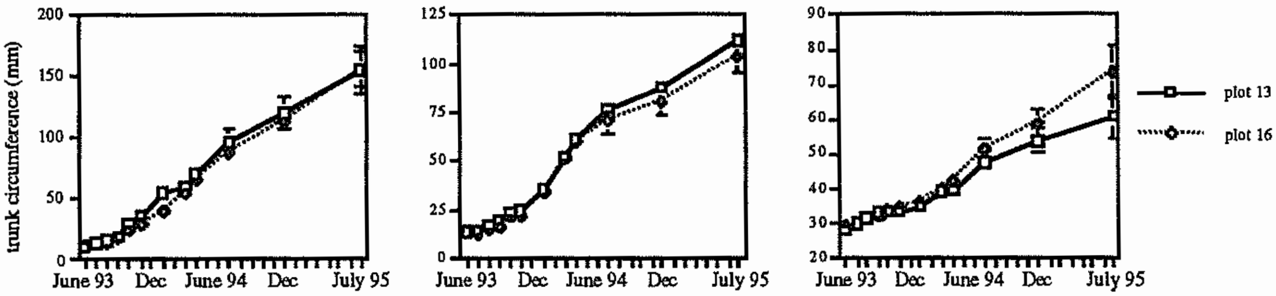

Figure 3. Native tree trunk circumference (mm) at 200mm above ground level for *Eucalyptus maculata*, *Acacia floribunda* and *Callistemon salignus*, over 2 years. Plot 13 and 16 are the 'native' plots.

There were never any *Salmonella* organisms detected in the soil mix in six months of monitoring. At the beginning of the experiment there was a mean of 220 CFU/g for fecal coliforms in the soil mix. After a month there were consistently <10 CFU/g, which remained at this level for six months. The new EPA guidelines for biosolids products have a limit of <1000 MPN per gram for fecal coliforms and no *Salmonella* sp detected in 50g, from a composite sample of five individual grab samples (EPA 1995)

Discussion

Physical soil development

The physical environment of the soil mix seems capable of supporting plant growth, by providing little restriction to root penetration, a range of particle sizes and adequate supply of available water. The results of this experiment suggest that weathering is occurring as there is a significant shift in the particle size distribution. The finer fraction of the soil mix has decreased over time which means that some larger particles have broken down to smaller components and moved down the profile. Coal washery refuse is the most likely component for this to occur as the clay minerals are readily broken down. Further weathering of the other components would also contribute to this increase. It was surprising to find the bulk density remaining the same after two years. An improvement in soil structure would have resulted from an increased value, as the loosely packed material becomes more aggregated. It is possible that the pozzolanic character of the soil mix has decreased with time which would counteract this trend. The sampling equipment may have influenced the accuracy, as the diameter of the corer was 20mm, and perhaps too small for this type of gravelly media.

Available nutrients

The nutrients available were provided by the conversion of the organic N and P source into readily available nitrate and phosphate. Plants did not show any signs of nutrient deficiencies, but clear indications of these have not been reported for the native species used. The initial flush of nitrate from the biosolids did not stay high for long. When the layer of soil mix was applied organic nutrients were exposed to oxygen and water. The aerobic organisms would be able to initiate their biochemical transformations under these optimal conditions (Alexander 1977).

The plants rapidly used the available nutrients, and any excess would have leached down the profile. As very little nitrate and virtually no phosphate or ammonia were detected in the leachate waters, we can assume that most of the available nutrients in the soil were used. This has great benefits, as the potential pollution problem from excess nutrients in the leachate may be minimised if there are enough plants to utilise the resource. The nitrogen cycle (transformations, additions and losses of N) of a community is of vital importance, and the establishment of one is often responsible for disturbed or degraded ecosystem recovery (Cundell 1977, Tate 1985, Sorensen & Fresquez 1991).

The pH of the soil mix decreased over one year which indicates that acidification processes had occurred. There are several ways in which this can happen, for example organic matter oxidation and leaching of carbonate materials. This has relevance to the increased availability of some metals to plants at lower pH values.

Plant growth

Plant growth and condition is a good indicator of soil fertility and potential toxicities. As the growth of the native species on this soil media was considered very good it was a positive sign for the short term success the soil mix. Of course these plants do not represent the vast range of conditions required for all growth, but observations in the established gardens on site suggest that limitations are not common. As the trees grew, shading / competition may have affected the growth rate of some trees, which would increase the variance within a plot. Insect attack may also have influenced relative growth rate. Several types of soil invertebrates were observed but not identified of quantified, these include springtails, Diplurans, Isopods, many ants and earthworms.

Comparisons of soil development

As there is no other artificial soil mix similar to this one, comparisons of rate and direction of change with other systems must be accomplished with caution. Some studies of soil genesis on mine spoil encounter similar conditions; for example, an initial homogeneous, gravelly mix, may be analogous. In these systems, in contrast to the artificial soil studied here, a lack of organic matter and nitrogen, severely limited plant establishment and development of a functioning ecosystem (Stroo & Jencks 1982, Sorensen & Fresquez 1991).

The revegetation attempts of coal mine spoil with sewage sludge in coal mining areas of the US, provides a more realistic comparison for soil formation. Joost *et al.* (1987) conducted a study on revegetation and minesoil development of coal waste, amended with sewage sludge and limestone. They found that after two years there was an improvement in soil structure, a reduction in bulk density and an increase in water holding capacity. Similar results may have occurred for the BHP soil mix had the same parameters been measured.

Another plant growth medium made of wastes, N-Viro Soil, is used in USA, Australia and England as a lime substitute, soil amendment and soil substitute. This material is composed out of dewatered sewage sludge and alkaline industrial by-products, such as lime kiln dust and cement kiln dust (Logan & Harrison 1995). There are many similarities with this media and the BHP soil mix, although the gravelly coal washery refuse would determine the difference in the water holding capacity, bulk density and other physical characteristics. The success of the N-Viro Soil in improving existing soil qualities over two years is recognised, and it would be interesting to determine the long term viability of the material.

Long term viability of the BHP soil mix can not be estimated by extrapolation from a two year study. A survey will be undertaken on site in the future of the many gardens that have been constructed in the last eight years. Many physical, chemical and biological parameters will be measured to quantify trends in soil development over time. The biota of the soil system, i.e. plants, roots, microorganisms and invertebrates will be the focus of this study, due to their importance in nutrient cycling and ecosystem functioning in a new and developing native vegetation community.

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