ELSEVIER Journal of Hazardous Materials 41 (1995) 123–134

JOURNAL OF HAZARDOUS MATERIALS

Revegetation of coarse taconite iron ore tailing using municipal solid waste compost

Michael R. Norland, David L. Veith*

US Bureau of Mines, Twin Cities Research Center, Minneapolis, MN 55417, USA

Received 5 July 1994; accepted in revised form 15 November 1994

Abstract

On Minnesota's Mesabi Iron Range, coarse taconite iron ore tailing is often used as the principal material in the construction of dams for large tailing impoundments. Mineland reclamation rules in Minnesota require that tailing dams be vegetated to control erosion for dam stability and safety. Coarse taconite iron ore tailing is characterized chemically by an alkaline pH, low organic matter content, lack of plant-essential nutrients, and low cation-exchange capacity; physically by its coarse texture, lack of structure, low water-holding capacity, and dark color; and biologically by a lack of microorganisms. To investigate the potential of composted municipal solid waste to ameliorate these conditions and make the material more amenable to plant establishment and growth, the US Bureau of Mines implemented a series of factorial experiments at two active taconite mine sites in northeastern Minnesota. At each experimental site, vegetative cover has improved depending on the type of municipal solid waste compost used and rate of application. At site I, overall plant cover across all treatments has improved from zero prior to experimental manipulation to 72% after four years, with seven treatment combinations exceeding 90% cover. At site II, overall plant cover has improved from zero prior to experimental manipulation to 83% after four years, with 23 treatment combinations exceeding 90% cover. At both sites, total cover has progressively increased over four years and has not reached steady-state conditions. These results suggest a possible new strategy for reclaiming difficult sites through the use of municipal solid waste compost.

1. Introduction

Increased awareness of environmental issues during recent years has caused a greater emphasis on research to resolve environmental problems associated with both coal and noncoal mining. A major concern of the mining industry is the stabilization of solid wastes produced by mineral processing, as these wastes

* Corresponding author. Tel.: 612-725-4709. Fax: 612-725-4526.

SSDI 0304-3894(94)00115-4

account for more than 80% of the nation's nonagricultural, land disposed solid wastes [1]. Johnson and Paone [2] estimated that between 1930 and 1980 more than two million hectares of land in the United States were affected by mining operations, with 85% of that total affected by surface mining sites. Soni and Vasistha [3] estimated that by the year 2000, almost a million hectares per year would be affected by mining.

The primary purpose of reclaiming mineral-related mining waste sites is to prevent the waste from being moved by wind and water. Physical, chemical, and vegetative methods are used to stabilize mineral wastes [4–6]. Physical stabilization protects or isolates the wastes from the environment with physical barriers such as liners and clay caps. Chemical stabilization involves the incorporation of chemical compounds into the wastes to form a resistant crust to reduce wind and water erosion. Vegetative stabilization is the preferred reclamation technique for mineral-related wastes; it is more permanent, has better aesthetics, and allows a wider range of end uses at closure of the mining operation [6].

Above and below ground plant structures provide protection from the physical effects of wind and water erosion. Vegetation reduces wind velocity at the surface, captures fugitive dust particles, reduces raindrop impact, reduces runoff by increasing infiltration, and reduces the overland flow of water and sediment. Vegetative stabilization also improves the chemical and biological characteristics of the mine waste by increasing the organic matter content, nutrient level, cation exchange capacity, and biological activity. These chemical, biological, and physical improvements can accelerate the development of a viable nutrient cycle and self-sustaining vegetative cover, and restore the affected area to some acceptable steady-state condition for secondary land use.

Stabilization or reclamation of mineral waste varies according to the waste type. In general, hard rock mine tailing is nutrient poor, and may contain excessive salts and heavy metals that are toxic to plants, lacks organic matter and normal microbial populations, is low in plant-available water, is subject to erosion resulting in air and water quality problems, and lacks other physical properties such as structure that are required to support a vegetative community.

This paper discusses US Bureau of Mines (USBM) revegetation research on the Mesabi Iron Range of northeastern Minnesota. The technology being developed is an ecological approach to stabilize mineral wastes that attempts to stimulate inherent soil processes to restore soil productivity and vegetative cover to some acceptable steady-state condition. This involved research to improve the chemical, physical, and biological properties of the coarse tailing wastes associated with iron ore mining in northeastern Minnesota.

Historically, the approach used to stabilize iron ore tailing wastes in northeastern Minnesota has been to use inorganic fertilizers to establish vegetative cover. The USMB ecological approach involves the development of a combination of chemical and physical stabilization techniques, specifically, additions of organic residues to enhance vegetative establishment and stimulate inherent soil processes.

2. Materials and methods

The Minnesota Department of Natural Resources, Minerals Division, identified the stabilization of coarse taconite tailing materials as a major environmental concern in Minnesota. Coarse tailing is used to construct retaining dams on the Iron Range, and these structures must be revegetated as required by the State of Minnesota Department of Natural Resources Rules Relating to Mineland Reclamation (6 MCAR 1.0401–1.0406). All tailing basins, dikes, and dams must have a 90% ground cover of living vegetation and its litter after three growing seasons on all areas except slopes which face south or west. Such sloped areas must meet the 90% ground cover criteria within five growing seasons since last disturbance. Within 10 growing seasons since last disturbance, the area should have a vegetative community similar to an approved reference area; it should be self-sustaining, regenerating, or in a stage of recognized vegetative succession leading to an acceptable end use [7].

Minnesota's taconite iron ore industry currently produces 40–45 million metric tons of taconite pellets per year as a feed material for the domestic production of iron and steel products. As a result of this production, 80–100 million metric tons of coarse d fine tailing materials (about half-coarse and half-fine) are generated and must be disposed of each year. The mining companies are quite successful in storing and reclaiming the fine tailing materials to State regulations, but the coarse tailing defies all reasonable revegetation efforts, mainly because of its coarse texture and lack of nutrients. Since the coarse tailing material is used to construct dams to contain the fine tailing, it will obviously be exposed to the elements and a highly visible structure. Therefore, it must be stabilized in an acceptable manner before mine closure.

3. Sites

Organic amendment of coarse tailing for revegetation research began at the Minntac and Eveleth Mines sites on the Mesabi Iron Range in 1990, with the installation of test plots incorporating locally available or potentially available organic amendments to simulate the organics in a natural soil. Minerals of concern at the Minnesota sites include iron oxides and silicates, with some aluminum and manganese oxides, but very little else. Table 1 shows some of the chemical properties of the two Minnesota sites.

One site (Site I) selected for this research was the USX Corporation's Minntac taconite mine near Mt. Iron, Minnesota, 325 km north of Minneapolis-St. Paul. This plant is the Minnesota Ore Operations of USS Division of USX. The fine tailing is placed in sectors of the tailing basin, created by a combination of coarse and fine tailing dams. The disposal site consists of over 27 km of coarse tailing dam covering about 3000 ha. The dam consists of inner and outer segments of coarse tailing each about 45 m wide, and a central core of fine tailing about 30 m wide. The overall height averages 10 m.

The other site (Site II) is at the Eveleth Mines Fairlane Plant, located near Forbes, Minnesota, 30 km south of the USX site. The 300 ha tailing basin is constructed

Table 1
Chemical properties of Minnesota taconite tailing materials prior to organic residue application

Property, unit	Research site	
	Minntac	Eveleth
pH[a]	8.1	8.2
Conductivity, dS/m[a]	0.2	0.2
Total organic nitrogen, %[b]	0.01	0.0
Total organic carbon, %[c]	0.17	0.08
Carbon : nitrogen ratio	17 : 1	—
Organic matter, %[d]	0.3	0.1
CEC, cmol (+)/kg[e]	6.9	5.1
Extractable analysis (mg/kg)		
Phosphorus[f]	2	3
Calcium[g]	800	481
Magnesium[g]	147	156
Potassium[g]	404	493
Sodium[g]	5	11
Sulfate[h]	10	3
Iron[i]	5108	4203
Copper[i]	2	2
Zinc[i]	20	4
Manganese[i]	1803	811
Aluminum[i]	71	77
Cadmium[i]	0.7	0.5
Chromium[i]	1.3	0.9
Nickel[i]	0.7	0.6
Lead[i]	5	3

[a] Soil/water ratio 1 : 1.
[b] Kjeldahl method.
[c] High temperature induction furnace.
[d] Walkley Black method.
[e] NH_4/KCl replacement.
[f] Olsen (0.5 *M* $NaHCO_3$) extracts, analyzed colorimetrically.
[g] 1 *M* NH_4OAc (pH 7) extracts, analyzed AAS.
[h] 0.008 *M* $CaCH_2(PO_4)_2$, methyleneblue estimation.
[i] 1 *N* HNO_3 extracts, analyzed ICP-AES.

in a series of lifts using coarse tailing at the angle of repose to form the dam. The final height of the dam will be about 46 m.

Northeastern Minnesota is characterized by harsh climatic conditions; short, warm summers and long, cold, snowy winters. Both sites receive about 635 mm of precipitation per year, with about 109 frost-free days and seasonal temperatures varying from − 38 °C in the winter to 33 °C in the summer.

In 1993, a total of 823 mm of precipitation was recorded on the Iron Range (Hibbing, Minnesota), which is 188 mm above normal. About 73% of the annual precipitation occurred during May through September 1993. The average temperature from May through September was 13.3 °C. In general, the weather in 1993 can be characterized as cooler and wetter than normal.

4. Experimental design

Unbalanced factorial experiments arranged in randomized complete block designs with three replications were initiated in the spring of 1990 at each tailing basin site. Each experiment included three levels of organic residue and three levels of fertilization. Control plots were included in each experiment and all treatment combinations were randomly assigned to 2.5×4 m test plots. Site I (Minntac) contained a total of 90 individual plots divided into three replications of 30 plots each, while Site II (Eveleth Mine) contained a total of 117 individual plots divided into three replications of 39 plots each.

At Minntac, three municipal solid waste (MSW) composts were applied as soil amendments. The composts varied in maturity: the mature windrowed for 180 days, intermediate-aged windrowed for 90 days, and immature windrowed for 45 days. Each compost was applied at rates of 10, 20, and 40 Mg/ha.

At Eveleth Mines, four organic residues were used as soil amendments: composted yard waste, 180-day old MSW with 2% disposable diapers in the feedstock, 180-day old MSW with 8% disposable diapers in the feedstock, and a reed/sedge peat. The amendments were added at the rates of 22.4, 44.8, and 89.6 Mg/ha.

Fertilizer applications at both sites were based on the rate normally used for the revegetation of northern Minnesota fine tailing materials, typically 448 kg/ha of granular diammonium phosphate (DAP) with a grade of 18-46-0. Levels of fertilizer used were 0, 224, and 448 kg/ha, with the zero level included to test the effects on vegetative development of each organic amendment alone.

Control plots consisted of no organic amendment or fertilizer application, no organic amendment but 224 kg/ha DAP, and no organic amendment but 448 kg/ha DAP.

Table 2 summarizes the specific site conditions for each of the two sites. The MSW compost used at Eveleth Mines was unique, in that it contained 2% or 8% disposable diapers in its feedstock (2% disposable diapers is average for standard MSW).

The term PLS used in Table 2 actually refers to the net amount of pure live seed in the seed mix that must be applied to obtain desired vegetation germination density. To convert the PLS figure to the gross or bulk amount of seed mix needed, two calculations must be done, as follows:

$$\%\ \text{PLS} = \frac{(\%\ \text{germination} + \%\ \text{firm seed})}{100} \times \%\ \text{purity},$$

where % germination is the percent of the seeds in the seed mix as received that will germinate, as determined by standard germination tests. Germination is the resumption of growth by the embryo in the seed.

Table 2
Summary of Mesabi Iron Range coarse taconite tailing revegetation research site conditions

Plant site	Conditions
	Test plots
Minntac	Amendments – 10, 20, and 40 Mg/ha of 45, 90, and 180-day old composted MSW
	Fertilizer – 0, 224, and 448 kg/ha of 18-46-0 DAP
	Seed Mix – 57.1 kg/ha net PLS[a] of standard mix
	Mulch – 4.48 Mg/ha hay
	Netting – to cover plots individually
Eveleth	Amendments – 22.4, 44.8, and 89.6 Mg/ha of composted yard waste, 180-day old MSW compost with 2% disposable diapers, 180-day MSW compost with 8% disposable diapers, and reed/sedge peat
	Fertilizer – 0, 224, and 448 kg/ha of 18-46-0 DAP
	Seed Mix – 57.1 kg/ha net PLS[a] of standard mix
	Mulch – 4.48 Mg/ha hay
	Netting – to cover plots individually
	Control plots
Both sites	Amendments – none
	Fertilizer – 0, 224, and 448 kg/ha of 18-46-0 DAP
	Seed Mix, Mulch, and Netting Same As Other Plots

[a] See text.

% firm seed is the percentage of the seeds in the seed mix as received that did not germinate within the timeframe of the standard germination test. Firm seed is non-imbibed, i.e., it has not taken in water and swelled to begin the germination process.

% purity is the percentage of desired seeds in the seed mix, i.e., 100 − % (undesirable seeds + inert material).

$$\text{Gross PLS, kg/ha} = \frac{\text{Net PLS, kg/ha}}{\%\ \text{PLS}} \times 100.$$

Example. A given plot requires a planting rate of 50 kg/ha PLS (net) to achieve a desired plant density of 100 plants/square meter. The germination rate is 80%, the amount of firm seed is 10%, and the purity is 98%. Then,

$$\%\ \text{PLS} = \frac{(80 + 10)}{100} \times 98 = 88.2\%\ \text{PLS in the seed mix,}$$

$$\text{Gross PLS} = \frac{50}{88.2} \times 100 = 56.7\,\text{kg/ha}.$$

Therefore, in order to obtain a coverage of 50 kg/ha PLS of desirable seeds in the mix in question, 56.7 kg/ha of the as received seed mix must be applied.

Table 3
Species used to revegetate Minnesota coarse taconite tailing

Species	Amount of pure live seed (PLS) (kg/ha)
Grasses	
Smooth brome (*Bromus inermis* Leyss.)	14.6
Red fescue (*Festuca rubra* L.)	7.8
Perennial ryegrass (*Lolium perenne* L.)	6.7
Leguminous forb	
Alfalfa (*Medicago sativa* L.)	7.8
Non-leguminous forb	
Buckwheat (*Fagopyrum esculentum* Moench)	20.2
Total	57.1

Table 3 contains a complete listing of the grass and forb species selected for study at both Minnesota sites. These species and their rates are typical for tailing revegetation on Minnesota taconite properties, and they were consistently applied across all coarse tailing plots.

At both Sites I and II, the responsible mining company leveled the coarse tailing material and the plots were first laid out in regular fashion. The appropriate amendments were applied. Fertilizer was then added if scheduled, and each 10 m^2 plot was roto-tilled to a depth of 15 cm. Seeds were then broadcast and lightly raked into the plot surface, hay mulch was spread over the plot at the rate of 4.48 mg/ha, and netting was applied to keep the protective mulch in place.

5. Results

Results of the Minnesota revegetation study after four growing seasons showed that total plant cover (living vegetation and its litter) increased and bare tailing decreased with increasing levels of organic amendments. The best results were obtained when the amendments were applied at a rate of 89.6 Mg/ha with at least 224 kg/ha of diammonium phosphate fertilizer.

Additionally, as shown in Figs. 1 and 2, vegetative cover is continuing to increase at a regular rate and shows no signs of levelling off. We expect the cover to continue increasing until it reaches 100% in all cases where organics were used as amendments. There is no indication of vegetative deterioration.

At both the Minntac and Eveleth test sites, total cover across all treatment combinations increased progressively through the four growing seasons, and continues to improve. At Minntac, total cover increased from zero to 34% the first growing season, 41% the second growing season, 56% the third growing season, and 72% the fourth growing season (Fig. 1). There was no significant difference in cover

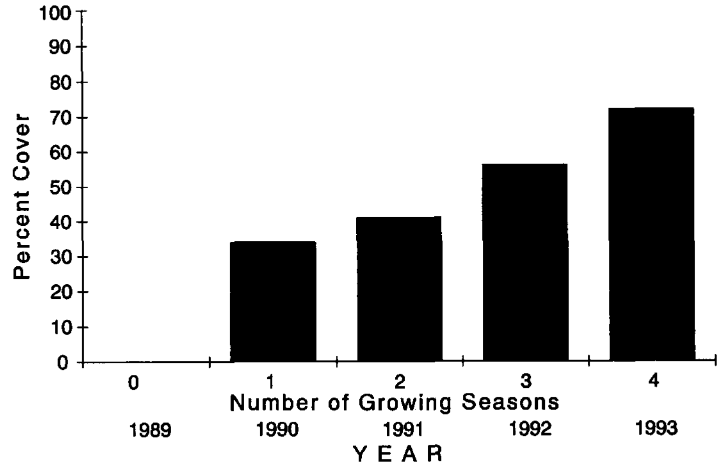

Fig. 1. Average total vegetative cover at Minntac across all treatment combinations.

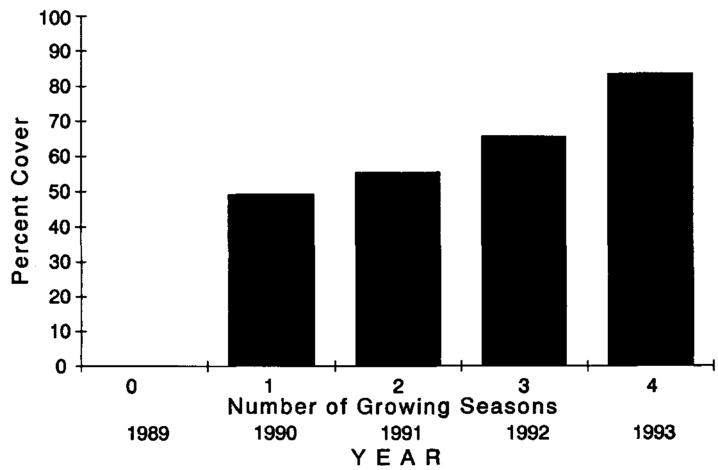

Fig. 2. Average total vegetative cover at Eveleth Mines across all treatment combinations.

response between the various aged MSW composts; they apparently composted in-place and matured in the tailing, thus giving comparable results. There was, however, a significant increase in total cover with an increase in amendment and fertilizer rates.

After four growing seasons, seven treatment combinations at the Minntac site exceeded the State requirement of 90% cover. An additional nine combinations were within 10 percentage points of the State requirement. These treatment combinations

Table 4
Minntac amendment combinations achieving total vegetative cover values exceeding or within 10 percentage points of the State requirements after four growing seasons

MSW amendment age and rate (Mg/ha)	DAP fertilizer rate (kg/ha)	Total cover (%)
45-day old		
10	224	80
10	448	85
20	224	89
20	448	92
40	224	89
40	448	97
90-day old		
10	448	91
20	224	81
20	448	89
40	448	98
180-day old		
10	224	81
10	448	93
20	224	80
20	448	87
40	224	91
40	448	92

are listed in Table 4. It appears that the best combination of amendments for cover at the Minntac site for coarse taconite tailing revegetation would be any of the various aged MSW composts applied at 40 Mg/ha with at least 224 kg/ha of DAP fertilizer.

At Eveleth Mines, total vegetative cover was significantly affected by the type of organic amendment, the rate of application, and the fertilizer rate. Total cover increased from none to 49% the first growing season, 55% the second growing season, 67% the third growing season, and 83% the fourth growing season (Fig. 2). As at the Minntac site, cover on the Eveleth Mines plots continued to increase through the fourth growing season, with no signs of leveling off.

Twenty-three treatment combinations of organic residue type, rate of application, and fertilization rate met or exceeded state requirements and five treatment combinations were within 10 percentage points of those State requirements. Table 5 contains these data.

Composted yard waste amendment resulted in significantly higher total cover values than did the MSW or peat amendments. Differences between MSW with and without added diaper residue were not significant.

The plant species present after the fourth growing season were significantly different between the two Minnesota sites, with 13 species of volunteer vegetation present at the

Table 5
Eveleth Mines amendment combinations achieving total vegetative cover values exceeding or within 10 percentage points of the State requirements after four growing seasons

Amendment and rate (Mg/ha)	DAP fertilizer rate (kg/ha)	Total cover (%)
Reed/sedge peat		
22.4	224	90
22.4	448	94
44.8	224	90
44.8	448	97
89.6	0	87
89.6	224	99
89.6	448	99
MSW with added diapers		
22.4	224	84
22.4	448	86
44.8	224	91
44.8	448	91
89.6	0	93
89.6	224	97
89.6	448	99
MSW without added diapers		
22.4	448	87
44.8	224	85
44.8	448	95
89.6	0	97
89.6	224	99
89.6	448	99
Composted yard waste		
22.4	224	90
22.4	448	90
44.8	0	94
44.8	224	95
44.8	448	92
89.6	0	94
89.6	224	98
89.6	448	98

Minntac site (Table 6) and 33 species present at the Eveleth site (Table 7). These are in addition to the five species seeded into the test plots. The difference in response between the two sites was due mainly to the native seed bank in the reed/sedge peat and the composted yard waste, both of which were applied only at the Eveleth site. Presumably, natural vectors such as wind, animals, and birds also contributed to the volunteer species observed at both sites.

Table 6
Common names of the 18 plant species present on the Minntac experimental site after four growing seasons

Seeded vegetation (5)	Volunteer vegetation (13)
Grasses (3)	Grasses (2)
Smooth brome	Red top
Red fescue	Yellow foxtail
Perennial ryegrass	Leguminous forbs (2)
Leguminous forbs (1)	Yellow sweetclover
Alfalfa	White clover
Non-leguminous forbs (1)	Non-leguminous forbs (9)
Buckwheat	Mouse-ear chickweed
	Ox-eye daisy
	Lambsquarters
	Hawk's-beard
	Horseweed
	Kochia
	Prostrate knotweed
	Smallflower buttercup
	Sheep sorrel

Table 7
Common names of the 38 plant species present on the Eveleth Mines experimental site after four growing seasons

Seeded vegetation (5)	*Volunteer vegetation* (continued)
Grasses (3)	Leguminous forbs (3)
Smooth brome	Yellow sweetclover
Red fescue	Red clover
Perennial ryegrass	White clover
Leguminous forbs (1)	Non-leguminous forbs (22)
Alfalfa	Velvetleaf
Non-leguminous forbs (1)	Common yarrow
Buckwheat	Prostrate pigweed
	Rough pigweed
Volunteer vegetation (33)	Yellow rocket
Grasses (8)	Indian mustard
Quackgrass	Shepard's-purse
Redtop	Mouse-ear chickweed
Crabgrass	Lambsquarters
Canada wildrye	Ox-eye daisy
Canada bluegrass	Canada thistle
Kentucky bluegrass	Hawk's-beard
Yellow foxtail	Horseweed
Green foxtail	Kochia
	White campion
	Field mint
	Black bindweed
	Common smartweed
	Rough cinquefoil
	Common skullcap
	Sheep sorrel
	Goat's beard

6. Conclusions

Results in the fourth growing season (1993) at both Minnesota sites are increasingly encouraging. The data show that acceptable vegetative cover can be achieved with at least 30 treatment combinations within four growing seasons. Within a few more years, the total vegetative cover is expected to exceed the State requirements in Minnesota with almost every organic residue combination tested.

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