VIABLE TECHNIQUE FOR DIRECT REVEGETATION OF FINE BAUXITE REFINING RESIDUE

J.W. Wong
Lecturer, Department of Biology
Hong Kong Baptist College
224 Waterloo Road
Kowloon
Hong Kong.

G.E. Ho
Associate Professor, School of Biological and Environmental Sciences
Murdoch University
Murdoch WA 6150
Australia.

ABSTRACT

One major issue confronting the alumina industry is the disposal and management of residues generated from the refining process. They occupy huge areas of land that are devoid of vegetation and subject to wind and water erosion. Hence rehabilitation of red mud storage areas is a high priority task for the industry. The major constraints in rehabilitation are the high alkalinity, salinity and sodicity of the fine residue (red mud). This paper describes a technique developed at Murdoch University aiming at direct revegetation of red mud aided with waste gypsum and sewage sludge. Gypsum amendment followed by 126 mm of rainfall leaching significantly reduced the pH, EC, Na content and ESP of red mud. The reduced pH also significantly suppressed the availability of Al in red mud. The improved soil conditions significantly enhanced the seedling emergence and growth of *Agropyron elongatum* (Tall wheat grass) and *Cynodon dactylon* (Bermuda grass) in pots receiving $\geq$ 5% gypsum amendment with the supply of fertilizer. Sewage sludge amendment gave an additional reduction in EC, Na and ESP for gypsum amended red mud. No evidence of any significant increases in heavy metal contents were observed in the leachate following sewage sludge amendment. Growth of *Agropyron* in sewage sludge and gypsum amended red mud was comparable to that of gypsum amended red mud without fertilizer. The results confirm that direct revegetation of red mud can be achieved by amending red mud with 8% waste gypsum and 16% sewage sludge but sufficient leaching following gypsum amendment and initial fertilization are required for initial plant establishment. The technique is cost effective and requires no expensive topsoil loading nor major earth moving.

VIABLE TECHNIQUE FOR DIRECT REVEGETATION OF FINE BAUXITE REFINING RESIDUE

J.W. WONG AND G.E.HO

1.0 INTRODUCTION

A total of about 42 million tonnes of bauxite refining residues is produced annually from the alumina industry around the world (Glenister, 1987), which contain high concentrations of dissolved Na^{+}, OH^{-}, CO_3^{2-} and $Al(OH)_4^{-}$ and are required to be disposed of in confined impoundments. Huge areas of land have been used for residue storage which are devoid of vegetation and subject to wind and water erosion posing serious threats to the surrounding environment. Therefore reclamation of these impoundments is a major task of the industry to reduce the environmental impacts of bauxite residues disposal and to re-utilize the land occupied. However, revegetation of these impoundments has been demonstrated to be difficult because of the high alkalinity, salinity, Na and Al content, low soil nutrients and poor soil permeability (Barrow, 1982; Fuller et al., 1982; Ward, 1983; Ho et al., 1985; Fuller and Richardson, 1986; Hossner et al., 1986; Wong and Ho, 1988).

The residues generally consist of two fractions, the coarse (red sand) and the fine (red mud) fractions in roughly equal amounts. The coarse fraction has a high permeability and the entrained soluble Na can be leached easily. Meecham & Bell (1977a;b) revegetated red sand successfully with 7% $FeSO_4$ amendment and leaching. Barrow (1982), in another glasshouse study, demonstrated that amending bulk bauxite residues with gypsum allowed pasture to grow with the provision of leaching and fertilization. However, no successful rehabilitation has been reported in the literature for the fine portion of the residues.

In 1987 funding was provided by ALCOA of Australia Ltd. for Murdoch University to develop a technique to revegetate red mud directly. A series of glasshouse experiments was set up aimed at developing means to improve permeability and to reduce the alkalinity and Na content of red mud. Gypsum and sewage sludge were selected as ameliorants for this purpose. Gypsum is commonly used in combating soil alkalinity and sodicity problems by providing a pH buffering capacity and Ca supply in soil (Barrow, 1982; Ho et al., 1985). Sewage sludge, on the other hand, increases soil organic matter content and improves soil aggregate stability and long term fertility (Seaker and Sopper, 1988; Wong and Ho, 1991). The following specific objectives were set to achieve the above aim: (1) to study the effect of gypsum and sewage sludge amendment on chemical properties of red mud, (2) to study the suitability of *Agropyron elongatum* (Tall wheat grass) and *Cynodon dactylon* (Bermuda grass) as revegetation species, and (3) the possibility of any heavy metal accumulation due to sewage sludge amendment.

2.0 MATERIALS AND METHODS

Red mud samples from Alcoa's Kwinana red mud impoundment were air-dried at room temperature and sieved through a 1 cm sieve. Properties of red mud can be summarised here as: pH (saturated extract) 10.5, EC (saturated extract) 7.7 dS m^{-1}, cation exchange capacity (CEC) 41.9 $cmol_c$ kg^{-1}, 0.3% organic carbon, 0.02% total nitrogen, and soluble Na 2000, Ca 16, K 1.9 and Mg 2.7 mg kg^{-1}. Waste gypsum

from CSBP & Farmers Pty. Ltd., manufacturer of superphosphate fertilizers, was oven-dried at 40°C and sieved through a 1 mm sieve to obtain a homogeneous sample. Water extractable metal contents of gypsum were (mg kg^{-1}): Na 755, Ca 2506, Mg 74, K 140, PO_4 2100, Fe 40, Mn 11, Cu 1, Zn 2.7, Cd 1.1, and Al 42. Sewage sludge, from Soil Ain't Soil Pty. Ltd., was air-dried at room temperature for 7 days, and was ground through a 1 mm sieve by an electrical grinder in order to provide a homogeneous sample. Chemical properties of the sewage sludge were as follows: pH 5.9, EC 3.5 dS m^{-1}, 34% total organic carbon, 2.1% total nitrogen, 1.5% total phosphorus, and water extractable metal contents (mg kg^{-1}): Na 408, Ca 1057, K 238, Mg 169, Mn 0.97, Cu 6.63, Zn 2.15, Al 0.13.

The first glasshouse experiment was designed to evaluate the effect of gypsum amendment on chemical properties of red mud and the growth of two alkaline and saline tolerant grass species i.e. *Agropyron elongatum* and *Cynodon dactylon*. Sieved gypsum at 0, 2, 5, and 8% (w/w) were mixed thoroughly with red mud manually in plastic bags. Triplicates 500 g of gypsum amended red mud were placed in pots of 11 cm in diameter containing 100 g of quartz sand at the bottom to retain the fine mud particles. Each pot was leached by slowly adding 1200 ml (equivalent to 126 mm of rainfall) of deionized water. Leaching time ranged from 8 - 24 hours increasing with a decrease in gypsum levels. A sandy soil control was also included for comparison.

After leached red mud mixtures had been dried to field capacity at room temperature, seeds were sown (50/pot for *Agropyron* and 100/pot for *Cynodon*) by pressing them into the soil to a depth of about 1 cm. All pots received a complete fertilizer application in the form of salts by mixing thoroughly with the leached soils. Pots were placed on a glasshouse bench top in a randomized block design, and watered daily to field capacity by weighing to ensure no further leaching. The number of seeds emerging was recorded daily for 20 days, and the plants were allowed to grow for a period of 10 weeks. At harvesting, plants were carefully removed, washed with tap water and rinsed twice with deionized water, oven dried at 70°C for 72 hours and dry weight yields were recorded.

Following the first glasshouse study, another factorial experiment was carried out testing the growth of *Agropyron* in red mud amended with/without gypsum and with three different amounts of sewage sludge (0, 8, and 16% w/w). The gypsum application rate used was based on the findings from the glasshouse study described above. Similar leaching and glasshouse procedures as described above were used in this study. Forty seeds of *Agropyron* were sown in each pot and all pots without sewage sludge treatment received a complete fertilizer treatment.

The final 100 ml of leachates from the gypsum-sewage sludge study were collected and pH and EC determined immediately. Sodium content in the leachates was analysed using flame photometry (FP), while Ca, Fe, Zn, Cu, and Cd contents by atomic absorption spectrometry (AAS). About 50 g of soil samples were removed from each pot before plant growth experiment, air-dried at room temperature for 7 days, and then ground lightly to pass through a 2 mm sieve. Soluble Ca, Mg, K, Na, Al and NO_3 content were extracted with double deionized water (soil:water = 1:5). Available Fe, Mn and PO_4 content of gypsum-sewage sludge soil samples were extracted with 1 M NH_4HCO_3 plus 0.005 M DTPA (Soltanpour and Schwab, 1977). pH and EC were determined using the water extract within 24 h. Calcium, Mg, Al, Fe, Mn were measured using AAS whereas K and Na were measured using

FP. Nitrate was determined using Azo-dye colorimetry, and PO_4 using molybdenum blue colorimetry on a Technicon Auto-analyser (Franson, 1975). Aerial portions of plant samples from the gypsum-sewage sludge study were ground in a stainless steel mill to pass through a 20 mesh screen and digested using a sulphuric acid-peroxide method (Lowther, 1980). Calcium, Mn, Fe, Na, K and Mg were measured as described previously. Total N and P were measured colorimetrically on a Technicon Auto-analyser.

Data were analysed using a SAS statistical package on an IBM-PC. One way ANOVA was carried out to compare the means of different treatments. Where significant F values were obtained, differences between individual means were tested using the Least Significant Difference Test at the 0.05 significance level. Correlation coefficients and p-values were determined for all possible variable pairs.

3.0 RESULTS AND DISCUSSION

3.1 Gypsum Amendment on Red Mud

Chemical properties of gypsum amended red mud are given in Table 1. The addition of gypsum reduced the pH of red mud significantly from 10.5 to 8.6 at ≥ 5% gypsum amendment. The reduction in pH is due to the precipitation of hydroxides and carbonates by Ca (Wong & Ho, 1988). However, EC of gypsum amended red mud remained high ranging from 2.7 to 4.5 $dS\ m^{-1}$. The soil EC is expected to remain high until all the sparingly soluble gypsum is leached. However the availability of Ca has an extended buffering effect on any further release of alkalinity in the form of Na from red mud and will maintain the soil pH at around 8.5 similar to that of a calcareous soil system. The resulting high soluble salt content can be removed with an extended period of leaching. Experience from the reclamation of a saline bentonite clay mine in U.S.A. also indicates that gypsum and/or $CaCl_2$ amendments require a long stabilization period (Moore et al, 1991).

TABLE 1

Soil chemical properties of gypsum amended red mud before plant growth experiment.

Treatment¶	pH	EC ($dS\ m^{-1}$)	Na	Ca	Mg (mg kg^{-1})	Al	ESP
R	10.5 a § (0.0)#	3.92 a (0.48)	1410 a (282)	5.43 b (0.77)	0.11 c (0.02)	1.04 a (0.31)	70.4 a (2.9)
RG2	9.98 b (0.06)	2.69 a (0.28)	925 b (106)	9.64 b (0.86)	0.27 c (0.01)	0.24 b (0.23)	55.9 b (3.3)
RG5	8.68 c (0.04)	4.45 a (0.26)	950 b (42)	694 a (48)	17.1 a (0.3)	0.14 b (0.05)	11.6 c (0.1)
RG8	8.56 c (0.08)	4.04 a (0.23)	925 b (50)	764 a (44)	16.8 a (0.2)	0.08 b (0.09)	10.8 c (0.3)
SS	7.32 d (0.13)	0.06 b (0.00)	7.5 c (2.1)	6.49 b (0.73)	0.66 b (0.22)	0.32 b (0.14)	0.15 d (0.04)

§ Values followed by the same letter within the same column do not differ significantly at the 5% level according to the Least Significant Difference Test.

Values in parentheses are standard deviation of mean of triplicates.

¶ Treatment explanation: R=red mud, G=gypsum, SS=sandy soil, 2,5 and 8=2, 5, & 8% respectively.

Addition of gypsum also increased the release of Mg from red mud through cation exchange between Ca^{2+} from gypsum dissolution and Mg^{2+} in the mud. The increase in soil Mg content will benefit plant growth because red mud may not release Mg without the addition of Ca^{2+} (Fuller, 1982). The increase in Ca and Mg, but a reduction in Na following gypsum amendment also reduced the ESP of red mud from 70 to around 11. The lower ESP of gypsum amended red mud indicates that there will be a better soil permeability.

Soluble Al content of unamended red mud was significantly higher than the toxicity level of 0.5 mg kg^{-1} recommended by Chapman (1966). The reduction in pH following gypsum amendment precipitated aluminate as aluminium hydroxide and reduced the soluble Al content in red mud.

Table 2 gives the results of seedling emergence and plant dry weight yields. All young seedlings of *Cynodon* died within the first week of growth in red mud control reflecting the unfavourable environment for plant growth. Seedling emergence was improved at ≥ 5% gypsum amendment and was comparable to that of sandy soil control, with over 93% seedling emergence for *Agropyron,* though only 56-61% for *Cynodon*. Similarly, dry weight yields were improved following gypsum amendment at ≥ 5% and *Agropyron* showed a better growth performance than *Cynodon*. The increase in root dry weight reflects the improved soil conditions for root growth. The highest total dry weight yield of *Agropyron* was about 163% of the sandy soil control while *Cynodon* was only 86%. Thus *Agropyron* appears to be a better revegetation species for red mud.

TABLE 2

Seedling Emergence and Dry Weight Yields of *Agropyron* and *Cynodon* grown in gypsum amended red mud and sandy soil control.

	Agropyron				Cynodon			
Treatment¶	Seedling Emergence (%)	Dry Weight (mg/pot) Root	Shoot	Total	Seedling Emergence (%)	Dry Weight (mg/pot) Root	Shoot	Total
R	66.0 b§ (5.7)#	2.6 c (2.1)	105 c (1)	107c (2)	22.0 c (1.4)	•	•	•
RG2	72.7 b (14.2)	24.7 c (32.7)	158 c (67)	183 c (98)	48.0 b (1.4)	11.6 c (0.7)	19.1 d (3.8)	30.7 d (3.9)
RG5	92.7 a (3.1)	1080 ab (77)	1126 b (20)	2207 b (79)	59.3 a (3.1)	94.8 b (13.7)	297 c (42)	392 c (50.6)
RG8	94.0 a (0.0)	1192 a (86)	1401 a (75.9)	2593 a (162)	56.0 a (4.0)	149 ab (40)	623 b (103)	772 b (142)
SS	94.0 a (2.0)	946 b (122)	1108 b (185)	2054 b (308)	56.7 a (3.2)	260 a (128)	789 a (31)	1049 a (136)

§ Values followed by the same letter within the same column do not differ significantly at the 5% level according to the Least Significant Difference Test.

Values in parentheses are standard deviation of mean of triplicates.

• Not enough sample for determination.

¶ Treatment explanation: R=red mud, G=gypsum, SS=sandy soil, 2,5 and 8 = 2, 5 & 8% respectively.

Seedling emergence and dry weight yields had high negative correlations with soil pH, Al and ESP ($p \leq 0.05$) for both plant species, but no significant correlations with EC, Ca, and Mg ($p > 0.05$). This indicates the excess salts and high alkalinity in red mud are the major factors affecting seed germination. Gypsum amendment caused a significant reduction in ESP which would improve the soil hydraulic conductivity and reduce soil impedance to seedling penetration. Reduction in soil pH also resulted in a significant reduction in Al content which would improve the initial establishment of plants. This allows a better root growth which in turn would enhance nutrient uptake.

This initial experiment indicates that gypsum is effective in reducing soil alkalinity and releasing Na from red mud. However, leaching is required to remove excess salts in red mud following gypsum amendment. The plant growth results are encouraging but organic amendment is needed to improve the soil nutrient status.

TABLE 3

Soil chemical properties of gypsum and sewage sludge amended red mud before plant growth.

Sample	pH	EC ($dS\ m^{-1}$)	Na	Ca	Mg	K	Al	Mn	Fe	PO_4	NO_3	ESP
			mg kg^{-1}									
R‡	10.22 a § (0.00)#	2.30 b (0.04)	1200 a (283)	3.7 b (0.8)	0.26 f (0.07)	23.4 b (6.5)	1.07 b (0.07)	0.25 b (0.14)	5.6 d (0.3)	3.8 e (0.1)	0.48 abc (0.06)	70.3 a (2.7)
RS1	10.16 a (0.01)	1.80 b (0.09)	704 bc (136)	7.6 b (1.2)	1.40 d (0.50)	39.1 b (1.4)	4.48 a (1.56)	0.22 b (0.04)	10.9 c (0.5)	8.9 d (0.3)	0.42 abc (0.14)	47.2 b (7.4)
RS2	9.97 b (0.16)	1.53 b (0.29)	580 c (28)	7.9 b (1.1)	1.10 de (0.20)	81.3 a (10.8)	4.73 a (1.03)	1.23 a (0.43)	21.5 a (3.0)	22.1 c (2.1)	0.38 c (0.09)	42.8 b (3.1)
RG	8.50 c (0.02)	4.39 a (0.11)	1345 a (64)	686 a (15)	17.1 c (0.0)	25.4 b (12.2)	0.10 c (0.06)	0.15 b (0.04)	5.5 d (0.4)	19.7 c (0.5)	0.40 abc (0.00)	12.7 c (0.6)
RGS1	8.38 cd (0.01)	4.14 a (0.04)	903 b (4)	693 a (5)	21.1 b (0.0)	74.5 a (6.0)	0.19 c (0.04)	0.55 b (0.01)	17.2 b (0.5)	35.8 b (3.2)	0.33 bc (0.01)	11.0 c (0.0)
RGS2	8.31 d (0.00)	4.06 a (0.02)	790 bc (70)	698 a (12)	24.2 a (0.4)	82.8 a (17.3)	0.31 c (0.12)	1.90 a (0.05)	19.6 ab (1.1)	43.4 a (0.8)	0.55 a (0.06)	9.5 c (0.8)
SS	7.32 e (0.13)	0.06 c (0.02)	4.2 d (3.1)	4.5 b (0.7)	0.66 e (0.22)	2.6 c (1.4)	0.23 c (0.01)	0.78 b (0.06)	7.1 d (0.4)	4.2 e (0.6)	0.38 c (0.03)	0.6 d (0.6)

§ Means within a column followed by the same letters are not significantly different at the 5% level according to the Least Significant Difference Test.

Values in parentheses are standard deviation.

‡ R = red mud, S1 = 8% sewage sludge, S2 = 16% sewage sludge, G = 8% gypsum.

3.2 Gypsum and Sewage Sludge Amendment

Amending gypsum or sewage sludge individually with red mud significantly reduced the pH and EC of the leachate as compared to red mud control (Figure 1a and 1b). Sewage sludge amendment showed no additional effect on pH and EC for gypsum amended red mud. The addition of 16% sewage sludge significantly increased Ca but decreased Na content in the final leachate. This indicates that either sewage sludge has a high adsorption capacity for Na or the improved hydraulic conductivity following sewage

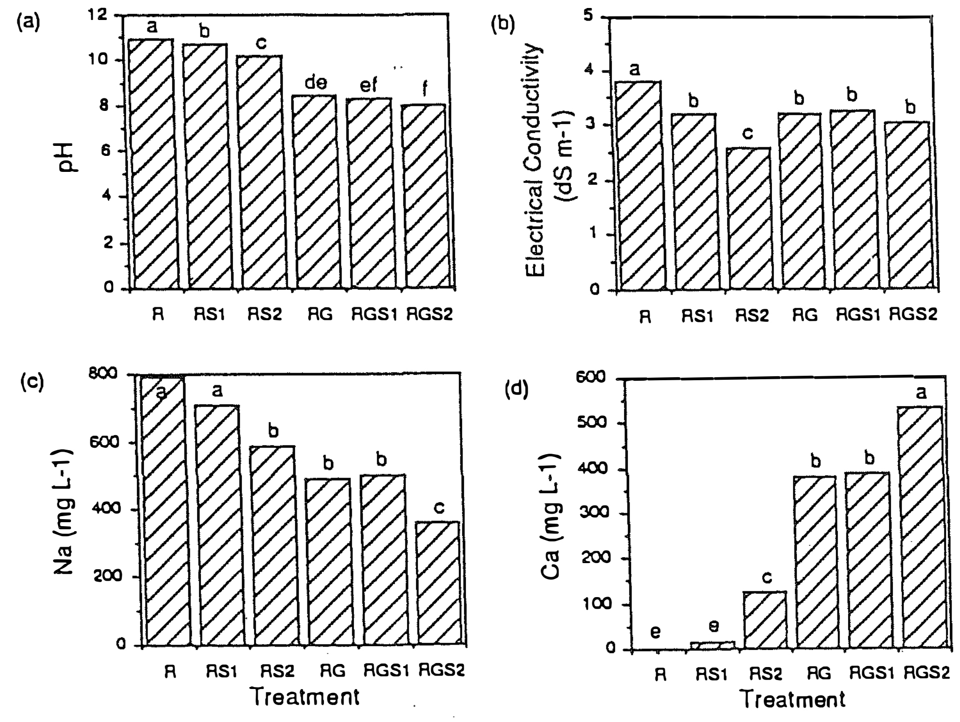

Figure 1. pH (a), electrical conductivity (b), Na (c) and Ca content (d) of the final leachate collected from red mud amended with gypsum and sewage sludge. Means without the same letter above bars are significantly different at 5% level according to the Least Significant Difference Test (R=red mud, G=gypsum, S=sewage sludge, 1=8%, and 2=16%).

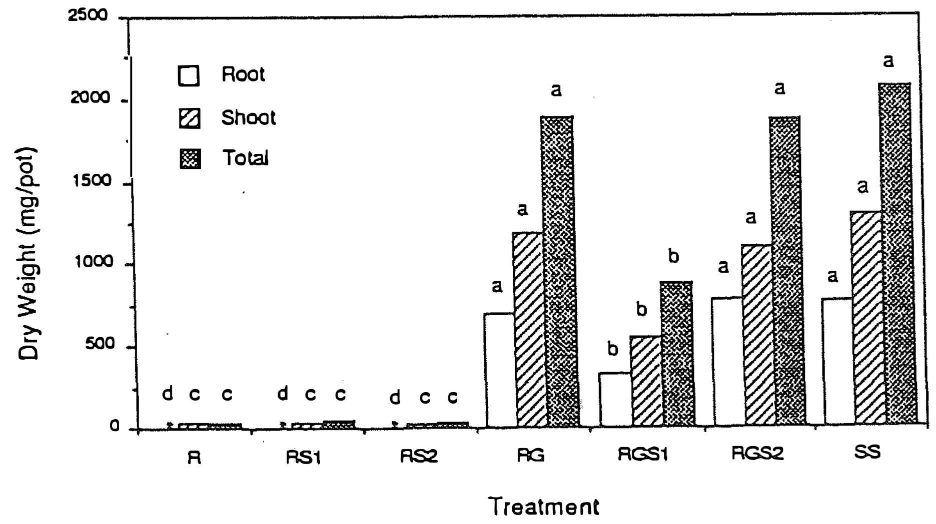

Figure 2. Dry weight yield of Agropyron grown in red mud amended with gypsum and sewage sludge. Means without the same letter above bars are significant different at the 5% level according to the Least Significant Difference Test (R=red mud, G=gypsum, S=sewage sludge, 1=8%, and 2=16%).

sludge amendment enhances the leaching removal of excess Na in red mud. It is likely that both play a role (Wong and Ho, 1991). No evidence of any significant increases in heavy metal contents in the leachate was observed due to the addition of sewage sludge (Data not shown). Hence, the addition of sewage sludge does not raise any potential risk of heavy metal contamination in red mud.

Results of analysis of the solids are similar to those of the leachate. Gypsum amendment was effective in reducing pH of red mud from 10.2 to 8.5 (Table 3). Addition of sewage sludge only resulted in a slight reduction in soil pH but a significant decrease in Na concentration of red mud. This in turn significantly reduced the ESP of red mud from 70 to about 50. However, this effect was not strong enough to cause any significant further reduction in the ESP of gypsum amended pots, which remained at an ESP of about 10-13. Magnesium and PO_4 contents on the other hand increased following gypsum and sewage sludge amendment. The increase can be explained by the enriched Mg content in gypsum and PO_4 contents in both gypsum and sewage sludge. Sewage sludge alone also enhanced K and Mn contents of red mud. These two elements were found to be low in red mud (Fuller et al., 1982). Nitrate levels remained very low, less than 0.5 mg kg^{-1} for all treatment groups. Addition of sewage sludge did not obviously increase NO_3 contents in soil. This is likely due to the high solubility of NO_3, and the high alkalinity and salinity of red mud which may also depress nitrification in soil (Kissel et al., 1985).

The addition of sewage sludge resulted in an increase in soluble Al content in red mud which is probably due to the dissolution of organic bound Al in sewage sludge at high pH condition. However, gypsum amendment buffered the pH of red mud to about 8.5 which significantly suppressed the availability of Al as indicated by the soil analysis.

Seedling emergence of *Agropyron* in red mud was significantly enhanced with the addition of sewage sludge (Data not shown). The effect of sewage sludge was however not as obvious in pots receiving gypsum amendment because of the already well improved soil conditions. Plant growth in red mud, as expected, was seriously depressed by the saline, alkaline and sodic conditions while addition of sewage sludge to red mud showed no obvious effect on plant growth (Figure 2). Gypsum amendment and fertilizer application significantly enhanced plant growth and was comparable to that of sandy soil control. Dry weight yields in sewage sludge and gypsum amended pots also increased significantly and were comparable to sandy soil control and gypsum amended red mud. The increase in dry weight yields is likely due to either the enhanced soil nutrient status or the improved soil physical properties for plant growth following sewage sludge amendment as revealed in a separate field study (Wong and Ho, 1991).

Results from this second glasshouse study indicate that sewage sludge is important in providing an organic medium for seed germination and adsorption sites for reducing Na in soil solution. However, addition of sewage sludge to red mud increased the level of soluble Al to about 4 mg kg^{-1}. This will deter root growth and result in a low root/shoot ratio. Therefore, sewage sludge by itself is not sufficient unless the red mud has been buffered to a pH of < 9. The latter can be achieved by incorporating gypsum.

Tissue nutrient analysis indicated that sewage sludge amendment also enhanced soil nutrient availability. Nitrogen and P contents in shoot tissue of *Agropyron* grown in gypsum amended red mud with 16% sewage sludge treatment were comparable to that of sandy soil control and its fertilizer treated counterpart (Table 4). This indicates P impurity in waste gypsum and both P and N in sewage sludge could provide sufficient N and P for plant growth. Although sewage sludge contained fairly high K content, tissue K contents were low in all sewage sludge amended group indicating the low availability of K in sewage sludge.

TABLE 4

Elemental contents of shoot tissue of *Agropyron* grown in gypsum and sewage sludge amended red mud.

Treatment‡	N	PO_4	K	Na	Ca	Mg	Mn	Fe	Zn	Cu
	%						mg kg^{-1}			
R†	2.67 a §	0.18 b	0.19 cd	2.84 a	0.08 b	0.05 e	28.9 ab	1753 a	43.7 a	17.1 d
RS1†	2.59 a	0.19 b	0.03 d	1.69 bc	0.12 b	0.05 e	28.5 ab	581 bc	45.7 a	101 b
RS2†	2.54 a	0.13 b	0.05 d	1.94 b	0.11 b	0.07 cde	40.1 a	719 b	48.1 a	134 a
RG	2.48 a (0.65) #	0.29 a (0.00)	2.01 a (0.25)	1.30 c (0.00)	0.47 a (0.11)	0.18 a (0.00)	16.5 b (1.0)	505 c (68)	8.6 bc (1.7)	11.7 d (3.5)
RGS1	1.37 a (0.29)	0.17 b (0.03)	0.72 bc (0.03)	1.52 bc (0.03)	0.45 a (0.00)	0.06 de (0.01)	22.8 b (6.6)	289 d (25)	41.8 a (6.8)	25.7 c (5.3)
RGS2	2.52 a (0.37)	0.22 ab (0.17)	1.04 b (0.31)	1.67 bc (0.01)	0.48 a (0.01)	0.08 bcd (0.01)	26.4 ab (1.9)	462 cd (38)	48.2 a (2.4)	27.1 c (4.6)
SS	1.59 a (0.08)	0.21 ab (0.01)	1.74 a (0.07)	0.10 d (0.08)	0.39 a (0.02)	0.10 b (0.01)	19.8 b (0.5)	59 e (25)	17.2 b (3.8)	9.3 d (1.5)

§ Means within a column followed by the same letters are not significantly different at the 5% level according to the Least Significant Difference Test.

Values in parentheses are standard deviation.

† Only enough sample for one single digestion.

‡ R = red mud, S1 = 8% sewage sludge, S2 = 16% sewage sludge, G = 8% gypsum.

Addition of sewage sludge significantly reduced Na uptake from 2.8%, considered to be toxic, in red mud control to about 2%. This further supports the previous finding that sewage sludge suppressed the availability of Na in soil. Gypsum amended red mud had significantly higher Ca contents than pots without gypsum treatment while sewage sludge amendment by itself had a slight but statistically insignificant role in increasing tissue Ca content.

Sewage sludge amendment significantly enhanced the availability of Mn, Cu and Zn in red mud and was considered more than sufficient for plant growth. The tissue Zn concentrations were all within the normal range of 25 to 150 mg kg^{-1} showing no accumulation. *Agropyron* growing in sewage sludge amended red mud in fact showed a high accumulation of Cu. Phytotoxicity might occur in these treatment groups as stunted growth was observed. Tissue Cu contents in sewage sludge and gypsum amended red mud was above the 20 mg kg^{-1} considered to be a level which might be excessive, though in this case only marginal.

4.0 CONCLUSION

The experimental results show that direct revegetation of red mud is possible through the use of gypsum and sewage sludge. The addition of gypsum to red mud significantly reduced soil pH to about 8.5 and released Na from red mud. The reduced pH also suppressed the availability of Al in the mud. Sewage sludge on the other hand reduced the availability of Na, improving soil permeability and provided a medium for seed germination. It also acted as a source of nutrient, both major and minor elements, for plant growth. However, direct addition of sewage sludge alone to red mud resulted in very poor root growth because of the high soil pH and the release of organic bound Al from sewage sludge, which would seriously inhibit root growth.
A co-amendment rate of 8% gypsum and 16% sewage sludge is recommended for red mud revegetation. The success in using sewage sludge and gypsum for red mud rehabilitation depends on a carefully managed residue disposal and revegetation programme. There needs to be a combination of mixing, leaching, chemical amendment and fertilization. The present technique can be incorporated to the final phase of the waste management plan for red mud disposal by mixing sewage sludge and gypsum with red mud before disposal. The mixture should be allowed to dry and drain off excess salts prior revegetation. Alternatively gypsum and sewage sludge can be added to dry surface red mud and mixed by rotary hoeing as in normal agricultural practice. A monitoring programme is recommended to assess the surface mud quality to ensure sufficient leaching has been achieved before the implementation of the revegetation programme. Leaching can be achieved simply by natural rainfall. Unpublished results show that a rainfall leaching of > 80 mm is sufficient (Wong, 1991). Supplementary fertilization must be supplied at the initial stage of revegetation to maintain sufficient growth because of the slow sewage sludge decomposition. Results from a pilot field revegetation programme indicate that the technique developed in the present study is very promising (Wong and Ho, 1991).

5.0 ACKNOWLEDGEMENTS

The financial assistance of Alcoa of Australia Pty. Ltd. is gratefully acknowledged. The authors would also like to thank Prof. J. Loneragan of Murdoch University and Dr. S. Ward of Alcoa of Australia Pty. Ltd for their invaluable comments.

6.0 REFERENCES

Barrow, N.J. (1982). Possibility of using caustic residue from bauxite for improving the chemical and physical properties of sandy soil. Aust. J. Agric. Res., 33:275-285.

Chapman, H.D. (1966). Diagnostic criteria for plants and soils. Univ. of California. 749 pp.

Franson, M.H. (1975). Standard methods for the examination of water and wastewaters. 14th Ed. American Public Health Association, Washington, D.C.

Fuller, R.D., Nelson, E.D.P. and Richardson, C.J. (1982). Reclamation of red mud (bauxite residues) using alkaline-tolerant grasses with organic amendments. J. Environ. Qual., 11:533-539.

Fuller, R.D. and Richardson, C.J. (1986). Aluminate toxicity as a factor controlling plant growth in bauxite residue. Environ. Toxicol. Chem., 5:905-915.

Glenister, D.J. (1987). Alcoa's experiences with alternative techniques for bauxite residue disposal and the rehabilitation of old residue areas. In N. Stockton, (Ed.), Tailings Disposal and Management Symposium, Murdoch University, Western Australia.pp.50-70.

Ho, G.E., Newman, P.W.G., Mathew, K. and De Potter, H. (1985). Neutralization of bauxite processing residue with copperas. CHEMECA, 85:102-108.

Hossner, L.R., Loeppert, R.H., Woodard, H.J., Moore, T.J. and Thompson, T.L. (1986). Reclamation and vegetation of bauxite residue. Alcoa Report No. 3. Soil and Crop Sci. Dept., Texas A & M Univ., Coll. Station.128 pp.

Kissel, D.E., Sander, D.H. and Ellis, R., Jr. (1985). Fertilizer-plant interactions in Alkaline soils. In O.P. Engelstad, F.C. Biswell, T.C. Tucker and L.F. Welch (Eds.), Fertilizer Technology and Use. pp.153-196. Soil Sci. Soc. Am. Inc., Madison, Wisconsin, USA.

Lowther, J.R. (1980). Use of a single sulphuric acid-hydrogen peroxide digest for the analysis of *Pinus radiate* needles. Commun. in Soil Science and Plant Anal., 11:175-188.

Meecham, J.R. and Bell, L.C. (1977a). Revegetation of alumina refinery wastes 1. Properties and amelioration of materials. J. Aust. Expt. Agric. & Husb., 17:679-688.

Meecham, J.R. and Bell, L.C. (1977b). Revegetation of alumina refinery wastes. 2. Glasshouse experiments. J. Aust. Expt. Agric. & Husb., 17:689-696.

Moore, K.S., DePuitt, E.J., Schuman, G.E., Meining, J.L. and Fisser, H.G. (1991). Revegetation of non-topsoiled, Orphan bentonite mine spoil in Wyoming as influenced by organic and inorganic amendments. In: W. Oaks & J. Bowden, (Eds.) Proceedings of the 1991 National Meeting of the American Society of Surface Mining and Reclamation. May 14-17, 1991, Durango, Colorado. pp.403-412.

Seaker, E.M. and Sopper, W.E.. (1988). Municipal sludge for minespoil reclamation: II. Effects on organic matter. J. Environ. Qual., 17:598-602.

Soltanpour, P.N. and Schwab, A.P. (1977). A new soil test for simultaneous extraction of macro- and micro- nutrients in alkaline soils. Comm. Soil Sci. Pl. Anal., 8:195-207.

Ward, S.C. (1983). Growth and fertilizer requirements of annual legumes on a sandy soil amended with fine residue from bauxite refining. Reclam. and Reveg. Res., 2:177-190.

Wong, J.W. (1991). Sodium release characteristics and revegetation of fine bauxite refining residue. Thesis (PhD). School of Biological and Environmental Sciences, Murdoch University, Western Australia. 461 pp.

Wong, J.W. and Ho, G.E. (1988). Neutralization and cation dissolution characteristics of bauxite refining residue. In M.M. Varma and J.H. Johnson, Jr. (Eds.) Hazardous and Industrial Waste. Proc. of the Twentieth Mid-Atlantic Industrial Waste Conf. Howard Univ., Washington, D.C. pp. 247-264.

Wong, J.W. and Ho, G.E. (1991). Effects of gypsum and sewage sludge amendment on physical properties of fine bauxite refining residue. Soil Sci., 152(5):326-332.

SELECTION OF TREES FOR REHABILITATION OF BAUXITE TAILINGS IN WESTERN AUSTRALIA

David T. Bell[1] and Samuel C. Ward[2]

[1]Department of Botany, The University of Western Australia
Nedlands, W.A. 6009, Australia and
[2]Alcoa of Australia Ltd., P.O. Box 252, Applecross, W.A. 6153, Australia

ABSTRACT

Tree species expected to tolerate the high-pH conditions of bauxite processing waste residue sites were initially identified in glasshouse trials using trickle irrigation and increasing levels of NaOH-induced alkalinity. Of 29 taxa tested, the most tolerant were *Casuarina obesa, Melaleuca lanceolata, M. armillaris, M. nesophila, Eucalyptus camaldulensis, E. halophila, E. loxophleba, E. platypus* and *Tamarix aphylla.* A field trial with 24 taxa was established in a bauxite tailings disposal impoundment at Kwinana, Western Australia in June 1990. Field trial conditions included soils with pH values as high as 11.00. In general, the relative survival and growth of field trial seedlings after eight months were predicted by the response under glasshouse trial conditions. Appropriately designed stress trials can be important ecological techniques in choosing species most capable of surviving difficult environmental conditions in the rehabilitation of damaged landscapes.