Revegetation of Pb/Zn Mine Tailings, Guangdong Province, China

Z. H. Ye[1,4]
J. W. C. Wong[1]
M. H. Wong[1,5]
A. J. M. Baker[2]
W. S. Shu[3]
C. Y. Lan[3]

Abstract

The Lechang lead/zinc mine is located in the north part of Guangdong Province, southern China. The tailings residue from the extraction of lead/zinc ores was permanently stored in tailings ponds, which required revegetation to reduce the environmental impact. A field study was, therefore, conducted to evaluate the effects of different ameliorants, including: (1) pig manure (PM); (2) mushroom compost (MC); (3) burnt coal residue (BC); (4) fly ash (FA); and (5) surface soil on the growth of *Agropyron elongatum* (tall wheat grass), *Cynodon dactylon* (Bermuda grass), *Lolium multiflorum* (Italian ryegrass), *and Trifolium repens* (clover) in the tailings residue. The results from the core profiles indicated that adding FA (10 cm) or BC (15 cm) as a barrier layer between the cover soil and the tailings could increase pH, compared to the treatment with soil only. *C. dactylon* grew well and had a high cover (90–100%) in all the treatment plots except the control plots without any amendment. *A. elongatum* and *L. multiflorum* had a higher cover when grown in plots covered with a barrier layer using FA or BC (both with surface soil), than those grown in plots covered with surface soil only. Treatment plots receiving a thicker soil cover (30 cm) had a better dry weight yield than those with a thinner soil cover (15 cm), regardless of the barrier layer. The results from this study indicate that the use of either 15 cm BC or 10 cm FA as a barrier layer with surface soil, or the use of 38 tonnes PM/ha and 6 cm MC, were effective for the revegetation of Pb/Zn mine tailings. *C. dactylon* was the best species among the four species used for revegetation.

Key words: reclamation, Pb/Zn mine tailings, burnt coal, mushroom compost, fly ash, Bermuda grass, Italian ryegrass, clover.

Introduction

In China there are over 8,000 national and 230,000 private mining companies presently operating, resulting in 200,000 km^2 of derelict land, which includes the loss of 370,000 ha of agricultural land (Young 1988). Therefore, it is essential to restore the productivity of these derelict or damaged lands. Lead (Pb) and zinc (Zn) mine tailings constitute the majority of the metal mine tailings produced in Guangdong Province, P. R. China. Our previous studies (Ye et al. 1992; Zhang et al. 1996; Lan et al. 1997; Shu 1997; Wong et al. 1999) indicate that the major problems of revegetation of Pb/Zn mine tailings in southern China include the following: (1) high metal concentrations that are phytotoxic, especially Zn and Pb; (2) poor soil fertility with insufficient essential plant nutrients (such as N and P); (3) poor physical properties; and (4) high contents of total sulfide (S) and low pH. The toxicity of heavy metals and deficiency of nutrients are common characteristics of metal mine tailings, and are major constraints on plant colonization (Shu 1997). Lechang Pb/Zn mine was selected in this field trial because of the following reasons. First, it is located in the Pb/Zn mine zone of southern China, so the climate is similar to another Pb/Zn mine in the same zone. Second, its geographical-chemical condition and process of refinery are also similar to the other Pb/Zn mine in the same zone. The main objectives of the present experiments are to evaluate the effectiveness of using different covering materials available locally, including soil and four different waste materials, namely pig manure (PM), fly ash (FA), burnt coal (BC), and mushroom compost (MC), and to select plant species for the revegetation of tailings. *Agropyron*

[1]Institute for Natural Resources and Waste Management and Department of Biology, Hong Kong Baptist University, Kowloon Tong, Hong Kong, PR China
[2]Department of Animal and Plant Sciences, University of Sheffield, Sheffield, S. York S10 2TN, U.K.
[3]School of Life Science, Zhongshan University, Guanzhou, PR China
[4]Current address: Department of Plant and Microbial Biology, 111 Koshland Hall, University of California, Berkeley, CA 94720-3102, U.S.A.
[5]Address correspondence to M. H. Wong, Institute for Natural Resources and Waste Management and Department of Biology, Hong Kong Baptist University, Kowloon Tong, Hong Kong, PR China

elongatum (tall wheat grass), *Cynodon dactylon* (Bermuda grass), *Lolium multiflorum* (Italian ryegrass) and *Trifolium repens* (clover) were used for the field trial.

The Lechang Pb/Zn Mine Operation (lat 24°40′N, long 113°20′E) is located about 4 km east of Lechang City in the northern part of Guangdong Province, P.R. China. The climate is sub-tropical and the annual rainfall is about 1,500 mm. The mean annual temperature is about 20°C and the extreme values are −7°C in January and 41°C in July. It is a conventional underground mining operation covering an area of 1.5 km^2, and produces approximately 30,000 tonnes of tailings annually, with a dumping area of 60,000 m^2. The refinery uses mainly the froth floatation method to separate the pyrite fraction. The rest of the waste material is discharged in slurry form into the tailings pond, with the fine fraction settled at the center and the coarse fraction at the periphery of the pond.

Materials and Methods

Sample Collection

Surface tailings samples of the top 20 cm for chemical analyses were collected from the Pb/Zn mine tailings pond in October 1995, before the field experiment. Samples of PM and MC were supplied by a local farm and FA was obtained from a local cement work. Burnt coal residue (BC), which included some domestic refuse, was collected from a nearby landfill, and surface soil (red-yellow podzolic soil a sandy loam) was collected from an uncultivated area far away from the mining area. All samples for chemical analyses were collected in triplicate.

Seeds of all four species, *C. dactylon*, *A. elongatum*, *L. multiflorum*, and *T. repens*, were obtained from a local seed company. *C. dactylon* has been commonly used as a tolerant plant species for mine residue revegetation (Williamson et al. 1982). Our early ecological survey of the Lechang Pb/Zn mine area indicated that *C. dactylon* is able to survive on metal-contaminated soils (2,168–9,353 mg/kg Zn, 1,073–3,704 mg/kg Pb, and 9.6–37 mg/kg Cd, respectively), and the metal-tolerant test using root elongation of tillers collected from different areas indicated that the mine population of *C. dactylon* has evolved co-tolerance of Pb, Zn, and Cd (Shu 1997). The seedlings of the strain of *C. dactylon* used for the field trial also possessed some degree of tolerance of Pb, Zn, and Cd according to the root elongation test. Some *Agropyron* species, such as *Agropyron desertorum* and *Agropyron intermedium* have also been used for mine reclamation (Williamson et al. 1982), whereas *A. elongatum* has been used to grow on salt-affected land (Roundy 1985). As a legume species, *T. repens* is used to colonize metal-contaminated soils for increasing soil nitrogen (Wu 1989; Johnson et al. 1994). Being a fast growing grass, *L. multiflorum* was chosen to provide a surface cover to increase soil organic material rapidly.

Revegetation

About half of the tailings pond was roto-tilled to a depth of 20 cm, and then divided into plots (2 × 2 m). There were eight treatments (Table 1) with four replicates each arranged in a completely randomized block. All plots received a lime application of 40 tonnes/ha by roto-tilling the top 20 cm before amending with the respective amelioration for each treatment plot. All plots received a N, P, K fertilizer (N:P:K = 16:16:16) at a rate of 150 kg/ha. Each plot was divided into four subplots of 1 × 1 m, and each subplot was hand broadcast with seeds of *C. dactylon*, *A. elongatum*, *L. multiflorum*, and *T. repens*, at rates of 2 g/m^2, 5 g/m^2, 4 g/m^2, and 4 g/m^2, respectively. All plots were watered once daily, except for rainy days, for the first five months.

After 9.5 months, the cover of each species in each subplot was recorded visually and the above-ground portion was harvested on 31 May 1997, except for *T. repens*, which was dead. Core profile samples (0–10 cm, 10–20 cm, 30–40 cm, 40–50 cm, 50–60 cm) were also collected with a core soil sampler (2 × 4″) from the treatment plots after collection of plant samples. After harvest, plant samples were transported to the laboratory and washed carefully with tap water to remove any attached particles, then rinsed three times with deionized water, and oven-dried at 80°C for 48 hr to a constant weight. Dry weight yields were recorded.

Chemical Analysis

Air-dried tailings, soil, PM, BC, MC, and FA samples were ground to pass through a 2-mm sieve and analyzed for the following physico-chemical parameters: pH (solid:distilled water = 1:2 w/v) (Beckman pH

Table 1. Experimental design for field trial.*

Treatments	
Control	*Tailings*
M6	Tailings amended with pig manure (37.8 t/ha, 0–15 cm) + 6 cm mushroom compost
S15	Tailings + 15 cm soil
S30	Tailings + 30 cm soil
B15S15	Tailings + 15 cm burnt coal residue + 15 cm soil
B15S30	Tailings + 15 cm burnt coal residue + 30 cm soil
F10S15	Tailings + 10 cm fly ash + 15 cm soil
F10S30	Tailings + 10 cm fly ash + 30 cm soil

*Lime was added to each plot at the rate of 40 t/ha before adding materials on the plots.

meter); total organic carbon (C) and total nitrogen (N) contents (PE 2400, CHNS analyzer); water-extractable NH_4^--N (indophenol-blue method), total and water extractable PO_4^{3-} contents (molybednum blue method); total metal (Zn, Pb, Cd, Cu, Fe, and Mn) contents (diacid digestion method, conc. HNO_3, and conc. $HClO_4$ = 5:1) and water-extractable metal (Zn, Pb, Cd, Cu, Fe, and Mn) contents (solid:distilled water = 1:2 w/v) using atomic absorption spectrometry (AAS) (Page et al. 1982).

The soil profile samples were air-dried for two weeks before grinding to pass through a 2-mm sieve. They were analyzed for pH (solid:distilled water = 1:2 w/v).

Statistical Analysis

The data were analyzed using a SPSS statistical package on an IBM personal computer (Little & Hills 1978). One-way analysis of variance (ANOVA) was carried out to compare the means of different treatments. Where signif-

Table 2. General properties of tailings (TL), surface soil (soil), burnt coal (BC), mushroom compost (MC), pig manure (PM), and fly ash (FA).*

	pH	EC (dS/m)	Organic matter (%)	N (mg/kg)	P	K	Zn	Pb	Cd	Cu	Fe	Mn
TL	6.05 ± 0.15	4.18 ± 0.06	0.65 ± 0.17	429 ± 92	52 ± 7.9	1,380 ± 220	2,132 ± 208	1,042 ± 62	12 ± 3.0	81 ± 9.3	46,366 ± 437	291 ± 36
Soil	6.62 ± 0.12	0.32 ± 0.04	1.2 ± 0.22	1,390 ± 288	15.71 ± 1.96	3,201 ± 1,117	303 ± 20	60 ± 5.3	ND	8.0 ± 2.1	2,240 ± 189	280 ± 11
BC	7.06 ± 0.11	1.56 ± 0.21	0.50 ± 0.06	922 ± 145	22.79 ± 5.06	2,557 ± 249	64 ± 6.7	234 ± 37	ND	30 ± 5.1	27,700 ± 3,444	141 ± 4.6
MC	7.94 ± 0.11	8.85 ± 0.28	15.83 ± 1.66	2,490 ± 172	284.3 ± 9.5	6,934 ± 1,422	15 ± 1.0	16 ±1.7	ND	29 ± 6.9	30,584 ± 9,793	181 ± 4.9
PM	7.65 ± 0.05	2.87 ± 0.12	70.87 ± 6.54	12,300 ± 1,100	1,100 ± 89	2,310 ± 21	11 ± 0.12	25 ± 2.3	ND	7.7 ± 0.75	6,620 ± 134	191 ± 3.2
FA	9.64 ± 0.14	1.86 ± 0.01	0.59 ± 0.06	690 ± 0.23	3.54 ± 0.001	2,273 ± 82	40 ± 1.6	386 ± 2.1	7.0 ± 0.43	61 ± 1.4	20,591 ± 1,114	140 ± 0.4
				Water soluble (mg/kg)		*DTPA-extractable*						
TL				0.11 ± 0.01	0.09 ± 0.01	0.20 ± 0.06	79 ± 6.4	196 ± 17.6	0.48 ± 0.03	5.04 ± 4.50	26 ± 4.7	30 ± 1.9
Soil				0.04 ± 0.003	0.06 ± 0.02	2.4 ± 1.5	30 ± 4.7	25 ± 2.7	0.24 ± 0.04	2.1 ± 0.17	13 ± 1.7	5.6 ± 0.42
BC				0.11 ± 0.0002	0.09 ± 0.002	1,423 ± 104	13 ± 1.8	4.3 ± 0.75	0.20 ± 0.01	3.1 ± 0.13	78 ± 5.7	18 ± 0.90
MC				0.22 ± 0.02	2.53 ± 0.46	1,834 ± 150	24 ± 1.3	10.0 ± 0.39	0.46 ± 0.02	5.7 ± 0.45	208 ± 16	53 ± 3.8
PM				0.40 ± 0.03	0.20 ± 0.03	879 ± 6.3	0.85 ± 0.07	0.26 ± 0.23	0.11 ± 0.002	2.14 ± 0.04	37 ± 0.06	36 ± 0.06
FA				0.06 ± 0.02	0.15 ± 0.02	142 ± 1.1	10 ± 0.27	16 ± 0.08	0.05 ± 0.01	1.2 ± 0.02	25 ± 1.6	0.64 ± 0.002

*Mean ± SE, n = 3.

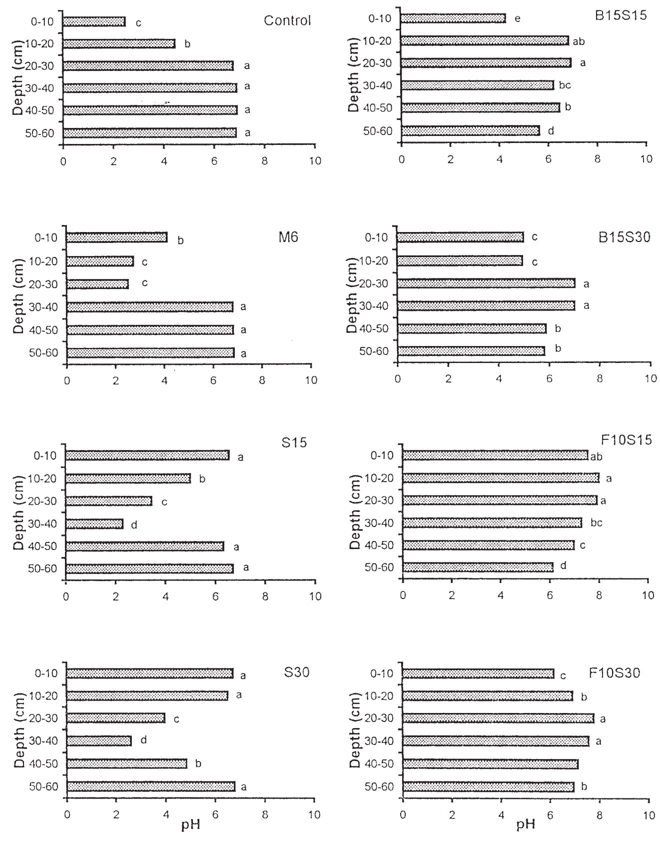

Figure 1. pH in the profiles of different treatments (mean, n = 4). Control, Tailings; M6, Tailings amended with Pig manure + 6 cm Mushroom compost; S15, Tailings + 15 cm Soil; S30, Tailings + 30 cm Soil; B15S15, Tailings + 15 cm Burnt coal residue + 30 cm Soil; F10S15, Tailings + 10 cm Fly ash + 15 cm Soil; F10S30, Tailings + 10 cm Fly ash + 30 cm Soil. Different letters in the same profile indicate significant difference at $p < 0.005$ according to Tukey-HSD test).

Table 3. Dry weights ($g/100cm^2$) of seedlings of *Cynodon dactylon*, *Agropyron elongatum* and *Lolium multiflorum* grown in the plots of Lechang Pb/Zn mine with different treatments (18 August 1996–31 May 1997).*

Species	*M6***	*S15*	*S30*	*B15S15*	*B15S30*	*F10S15*	*F10S30*
Cynodon dactylon	7.35 ± 1.24*a*	6.00 ± 0.49*a*	6.11 ± 1.38*a*	7.39 ± 0.88*a*	6.61 ± 0.86*a*	5.46 ± 1.82*a*	6.60 ± 0.93*a*
Agropyron elongatum	5.70 ± 1.29*bc*	2.16 ± 0.77*c*	7.91 ± 1.64*bc*	11.45 ± 2.06*ab*	10.43 ± 1.79*ab*	5.24 ± 0.91*bc*	16.92 ± 2.86*a*
Lolium multiflorum	8.65 ± 1.42*bc*	4.90 ± 0.87*c*	6.68 ± 1.06*bc*	11.78 ± 1.80*abc*	16.21 ± 2.61*a*	8.59 ± 0.87*bc*	11.93 ± 0.89*ab*

*Mean ± SE, $n = 10$. Different letters in a row indicate significant difference at $p < 0.05$ according to Tukey-HSD test.
**Please refer to Table 1 for the explanation of treatments.

icant F values were obtained, differences between individual means were tested using Tukey-HSD tests at 0.05 significance level. After being transformed to logarithm scale, pH values were analyzed using one-way ANOVA.

Results and Discussion

Table 2 shows the general properties of TL, PM, BC, MC, and FA. Tailings collected in October 1995 before roto-tilling were slightly acidic (pH 6.1). However, pH value of the TL samples (0–15 cm) collected from the same tailing pond in April 1996 was dramatically reduced to 1.8 after roto-tilling. FA was alkaline (pH 9.6), MC was slightly alkaline (pH 7.9) while the soil was near neutral (pH 6.6). TL had low total organic matter and N contents, and high contents of total Zn and Pb. However, only a small proportion of total Zn and Pb could be extracted by DTPA. Total Zn and Pb contents in the soil were within the soil background ranges of 10 to 300 mg/kg and 15 to 106 mg/kg, respectively (Alloway 1995). The PM and MC had higher organic matter and total N and K contents, and lower total Zn and Pb contents than TL, soil, BC, and FA (Table 2).

The pH of the soil profiles of each treatment is shown in Figure 1. The top 20 cm of the control treatment were highly acidic, especially for the first 10-cm layer (pH 2.52). However, tailings below 20 cm were near neutral. Total S content of the tailings was very high, ranging from 9.9 to 26.6% with an average of 15.4%, and had a high acid-generating potential of 540 kg H_2SO_4/t (Wong et al. 1999). From the surface of the tailings to a depth of 10 cm, pH decreased from 6.1 in October 1995 to 2.5 in April 1995, a decline that was possibly caused by oxidation of S in the tailings after roto-tilling. The results from control, M6, S15, and S30 indicated that acidification occurred mainly at the surface (0–20 cm) and had little effect on the stratum beneath 20 cm owing to the lack of oxygen. In these four treatments, pH values in the top 20 cm of tailings were significantly lower than those below 20 cm. Rapid oxidation of sulfide minerals, especially iron pyrite (FeS_2) in the tailings causes the release of acidity, resulting in a decrease in pH (Ahmed 1974). The rate of oxidation of pyrite is influenced by the surface area of the material available for weathering; small particulates such as mine tailings weather faster than larger pieces of rock (Williamson et al. 1982). The pH values of the F10S15, F10S30, B15S15, and B15S30 profiles were significantly higher than those of other profiles, especially in F10S15 and F10S30. The results indicate that both FA and BC were effective in raising the pH of tailings when they were used as barrier layers. This was possibly because of the alkaline nature of both FA (pH 9.6) and BC (pH 7.9). Fly ash has been used in the reclamation of many acidic coal mine spoils in the United States (Williamson et al. 1982).

All seedlings grown in the control plots were dead within four weeks. The results presented in Tables 3 and 4 show that all three plant species had higher dry

Table 4. Zinc and lead concentrations in shoots of *Cynodon dactylon*, *Agropyron elongatum*, and *Lolium multiflorum* collected from Lechang Pb/Zn mine field plots (18 August 1996–31 May 1997).*

	*M6***	*S15*	*S30*	*B15S15*	*B15S30*	*F10S15*	*F10S30*
Zn							
Cynodon dactylon	214 ± 88*ab*	271 ± 14*a*	198 ± 12*abc*	134 ± 11*bcd*	151 ± 15*bcd*	67 ± 8.8*d*	93 ± 8.0*cd*
Agropyron elongatum	97 ± 41*ab*	120 ± 45*a*	78 ± 12*ab*	51 ± 8.5*ab*	63 ± 8.8*ab*	37 ± 11*b*	56 ± 5.2*ab*
Lolium multiflorum	150 ± 46*ab*	163 ± 21*a*	163 ± 14*a*	98 ± 7.0*abc*	112 ± 8.2*abc*	52 ± 6.9*c*	85 ± 6.5*bc*
Pb							
Cynodon dactylon	33 ± 5.3*a*	27 ± 1.2*ab*	19 ± 2.8*bc*	21 ± 3.2*bc*	16 ± 2.4*c*	17 ± 2.9*c*	21 ± 1.1*bc*
Agropyron elongatum	35 ± 4.9*a*	37 ± 2.7*a*	20 ± 0.9*b*	18 ± 1.1*b*	17 ± 1.1*b*	19 ± 3.4*b*	15 ± 3.6*b*
Lolium multiflorum	31 ± 2.1*a*	31 ± 2.1*a*	25 ± 1.3*ab*	25 ± 4.8*ab*	22 ± 2.5*ab*	19 ± 3.5*b*	18 ± 2.0*b*

*Mean ± SE, $n = 4$. Different letter in a row and a same metal indicate a significant difference at $p < 0.05$ according to Tukey-HSD test.
**Please refer to Table 1 for the explantion of treatments.

Table 5. Coverage (%) (range and mean) of seedlings of *Cynodon dactylon*, *Agropyron elongatum*, and *Lolium multiflorum* grown in the plots of Lechang Pb/Zn mine with different treatments (18 August 1996–31 May 1997).*

Species	*Control***	*M6*	*S15*	*S30*	*B15S15*	*B15S30*	*F10S15*	*F10S30*
Cynodon dactylon	0	100	100	90–100 (96)	100	100	95–100 (99)	90–100 (95)
Agropyron elongatum	0	27–100 (60)	5–57 (25)	5–95 (59)	62–100 (84)	12–100 (72)	60–100 (77)	100
Lolium multiflorum	0	70–95 (83)	82–100 (92)	70–100 (91)	100	80–100 (95)	100	100

*Mean ± SE, $n = 4$.
**Refer to Table 1 for the explanation of treatments.

weights when grown in the plots with barrier layers and a soil cover than in the plots covered with a soil layer only. Treatment plots receiving a thicker soil layer (30 cm) had a higher dry weight yield than those with a thin soil layer (15 cm), regardless of the barrier layers. Field observations showed that plants grown in B15S15 and B15S30 plots had a deeper root system than those grown in other plots. This was possibly because of the coarser texture of BC, which improved soil aeration and facilitated root growth. Therefore, a barrier layer together with a 30-cm soil cover on tailings is a suitable reclamation method for acidic Pb/Zn mine tailings.

Cynodon grown in M6 plots had the second highest dry weight yield (Table 3) and a cover of 100% (Table 5). The other two species, *Agropyron* and *Lolium* did not grow well and chlorosis was noted on the leaf of *L. multiflorum* when grown in M6. PM and MC appeared to be simple, useful, and economic reclamation materials, but metal tolerant species such as *Cynodon* should be chosen. Both PM and MC had a high organic matter (70.9% and 25.8%, respectively), which could improve the poor physical characteristics and nutrient status of tailings for plant growth (Wong & Ho 1994). As the rate of organic residue application is increased in abandoned Pb/Zn mine tailings, Cd, Pb, and Zn will be prevalent in the weakly mobile, non-bioavailable forms (Johnson et al. 1994).

The results from the dry weights and cover (Tables 3 & 5), and field observation showed that *Cynodon* had a higher cover than the other two species in all the treatment plots. It grew luxuriantly in all the treatment plots, including S15 and M6, two treatments in which *Agropyron* and *Lolium* did not grow well. In fact, *Cynodon* not only covered the subplots but also invaded other nearby subplots. Our previous field survey in the Pb/Zn mine area found that it grew well around the mine areas, including the tailings-contaminated areas near the tailings pond. These results, together with the results from our root elongation tests using tillers and seedlings, suggested that *Cynodon* has a high metal (Zn and Pb) tolerance, besides being suitable for the local climate (Shu 1997).

In addition to its rapid establishment, persistence, and degree of productivity, *Cynodon* has also been found to have evolved Pb-, Zn- (Wu & Antonovics 1976; Shu 1997), and arsenic-tolerant (Wild 1974) ecotypes. Also, it was used effectively to stabilize copper mine tailing berms in southern Arizona (Day & Ludeke 1973). The present results indicate that *C. dactylon* could be used to revegetate Pb/Zn mine tailings in southern China.

Conclusion

The treatments of B15S15 (15 cm BC + 15 cm soil), B15S30 (15 cm BC + 15 cm soil) and F10S30 (10 cm FA + 30 cm soil) were the most effective methods to facilitate revegetation of the acidic Pb/Zn mine tailings. M6 (MC + PM) was also effective, but this method required the use of a metal-tolerant species, such as *C. dactylon*. The use of waste materials as barrier layers was effective in buffering against the toxic effects of the tailings. Use of either BC or FA as a barrier layer, together with the addition of a 30-cm soil layer on top, is recommended as a cost-effective means for reclaiming acidic Pb/Zn mine tailings. This also provides an alternative for the disposal of these waste materials. *C. dactylon* is an excellent revegetation plant material for Pb/Zn mine tailings reclamation in southern China.

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LITERATURE CITED

Ahmed, M. U. 1974. Coal mining and its effects on water quality. Pages 49–56 in R. A. Deju, editor. Extraction of minerals and energy. Ann Arbor Science, Ann Arbor, Michigan.

Alloway, B. J. , editor. 1995. Heavy metals in soils. 2nd edition. Blackie, Glasgow, United Kingdom.

Day, A. D., and K. L. Ludeke. 1973. Stabilizing copper mine tailing disposal berms with giant bermuda grass. Journal of Environmental Quality **2:**314–315.

Johnson, M. S., J. A. Cooke, and J. K. W. Stevenson. 1994. Revegetation of metalliferous wastes and land after metal mining. Pages 31–48 in R. E. Hester and R. M. Harrison, editors. Mining and its environmental impact. Issues in Environmental Science and Technology, Royal Society of Chemistry, London.

Lan, C. Y., W. S. Shu, and M. H. Wong. 1997. Revegetation of Pb/Zn mine tailings: phytotoxicity of the tailings. Pages 119–130 in D. L. Wise, editor. Global environmental biotechnology. Elsevier Science, London.

Little, T. M., and J. J. Hills. 1978. Agricultural experimentation: design and analysis. John Wiley & Sons, Chichester, United Kingdom.

Page, A. L., R. H. Miller, and D. R. Keeney. 1982. Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd edition. Soil Science Society of America, Madison, Wisconsin.

Roundy, B. A. 1985. Root penetration and shoot elongation of tall wheat grass and basin wild rye in relation to salinity. Canadian Journal of Plant Science **65:**335–343.

Shu, W. S. 1997 Revegetation of lead/zinc mine tailings. Ph.D. Thesis. Zhongshan University, Guangzhou, China.

Wild, H. 1974. Arsenic tolerant plant species established on arsenic mine dumps in Rhodesia. Kirkia **9:**265–278.

Williamson, N. A., M. S. Johnson, and A. D. Bradshaw. 1982. Mine waste rehabilitation: the establishment of vegetation on metal mine waste. Mining Journal Books, London.

Wong, J. W. C., and G. Ho. 1994. Sewage sludge as organic ameliorant for revegetation of fine bauxite refining residue. Resources, Conservation, and Recycling **11:**297–309.

Wong, J. W. C., C. M. Ip, and M. H. Wong. 1999. Acid-forming capacity of lead-zinc mine tailings and its implications for mine rehabilitation. Environmental Geochemistry & Health **20:**149–155.

Wu, L. 1989. Colonization and establishment of plants in contaminated sites. Pages 270–284 in A . J. Shaw, editor. Heavy metal tolerance in plants: evolutionary aspects. CRC Press, Inc., Boca Raton, Florida.

Wu, L., and J. Antonovics. 1976. Experimental ecology in *Plantago lanceolata* and *Cynodon dactylon* from a roadside. Ecology **57:** 205–208.

Ye, Z. H., G. Z. Chen, C. Y. Lan, and L. C. Li. 1992. The accumulation and distribution of heavy metals in Typha latifolia from the Pb/Zn mine waste water. Acta Phytoecologica et Geobotanica Sinica **16:**72–79.

Young, K. 1988. Destruction of ecological habitats by mining activities. Agricultural Ecology **16:**37–40.

Zhang, Z. Q., C. Y. Lan, and M. H. Wong. 1996. Revegetation of Pb/Zn mine tailings: germination and seedlings establishment of plants. Land Contamination and Reclamation **4:**269–280.