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Establishing Vegetation on Alkaline Iron And Copper Tailings

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ESTABLISHING VEGETATION ON ALKALINE IRON AND COPPER TAILINGS

by

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PREFACE

Since 1970, the Michigan Department of Natural Resources through the Geological Survey Division has funded a series of Mine Reclamation Research agreements with Michigan Technological University. The objective of these agreements was to establish criteria and methods for reclamation and control of erosion of mining areas as defined by Michigan's Mine Reclamation Act (Act No. 92, P.A. 1970, as amended). The research included feasibility studies and developing methods of revegetating iron and copper tailings basins.

The principal investigator of the vegetative reclamation project has been Dr. Stephen G. Shetron of Michigan Technological University. His efforts to establish vegetation on both iron and copper tailings have met with varying degrees of success. However, he has had good investigative results with the deactivated iron tailings basins at the Humboldt mine. During the first year of study, Dr. Shetron defined the problem areas by mapping coarse, stratified and slimes tailings for areal extent, and testing their chemical and physical "soil" characteristics. The areas were then seeded. The seeding process included (1) mulching and drilling of coarse area tailings, dikes, etc.; (2) drilling and fertilizing stratified areas, and (3) disking, drilling, and fertilizing slimes. Also included in the process was the planting of trees for windbreaks on the basins, dikes and stripping dumps. During successive years, areas of "blowouts" or areas which did not "take" were reseeded. The entire test area was given repeated applications of fertilizer.

Results in this particular project area have been favorable. The west tailings basin at the Humboldt Mine is considered stabilized, and presently the only question is how long the vegetation can sustain itself without additional maintenance. As problems are solved in revegetation of iron and copper ore tailings basins, it is hoped the research eventually will expand to other problem areas of mine reclamation.

This report is dedicated to Representative Russell "Rusty" Hellman who recognized the need for practical research in mined land reclamation. It was through his concern and effort that funding for this purpose was made available.

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CONTENTS

PREFACE **1**
ILLUSTRATIONS **1**
Figures *1*
Tables *2*
ABSTRACT **2**
INTRODUCTION **2**
MINE MILL WASTE SITES **3**
Iron Tailings *3*
Copper Tailings *3*
SEEDING AND TREATMENTS **3**
Field Criteria *3*
Erosion Control *4*
ANALYTICAL PROCEDURES **4**
TAILINGS CHARACTERISTICS **5**
Physical Properties *5*
Chemical Properties *5*
Mineralogical Properties *7*
Microbiological Properties *7*
Mulching Program *7*
PLANT ESTABLISHMENT AND GROWTH **8**
SUMMARY AND CONCLUSIONS **9**
LITERATURE CITED **11**

ILLUSTRATIONS

Figures

FIGURE 1. *View of a recently deactivated 40-acre tailings basin ready for vegetative stabilization.* **3**
FIGURE 2. *Aerial view of copper tailings deposit in an existing lake basin.* **3**
FIGURE 3. *Wind-eroded area in newly seeded iron tailings basin.* **4**
FIGURE 4. *Gully formation in iron tailings as a result of uncontrolled surface water runoff prior to seeding.* **5**
FIGURE 5. *Strips of baled hay laid perpendicular to erosive winds. Distance between strips is one chain. View is southerly across Torch Lake. Note open expanse of water allowing uncontrolled movement of winds.* **5**
FIGURE 6. *Hydro-mulching copper tailings.* **5**
FIGURE 7. *View of stabilized iron tailings basin after one growing season.* **8**
FIGURE 8. *Two-year-old willow cutting in iron tailings slimes.* **9**

FIGURE 9. *Excavated alfalfa root system. The star-shaped object in the center is a nodule attached to a root (arrow).* 9
FIGURE 10. *Roto-tilled and seeded strips on stratified iron tailings.*......................................Error! Bookmark not defined.

Tables

TABLE 1. *Mean values of selected physical properties of alkaline iron and copper tailings before seeding.* 6
TABLE 2. *Comparison of mean values of nine elements in alkaline iron and copper tailings before and after application of fertilizer.* 6
TABLE 3. *Major mineral composition of alkaline iron and copper tailings and the probable chemical contribution of the various minerals after weathering.*..7
TABLE 4. *Estimates of total numbers of bacteria, fungi, and spore-forming bacteria present in alkaline iron and copper tailings (103). Values are an average of 5 samples taken during the growing season. All rhizosphere samples were different.*..8
TABLE 5. *Mean root, shoot, and root/shoot ratios by textural class of alfalfa grown on alkaline iron and copper tailings sampled at 1/10 to 1/3 bloom.*..10
TABLE 6. *Elemental contents of whole tops and roots of alfalfa grown on alkaline iron and copper tailings. Values are means of all clones sampled.* 11

ABSTRACT

Large scale field plantings commenced in the fall of 1970 and spring of 1971 to determine the potential of fine-grained alkaline iron and copper mine mill wastes for the growth of vegetation. Prior to seeding, a sampling of both materials for available nutrient essential to plant growth revealed the following: traces of nitrogen, 1-5 ppm phosphorous, 10-25 ppm potassium, 75-320 ppm calcium and 5-61 ppm magnesium. Traces of copper ranged from 4 ppm in iron tailings to 570 ppm in copper tailings. Iron content varied from 137 ppm in copper tailings to 1,248 ppm in iron tailings. Particle size separates ranged from fine sand to clay. The tailings are structureless with no consistency, and are easily eroded by wind and water. Moisture retention data for 0.1 to 1.0 bar of tension showed a 90% loss of water for the fine sands and a 30% loss for the fine textured materials.

Mineralogical assay of the copper tailings revealed that 80 to 90% by volume were moderately soluble feldspar and pyroxenes. Iron tailings, on the other hand, contained 60% by volume quartz. The mineralogy of these wastes has provided clues to the potential behavior under intensive vegetive management.

Microbiological populations were also found to vary widely between copper and iron tailings. Copper tailings contained less bacteria and fungi than iron tailings.

The lack of essential nutrients such as nitrogen necessitated development of a special fertilizer blend and application rates to compensate for deficiencies. Three applications the first year, two the second and a spring top dress each year thereafter have proven satisfactory in maintaining adequate plant growth. Excessively high levels of micro-nutrients such as iron in the iron tailings have not hindered plant growth. However, the same management on copper tailings has resulted in low plant survival.

Severe wind and water erosion of the materials made supplemental management necessary. This consisted of the surface application of mulches such as wood fiber, hay and straw, manure and chemicals. In those areas subjected to severe wind erosion, surface mulching resulted in greater plant survival.

[1] *Contribution from the Ford Forestry Center of Michigan Technological Univ., L'Anse, Michigan.*
Financial support from Cleveland Cliffs Iron Co., Universal Oil Co., and Geological Survey Division of the Michigan Department of Natural Resources.

[2] *Professor of Forestry Research, Associate Professor of Geology, Associate Professor of Forestry, Geologist for the Michigan Geological Survey Division and Graduate Students, respectively.*

*Contents of elemental nitrogen and calcium in alfalfa foliage (*Medicago satifa L. vernal*) were low in plants grown on iron tailings, whereas nitrogen and potassium were low in those grown on copper tailings. Phosphorous content was adequate in both cases. Excessive amounts of copper and iron were found in alfalfa grown on the copper tailings.*

INTRODUCTION

Two classes of waste result from the mining of ores: (1) piles of surface overburden, waste rock and lean ore, and (2) a fine grained waste resulting from the ore beneficiation process and deposited in man-made basins. Both classes of waste may occupy large segments of landscape in the vicinity of a mine and can detract from the aesthetic quality of the natural landscape.

In a continuing vegetative stabilization program, research was conducted to study the potential of fine-grained mine mill wastes, hereafter referred to as tailings, to sustain vegetation. This paper reports results of a five-year study on tailings from the processing of two different ores: iron and copper.

* See Literature Cited

Vegetative stabilization of mine mill wastes is not a new endeavor. Actually, some mining companies have been working on the problem of stabilization for 40 years (6, 26)*. Published results of research over the past decade have defined problems associated with the growth of plants on wastes. Some of the important problems associated with vegetative stabilization arise from lack of fertility of these wastes, physical properties, diversity of mineralogy, environmental setting and beneficiation process for the extraction of the metal (12, 14, 15, 16, 23, 26, and 30). Generally, physical, chemical and vegetative methods are the three most commonly used means of stabilization for controlling wind and water erosion of these wastes (11, 12, 14, 15, 19, 26, and 30). Of these methods, vegetative stabilization is preferred. It is economical and rapid, and results in the most complete surface protection against wind and water erosion. In addition, plant cover improves the aesthetic appearance of the waste area which would otherwise remain barren (Figure 1).

Figure 1. View of a recently deactivated 40-acre tailings basin ready for vegetative stabilization.

MINE MILL WASTE SITES

In 1968 a small-scale vegetative rehabilitation study was begun on a deactivated tailings basin at an iron pellet plant located within the Marquette Iron Range District in the Upper Peninsula of Michigan. Results have been reported elsewhere (30). In 1971 a similar, but larger in scope, study was initiated on iron tailings deactivated in 1970 and on copper tailings in Houghton County, Michigan.

Iron Tailings

The iron ore tailings consist of finely ground rock left after a mixture of hematite and magnetite is separated from the ore (banded chert and specular hematite) by a combination of wet separation and flotation. The wastes from beneficiation are a water-solid effluent transported by pipelines and deposited under controlled conditions in engineered basins. Water is decanted through a series of basins for reuse in the beneficiation process. This results in a systematic segregation of fine and coarse materials across the initial basin away from the pipeline discharge. Figure 1 shows a recently deactivated 40-acre tailings basin ready for vegetative stabilization. The dead trees midway across the basin were growing on a natural landform. The view is toward the clear water discharge end of the basin. Slope gradient is 1% per thousand feet.

Copper Tailings

The copper tailings are the result of a process whereby the ore, containing grains and masses of metallic copper, was crushed to about 20-mesh and the liberated copper removed by gravity separation. The waste rock was deposited as a water slurry in a nearby deep lake, filling in a portion of the lake basin above water level.

A second copper extraction process on the original deposit involved removing the tailings by dredging, regrinding and leaching with cuprous ammonium carbonate (Benedict Process) to extract copper left by the crushing and gravity separation process. Two types of host rocks, tholeitic basalt and rhyolite-felsite conglomerate, constitute the waste materials. The numerous recyclings and uncontrolled deposition of the wastes have resulted in a random intermixture of the two rock types.

Figure 2 is an aerial view of the copper tailings. In the lower right corner are a series of two-strand high snow fences partially buried by wind erosion. The dark strips are rows of baled hay used for wind erosion control; the light areas are hydromulched with wood fiber.

Figure 2. Aerial view of copper tailings deposit in an existing lake basin.

SEEDING AND TREATMENTS

Field Criteria

The initial small-scale iron tailings study in 1968 involved an empirical approach to vegetative stabilization. Species of plants, seeding and fertilizer recommended in previously published studies were used (19). Primary purposes of the study were to establish a methodology for seeding and to determine if tailings would support vegetation. We learned, however, that specific criteria were needed for vegetative stabilization. The tailings were deficient in plant nutrients, retained less water than natural soils, and were subject to severe wind erosion and sand abrasion.

After the second year from deactivation, an 80-acre tailings basin was made available for vegetative stabilization. A series of plantings was designed to test the best species performances of the 1968 study. Five-acre blocks were established so that conventional farm equipment--tractor, grain drill, disc and roller—could be used and more realistic costs could be determined.

Prior to full-scale seeding the tailings were investigated systematically with a soil auger. A general map depicting the major particle size distribution areas within the basin was made, and samples were collected for laboratory tests.

Erosion Control

Tests for available nutrients such as nitrogen, phosphorous and potassium guided the rate at which inorganic fertilizer was applied. A blend was developed to raise the nutrient status of the iron and copper tailings to levels sufficient to sustain alfalfa. This was a blend which would supply 45 pounds of nitrogen, 20 pounds of phosphorous and 60 pounds of potassium per acre. Ammonium nitrate, triple-super phosphate and muriate of potash were used as nutrient carriers. Applications were made three times the first year and two the second year, using 300 pounds per acre for each application. A top dressing of fertilizer has been applied each year at a rate of 300 pounds per acre.

Criteria for species selection were: (1) general ability to adjust to a harsh environment; (2) good seedling, seed or cutting availability at a reasonable cost; (3) past performance (if any) on similar sites. The following genera were tested: tree (22 species), *Prunus, Larix, Pinus, Pica, Thuja, Salix, Populus* (hybrids), *Liriodendron*; Grasses (13 species), *Phalasis, Festuca, Lolium, Dactylis, Phleum, Agropyron, Stipa, Panicum*; tree and forage legumes (7 species), *Coronilla, Robina, Cara, Gena, Alnus, Trifolium, Medicago; Shrubs* (4 species), *Corus, Elaeagnus, Shepherdia, Rosa*. Seeding rates for legumes (except trees and shrubs) and grasses were twice the recommended rates for pasture improvement. Trees and shrubs were planted at a rate of 1,000 seedlings and cuttings per acre. (Tree seedlings and cuttings received one-fourth pound of the fertilizer blend per tree.)

Initial seedings were completed with conventional farm equipment. A medium-sized tractor, a standard-sized grain drill with a legume seed attachment, and a roller for compaction were used. Seeding the slime area of the tailings basin presented more problems than seeding the coarse tailings. When the material was wet, equipment became mired; when the material was dewatered and very dry, the grain drill disks would not penetrate the surface. Disking and rototilling were tested for breaking the surface and both techniques proved to be satisfactory. Following the seeding operation the slimes were rolled to pack the surface for proper seed placement and retention.

A tailings sampling program was established to examine physical and chemical property changes. The following properties were investigated: bulk density, moisture retention, particle size, pH, available macro and micro nutrients, soluble salts and mineralogical composition. All sampling locations were plotted on a base map of the study area so that future sampling could be done in the same locations.

The loss of several acres of the coarse tailings owing to severe wind erosion necessitated testing the practicality of mulches. A series of surface mulch tests was designed to control wind and water erosion (Figures 3 and 4) and reduce the loss of water in the upper 6 inches of the copper and iron tailings (31). At the time of seeding, the following materials were applied: wood fiber at 1 ton/ acre; a resinous adhesive chemical mulch which would form a crust, at 250 gallons per acre in a 1 to 7 water mix; a mixture of wood fiber and resinous adhesive; cow manure at 5 to 10 tons/acre; baled hay (Figure 5); and hay-asphalt. The wood fiber and resinous adhesive were applied with a hydro-seeder (Figure 6).

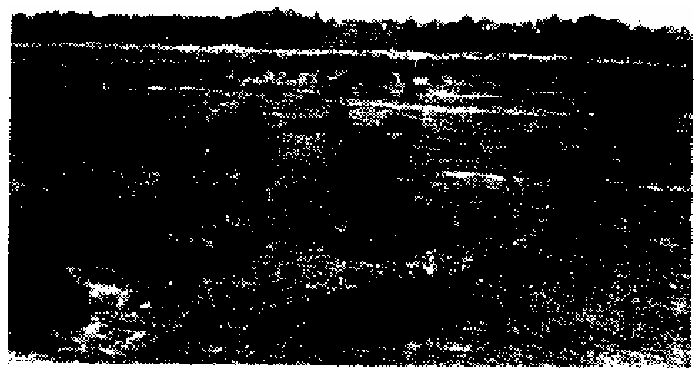

Figure 3. Wind-eroded area in newly seeded iron tailings basin.

ANALYTICAL PROCEDURES

Laboratory analyses can reveal problems which could hinder establishment of vegetation on the mine tailings. This section of the report outlines the kinds of tests conducted.

Mineral assemblages of the tailings were determined from petrological descriptions of the ore zones, microscopic examination and X-ray diffraction. Semi-quantitative estimates of the minerals were made visually by microscope and then compared with relative X-ray peak heights.

Selected physical and chemical properties of the tailings were determined as follows: particle size analysis by the hydrometer method (13), soil pH by the glass electrode (25), soluble salts by electrical conductivity (5), percent by weight retention of water by the pressure plate apparatus (27), and bulk density by the core method (4).

The amounts of available nutrients in the tailings were determined as follows: nitrogen by micro kieldahl, phosphorous by Bray's p_1, potassium by flame emission, and all others by atomic absorption. Similarly, elements in the plant foliage were determined and reported as percent ash for the macro nutrient and parts per million for all others.

Estimates of microbiological populations in the tailings were made from tests involving the plant roots. Roots and adhering particles collected from individual plants were each placed in 99 ml of sterile water and shaken for 10 minutes. For each plant five replicate petri dishes containing 15 ml of agar were inoculated with the water-root mixture. Dextrose-peptone-yeast extract agar was used for estimating fungal populations (24). Numbers of spore-forming bacteria were also estimated from the soil extract medium (10). All samples were incubated at room temperature (22-25°C) and counts were made as follows: bacteria after 14 days; fungi, actinomycetes, and acid producing organisms after 7 days; nitrifying bacteria after 21 days.

Alfalfa was selected for foliar analysis because of the availability of plant analysis data in the literature (2, 22). Each summer for three years, about 50 stalks from as many clones exhibiting 1/10 bloom were randomly selected for analysis. Also 10 complete clones were randomly selected for root tissue analysis. All samples were washed with de-ionized distilled water, oven-dried 24 hours at 60°C and ground to pass through a 40-mesh sieve. Stainless steel sieves were used to prevent contamination of the samples, especially from copper.

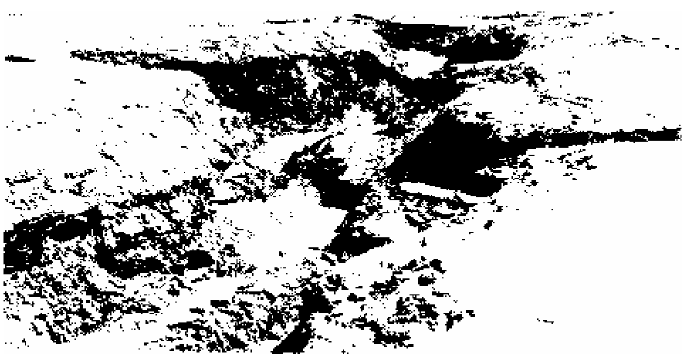

Figure 4. Gully formation in iron tailings as a result of uncontrolled surface water runoff prior to seeding.

TAILINGS CHARACTERISTICS

Physical Properties

Particle size analysis data from the sampling locations in both copper and iron tailings deposits indicated three distinct regions within these deposits (Table 1). At the end of the tailings basin where the tailings were discharged, the particle size is medium to fine sand. A second portion farther from the tailings discharge area is stratified loamy fine sands, fine sandy loam, very fine sands and silt loam. A third area, the clear water discharge end, is composed of silt loam or silty clay loam materials often referred to as slimes. The textural gradient across the tailings basin governed the treatment for testing the potential of these areas as sites for growth of vegetation. Comparison of particle size groupings within each study area showed statistical differences of .05 confidence level in bulk density, water retention values, and percent available water between the coarse and slime areas (Table 1). The sands are unstructured with a loose consistency when moist. Slimes, on the other hand, are massive and plastic when wet. When dewatered, slimes become hard, developing 1- to 3- inch wide shrinkage cracks in the surface two feet. These shrinkage cracks do not close up upon rewetting. The color of the moist tailings varied from dark reddish gray (10R 4/1 Munsell) in the sands to dusty red (10R 3/4 Munsell) in the slimes. With the exception of the color, the tailings possess physical characteristics comparable to natural soil materials lacking partially decomposed, surface organic materials.

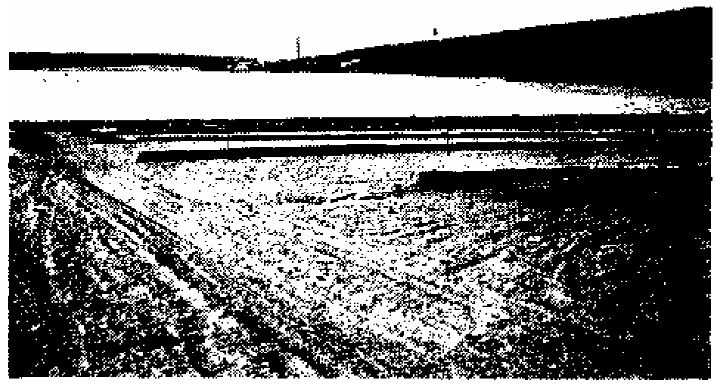

Figure 5. Strips of baled hay laid perpendicular to erosive winds. Distance between strips is one chain. View is southerly across Torch Lake. Note open expanse of water allowing uncontrolled movement of winds.

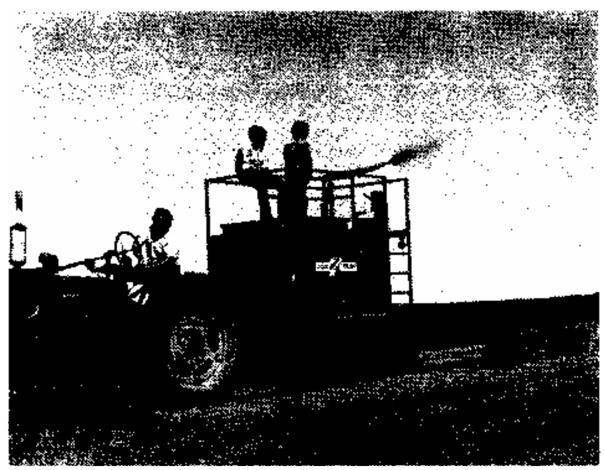

Figure 6. Hydro-mulching copper tailings.

Chemical Properties

A primary requirement for planning a fertilization program to establish vegetation on these mine mill wastes is to determine the amounts of nitrogen, phosphorous, potassium, calcium and magnesium available to the plants. These nutrients are consumed in large quantities by the plants and unless they are present in sufficient amounts, plant establishment and growth will be difficult.

Types of Tailings	U.S.D.A. Textural Classification	Bulk Density (gm/cc)	Water-Holding Capacity by Weight Bars of Tension					Avail. Water
			.1	.3	1	3	15	.3-15
			Percent					
Iron Tailings								
Coarse	Fine Sand	1.85	21.2	3.4	1.4	1.0	1.0	2.4
Stratified	Loamy Fine Sand	1.65	27.3	6.4	2.0	1.0	0.9	5.5
	Silt Loam	1.55	32.3	30.2	18.3	4.8	2.4	27.8
Slimes	Silt Loam	1.49	37.2	33.3	23.7	9.4	3.5	29.8
Copper Tailings								
Coarse	Fine Sand	1.65	15.1	10.5	3.4	2.0	1.9	8.6
Stratified	Loamv Fine Sand	1.49	20.3	11.6	8.4	3.2	2.0	9.6
	Silt Loam	1.52	25.4	14.0	10.9	4.1	2.6	11.4
Slimes	Silty Clay Loam	1.28	46.0	43.0	34.9	28.3	12.7	30.3

Table 1. Mean values of selected physical properties of alkaline iron and copper tailings before seeding.

The samples collected for determination of physical properties were also used for chemical tests. They were separated according to particle size classes (Table 2). The arithmetic mean values of chemical elements present in the iron and copper tailings in 1971 reflect the initial poor nutrient status prior to seeding and fertilization. Especially evident is the total lack of nitrogen. The tailings contain no organic matter, which is the common source of nitrogen in natural soils. Values shown for 1973 (Table 2) indicate the increase in nutrients, resulting from three years of fertilization. Iron tailings retained greater amounts of nitrogen than did the copper tailings. Perhaps this is a reflection of the better micro-biological populations (Table 4) and other physical and chemical properties of the iron tailings.

Separating the tailings deposits into major particle size areas aided in developing an understanding of potential plant-nutrient problems. Significant differences were identified at the .05 confidence level between some of the nutrients and metals when comparing particle size classes in the two types of tailings, iron and copper, as well as sampling years, 1971 vs. 1973. As the texture in both kinds of tailings becomes increasingly finer, greater amounts of available nitrogen, phosphorous, potassium and magnesium are present. The slime fraction possesses the best nutrient regimes for plant establishment. After three years the amount of calcium decreased, possibly because of leaching, plant uptake or interaction with phosphorous. Iron and manganese content increased significantly in iron tailings, while iron and copper content increased in copper tailings. Comparison of the two types of tailings shows no significant differences in phosphorous, potassium, zinc and manganese content, but differences were significant for calcium, magnesium, iron and copper. Copper tailings showed higher amounts of calcium, magnesium and copper than did iron tailings. Electrical conductivity of the saturation extracts used to approximate soluble salt contents was found to be less than 2 mmhos/cm for both types of tailings.

Type of tailings	Year	No. of Fertilizer Applications	pH	Macronutrients			
				N	P	K	Ca
				pounds/acre			
Iron Tailings							
Coarse	1971	0	7.1	0	2	21	151
	1973	6	6.1	11	5	36	326
Stratified	1971	0	7.2	0	6	34	368
	1973	6	6.7	48	12	96	331
Slimes	1971	0	7.4	0	10	36	1700
	1973	6	6.6	63	17	122	1171
Copper Tailings							
Coarse	1971	0	8.2	0	2	31	192
	1973	6	8.2	trace	4	40	141
Stratified	1971	0	8.4	0	10	41	218
	1973	6	8.2	trace	19	60	166
Slimes	1971	0	8.4	0	3	53	12644
	1973	6	8.2	trace	5	74	10204

Type of tailings	Year	No. of Fertilizer Applications	pH	Micronutrients				
				Mg	Fe	Cu	Zn	Mn
				ppm				
Iron Tailings								
Coarse	1971	0	7.1	11	152	9	4	56
	1973	6	6.1	48	328	7	4	70
Stratified	1971	0	7.2	15	446	7	3	22
	1973	6	6.7	96	328	5	5	48
Slimes	1971	0	7.4	23	1248	5	5	136
	1973	6	6.6	105	2134	7	13	177
Copper Tailings								
Coarse	1971	0	8.2	33	137	445	3	36
	1973	6	8.2	71	274	570	3	34
Stratified	1971	0	8.4	120	333	570	2	36
	1973	6	8.2	175	666	650	2	55
Slimes	1971	0	8.4	122	652	388	4	63
	1973	6	8.2	244	1104	338	4	67

Table 2. Comparison of mean values of nine elements in alkaline iron and copper tailings before and after application of fertilizer.

Amounts of heavy metals which could be detrimental to plant growth are small, with the exception of copper in the copper tailings. The copper does not appear to be toxic at these pH values (7, 8). It has been reported to be toxic to plant growth in other mine wastes at pH's below 6.0 (14, 27). The blue-green foliar symptoms or stunted rooting of alfalfa, a typical indication of copper toxicity, has not been observed on the vegetation growing on the copper tailings. It is interesting to note that in both kinds of tailings heavy metal contents vary with texture. Slime materials have consistently higher content of all elements. Although they are the most difficult to seed, slime tailings have the best potential for sustaining vegetation.

Since the beginning of the iron tailings study in 1971, the pH of the materials has decreased an average of one value (7-1 to 6.1). The tailings are beginning to show the effects of the addition of inorganic fertilizers, plant growth and leaching. The continual growth and decomposition of vegetation and application of fertilizer have initiated acidification. Continuation of this process could lead to a need for application of supplemental lime to maintain pH levels for optimum nutrient availability.

Mineralogical Properties

Table 3 contrasts the mineralogy of the copper and iron tailings. The mineral composition of the copper tailings appears to be a prime influence on pH and metals (e.g. Ca and Mg.). The source of calcium and magnesium in the copper tailings appears to be primarily calcite. Another possible source of these elements is the accessory mineral magnetite (which can contain up to 2% calcium, magnesium, manganese) and plagioclase feldspars (which make up the bulk of the tailings). These minerals, as well as the pyroxenes present, will deteriorate over a period of time in acid environments, induced by continued vegetative cover, to form clay-micas such as sericite and chlorite. Our initial X-ray study of the tailings did not detect such minerals in large quantities. Perhaps, as a result of the mode of formation, the fine fraction of the tailings was flushed out, or the time for weathering the acid-soluble minerals has not been sufficient to form clays.

The iron tailings, predominantly quartz, result in materials more closely approximating a natural soil in mineralogical composition than the copper tailings. The source of ions appears to be the residual iron oxides, pyroxenes and amphiboles. The total magnesium and manganese available within the iron tailings apparently is somewhat greater than in the copper tailings, possibly because of the more abundant soluble iron oxides containing a high percentage of trace elements.

Microbiological Properties

Significant differences at the .05 confidence level in mean microbial numbers were found between the rhizosphere and root-free material of all vegetation types on both copper and iron tailings (Table 4). Bacterial populations are greater in the rhizosphere from iron tailings but less in the tailings themselves compared to the respective zones from copper tailings. The rhizosphere/tailings ratio (R/T) clearly illustrates these differences (Table 4). The average values in the alfalfa non-rhizosphere samples are much higher than the values obtained for comparable zones for the grass and willow areas on copper tailings. This owes to an unusually large bacterial population estimate for a July sampling date. Five tons per acre of cow manure had been disked into the alfalfa area, and some organic matter from this source may have been present in this sample. This would also account for the high July populations of fungi and spore-forming bacteria found in the alfalfa area.

Table 4 summarizes the results obtained for the spore-forming bacteria found in the copper and iron mine tailings. The data shows no general patterns, although the average rhizosphere effect based on the R/T ratio was greater for the copper tailings. Spore-forming bacterial populations show similar rhizosphere effect but are not favored over non-scoring forms. Fungi populations were similar in both tailings materials, and rhizosphere differences were not consistent. These data clearly show that these kinds of wastes will support micro-flora such as bacteria and fungi.

Type of Tailings	Mineral	Volume %	Major Metals	Acid Solubility	Probable Elements Contributed
Iron	Magnetite Hematite	10	Mn, Ti, Ca, Mg.	high	Fe, Mn, Mg, Ca
	Amphibole Pyroxene Biotite	30	Ti, Mn	moderate	Ca, Na, K, Fe, Mg, Al, Mn
	Quartz	60	None	insoluble	None
Copper	Magnetite Hematite	1	Mn, Ti, Ca, Mg	high	Fe, Mn, Mg, Ca
	Pyroxene	10-15	Ca, Mn	moderate	Mg, Fe, Ca, Mn
	Feldspars	80-90	None	moderate	Na, Ca, Al, K
	Calcite	1-2	Mn, Mg, Fe	high	Ca, Mn, Mg, Fe
	Quartz	1	None	insoluble	None
	Copper	trace	Cu	moderate	Cu

Table 3. Major mineral composition of alkaline iron and copper tailings and the probable chemical contribution of the various minerals after weathering.

Mulching Program

Chemical surface mulches tested on copper tailings eliminated surface erosion and reduced evaporation but did not help establish vegetation. The surface became darker upon application of the chemicals, which in turn tended to widen temperature ranges. Hydro-application of wood fiber mulch (short fiber) at one ton per acre on both types of tailings proved effective in reducing both, evaporation and surface temperature. However, several problems arose. Each gram of mulch, when dry, is capable of absorbing 10.8 times its weight in water.

The mulch intercepted and retained most or all precipitation from storms producing less than 1 inch of rainfall. When these fiber-mulched areas were refertilized, the leaching of nutrients into plant absorption zones was restricted. After several storms, particles of fertilizer could be observed on the surface. After three years, less than 10% of the original fiber-mulched area supported vegetation. In this area, tailings were blown over the surface of the fiber mulch. The buried mulch acted as a moisture retention zone, as do the slime layers in stratified tailings. Application of a mixture of chemical and wood fiber with a hydroseeder proved ineffective because the materials balled and plugged the hydro-mulcher.

Microorganism	Plant Type	Iron			Copper		
		Rhizospher	Tailings	R/T	Rhizospher	Tailings	R/T
Bacteria	Alfalfa	190,000	1,140	167	99,000	1,300	76
	Grass (fescue sp)	286,000	590	485	70,000	310	22
	Willow	98,000	720	136	83,000	5,120	16
	Average	191,000	820	233	84,000	3,200	26
Spore-forming Bacteria	Alfalfa	313	22	14	370	11	34
	Grass (fescue	307	3	102	180	18	10
	Willow	8	1	8	217	60	4
	Average	209	9	23	255	30	9
Fungi	Alfalfa	60	3	20	20	1.4	14
	Grass (fescue sp)	11	1.1	10	21	0.5	33
	Willow	10	0.6	20	27	0.9	46
	Average	27	1.5	20	26	0.9	22

Table 4. Estimates of total numbers of bacteria, fungi, and spore-forming bacteria present in alkaline iron and copper tailings (10^3). Values are an average of 5 samples taken during the growing season. All rhizosphere samples were different.

Cow manure with its accompanying straw used as a mulch was applied at 5 to 10 tons per acre. It helped to establish and maintain growth of vegetation on copper tailings. The cow manure, when partially buried, acted as a reservoir for water and nutrients. Furthermore, the roughness of the surface after disking was sufficient to reduce wind erosion and thus promote adequate germination and survival of plants.

Of the surface mulches tested on both types of tailings, baled hay in strips perpendicular to erosive winds, and hay and straw, or hay-asphalt and manure, were effective in controlling erosion. Temperatures at the surface of the tailings were greatly reduced. Surface temperatures can reach 130 to 150°F, but the addition of the straw and hay-asphalt mulches reduced temperatures to between 95 and 115°F. Field run, poor quality, baled hay placed in rows one chain apart and perpendicular to erosive winds reduced wind erosion. After three years a total of 9,000 bales on the copper tailings has trapped approximately 2,700 tons per acre of tailings blown by the wind.

PLANT ESTABLISHMENT AND GROWTH

At the end of the first growing season, legume-grass mixtures, consisting of alfalfa (*Medicago sa*), orchard grass (*Dactylis glomerata*), tall fescue (*Festuca arundacca*), and perennial rye grass (*Lolium multiflorium*), provided 90% ground cover in all seeded blocks including mulched areas in the iron tailings (Figure 7). Observations of seedings on the copper tailings indicated severe wind erosion had removed more than 80% of the seedings on the unmulched areas. Approximately 10% of the seedings survived in the various mulched blocks.

Figure 7. View of stabilized iron tailings basin after one growing season.

Tree and shrub survival was poor on both types of tailings. Conifer species such as jack pine (*Pinus banksiana*), red pine (*Pinus resinosa*), and northern white cedar (*Thuja occidentalis*) failed after two years. Hybrid aspen (*Populas* sp.), black locust (*Robinia pseudoacacia*), European black alder (*Alnus glutinosa*), cardinal autumn olive (*Elaeagnus umbellata*) and willow (*Salix* sps.), exhibited more than 50% survival on both types of tailings (Figure 8). Evidence of wind and water erosion was prevalent after three years in all areas planted to trees and shrubs.

A measure of success in establishment of vegetation on these types of mine mill wastes is the growth, yield and density of coverage. All iron tailings test blocks averaged 70-90% coverage. Of the 25 acres originally planted on the copper tailings, only six acres have vegetative cover. Lack of success is presumed to be caused by a combination of low water-holding capacity, undesirable mineralogy, nutrient imbalance, lack of micro-organisms, and erodibility.

Table 5 compares root and shoot growth for alfalfa on both types of wastes. Statistical tests revealed significant differences at .05 confidence level in root as well as shoot growth differences within and between materials. Alfalfa yield and root systems in all three textural regions show restricted root development in both slime and coarse materials. Roots in the coarse materials were short but finely divided. In the stratified materials, alfalfa roots are best developed. Penetration up to 36 inches was found in three-year-old plants. On a gross yield basis, alfalfa-grass mixtures, air-dry from the field, averaged 2-3 tons per acre at 1/10 to 1/2-bloom stage.

Stratified areas of both types of tailings deposits are interlaced at varying depths with slime layers. To determine if these layers were influencing plant growth and downward movements of nutrients, samples from fine-textured layers, as well as coarse material above and below, were analyzed for nitrogen, available phosphorous, potassium, calcium and magnesium. Greater amounts of nitrogen and potassium were found in the slimes, but content of phosphorous was less. The status of remaining elements remained about the same in all layers. Furthermore, moisture retention was greater in the slime layer. Excavations of the root systems revealed a matting of plant roots along the surface of the slime layers. The number of root nodulations on the legume plants was found to be greatest at the interface between textures (Figure 9). Most success in establishing vegetation has been achieved on stratified tailings. These also require the least amount of site preparation. Seeded, roto-tilled strips on these areas provided sufficient coverage the first year (Figure 10).

Analyses of alfalfa foliage indicate the foliage is deficient in nitrogen and calcium when grown on iron tailings, and in nitrogen and potassium on copper tailings, but contains sufficient phosphorous in both instances (Table 6). The low nitrogen values from both sites are a reflection of the total lack of nitrogen in the tailings from natural sources such as organic matter. A clue to the imbalances may be the mineralogy of the tailings. For instance, low calcium content in alfalfa grown on the iron tailings could be the result of a lack of calcium-rich minerals, which would weather and release calcium. The high calcium content of alfalfa foliage grown on copper tailings could be the result of the breakdown of calcite. Phosphorous levels are adequate, and this indicates that, although pH levels are high, sources of phosphorous in the tailings are adequate. Content of micro-nutrients (manganese, copper and aluminum) in whole tops and roots is excessive in comparison with reported research results for alfalfa grown on unlimited soil materials (20). Greater accumulations of these metals in the roots than in the tops of alfalfa plants agree with findings reported elsewhere (22).

Concentrations of copper in the roots of the alfalfa grown on copper tailings are high and could be toxic to the plants. Excessive iron (up to 3,000 ppm) in the alfalfa plant grown on natural soils has been reported as nontoxic (7), but excessive aluminum is toxic (3). Under the alkaline conditions existing in these mine mill wastes, aluminum hydroxides could be formed as a product of weathering of the primary materials (3). According to records, green weights of alfalfa decrease with increasing contents of heavy metals such as copper in roots and tops (28). Our research disclosed a highly variable growth pattern for alfalfa among the three major textural classes (Table 5). It will take further study to determine whether variable alfalfa growth is related to the heavy metal concentrations and their effect on the plant chemical composition, or the variations in the chemical and physical properties of the tailings.

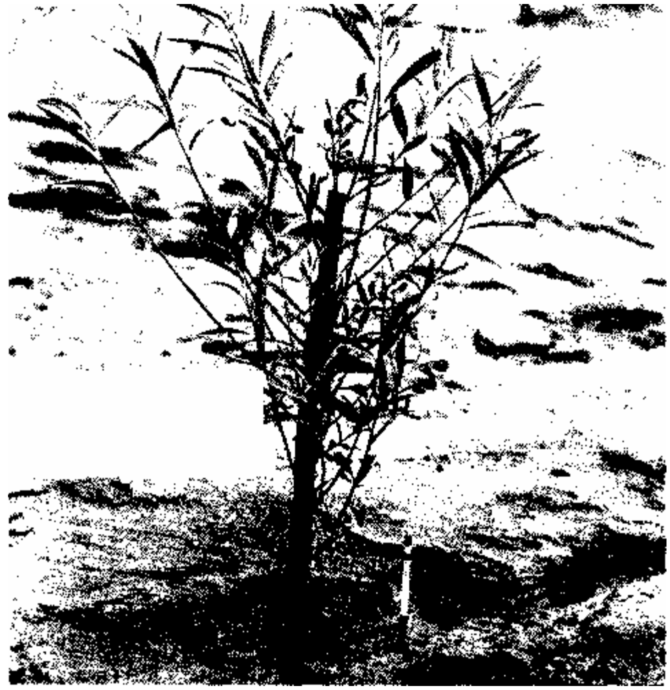

Figure 8. Two-year-old willow cutting in iron tailings slimes.

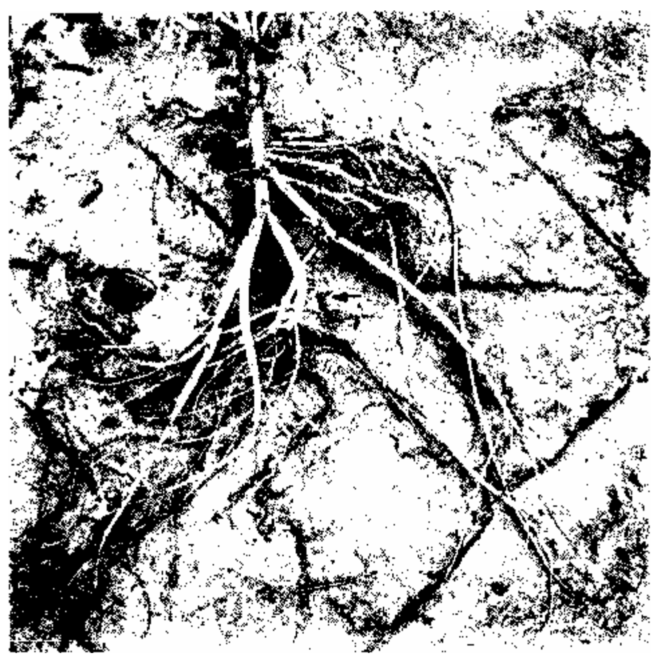

Figure 9. Excavated alfalfa root system. The star-shaped object in the center is a nodule attached to a root (arrow).

SUMMARY AND CONCLUSIONS

Research over a period of five years on alkaline mine mill tailings has revealed that these materials have variable physical and chemical properties. Recognition of this variability is essential for planning and managing the establishment of vegetation. Procedures and methods which resulted in permanent plantings on the iron tailings did not assure success on the copper tailings. The microclimate, available nutrient contents and existing moisture regime of the media exert more effect on vegetative growth and survival, perhaps, than any other factor. These wastes are capable of supporting vegetation, with additions of fertilizer to raise the available macronutrients to meet the demands of plants to be established. In these tailings of less than five years' exposure, microbiological populations were found, but differences occurred among deposits. Results of alfalfa plant analyses have revealed that concentrations of nutrients in both tops and roots show similar trends when compared to alfalfa grown on natural soils. Future nutritional problems may arise as weathering and heavy applications of fertilizer continue.

Figure 10. Roto-tilled and seeded strips on stratified iron tailings

Grass and legume species planted on the mine mill tailings were effective in stabilizing the tailings in one growing season. But we found it necessary to consider the tailings deposits as separate management areas to assure successfully established and sustained plant growth. Management practices consisted of hay or hay-asphalt mulching on the coarse materials, disking and rolling on the slime materials. Furthermore, because drought conditions can develop quickly owing to the low water retention of iron and copper tailings, supplemental irrigation may be required in the future during periods of extreme dryness.

When contemplating the vegetation stabilization of mine mill wastes, it is important to consider the makeup of the materials. Proper planning and selection of species are important (9). With respect to the permanency of the planting, grass and legume species attain a protective covering of the copper and iron tailings more quickly and successfully than tree and shrub species. Progress during the past six years shows that herbaceous species should be planted first and then followed by tree and shrub species. This relationship has been found elsewhere (17, 18). On mine wastes such as these, the primary goal of vegetative stabilization is a quickly established, self perpetuating plant community which enhances the aesthetic value of the area (11).

Type of Waste	Age of Stand	Root (inches)	Shoot (inches)	Root/ Shoot	Root (ounces)	Shoot (ounces)	Root/ Shoot Ratio	Rooting Habit
Iron Tailings								
Coarse		58.9	51.3[a]	1.15[b]	29.0[c]	27.1[d]	1.07[e]	Large coarse roots, no branching.
Stratified	3 years	69.1*	84.8	.82	40.5	96.3	.42	Branched, especially in surface fine layers.
Slimes		59.0	56.7	.89	20.4	15.2	1.34	Fine mat, well-branched root
Copper Tailings								
Coarse		20.1	22.4	.97	22.4	18.2	1.22	Large coarse roots
Stratified	3 years	28.9	53.6	.58	48.5	61.3	.79	Branching – layered
Slimes		25.6	56.9	.46	39.3	45.3	.87	Branching fine root mat

a. Statistical difference @ .05 in shoot length between stratified, coarse or slimes for all but copper tailings.

b. Statistical difference @ .05 in r/s between coarse, stratified and slimes.

c. Statistical difference @ .05 in root wts. between texture all sites.

d. Statistical difference @ .05 shoot wts. between texture all sites.

e. Statistical difference @ .05 r/s between texture all sites.

*Penetration observed to 120 cms.

Table 5. Mean root, shoot, and root/shoot ratios by textural class of alfalfa grown on alkaline iron and copper tailings sampled at 1/10 to 1/3 bloom.

Site	Age of Stand Years	Macronutrients					
		N	P	K	Ca	Mg	Na
		percent					
Iron							
Tops	3	2.39	.29	2.38	1.92	.42	.01
Roots Tailings (0-4 inches)	3		.30	.59	.37	.26	.01
Pounds/acre	3	45	5	94	2.74	1.00	
Copper							
Tops	3	2.33	.38	1.70	4.09	.48	.06
Roots (0-4 inches)	3		.42	.42	1.31	.98	.11
Pounds/acre	3	trace	16	.48	6/30	166	

Site	Age of Stand Years	Micronutrients						
		Zn	Mn	Cu	Fe	B	Al	Ba
		ppm						
Iron								
Tops	3	25	379	16	1085	60	485	9
Roots Tailings (0-4 inches)	3	35	226	22	1145	41	908	6
Pounds/acre	3	10	134	8	2%	45	1308	14
Copper								
Tops	3	39	110	87	1040	85	716	44
Roots (0-4 inches)	3	57	193	164	1249	47	981	23
Pounds/acre	3	4	52	589	2%	72	1220	38

Table 6. Elemental contents of whole tops and roots of alfalfa grown on alkaline iron and copper tailings. Values are means of all clones sampled.

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When You Know	(Symbol)		Multiply By	To Find	(Symbol)
LENGTH					
millimeters	(mm)	X	0.039	inches	(in.)
centimeters	(cm)	X	0.394	inches	(in.)
meters	(m)	X	3.281	feet	(ft.)
meters	(m)	X	1.094	yards	(yd.)
kilometers	(km)	X	0.621	miles	(mi.)
inches	(in.)	X	2.540	centimeter	(cm)
feet	(ft.)	X	30.480	centimeter	(cm)
yards	(yd.)	X	0.914	meters	(m)
miles	(mi.)	X	1.609	kilometers	(km)
AREA					
square centimeters	(cm^2)	X	0.155	square inches	($in.^2$)
square meters	(m^2)	X	10.764	square feet	($ft.^2$)
square meters	(m^2)	X	1.196	square yards	($yd.^2$)
square kilometers	(km^2)	X	0.386	square miles	($mi.^2$)

square inches	(in.^{2})	X	6.452	square centimeters	(cm^2)
square feet	(ft.^{2})	X	0.093	square meters	(m^2)
square yards	(yd.^{2})	X	0.836	square meters	(m^2)
square miles	(mi.^{2})	X	2.590	square kilometers	(km^2)
MASS (weight)					
grams	(g)	X	0.035	ounces	(oz.)
kilograms	(kg)	X	2.210	pounds	(lb.)
ounces	(oz.)	X	28.350	grams	(g)
pounds	(lb.)	X	0.454	kilograms	(kg)
VOLUME					
milliliters	(ml)	X	0.352	fluid ounces	(fl.oz.)
liters	(l)	X	2.113	pints	(pt.)
liters	(l)	X	1.057	quarts	(qt.)
liters	(l)	X	0.264	gallons	(gal.)
cubic meters	(m^3)	X	35.314	cubic feet	(ft.^{2})
fluid ounces	(fl. oz.)	X	28.383	milliliters	(ml)
pints	(pt.)	X	0.473	liters	(l)
quarts	(qt.)	X	0.946	liters	(l)
gallons	(gal.)	X	3.785	liters	(l)
gallons	(gal.)	X	0.0283	cubic meters	(m2)
TEMPERATURE					
Fahrenheit	(°F)	X	(°F-32)/1.8	Centigrade	(°C)
Centigrade	(°C)	X	(1.8°C+32)	Fahrenheit	(°F)

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