SOIL PROPERTIES OF SOIL MATERIALS IN COPPER MINE TAILING DISPOSAL BERMS

by

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ABSTRACT

Research was conducted at Pima Mining Company, Tucson, Arizona to study the physical and chemical properties of soil materials in copper mine tailing disposal berms.

Concentrations of exchangeable and available mineral elements were higher in tailing soil material than they were in tailing-overburden, overburden, and desert soil materials. Old, natural-weathered tailing contained more exchangeable iron, magnesium, zinc, manganese, and copper than did fresh, oven-dried tailing and fresh, wet tailing. Concentrations of iron, magnesium, and copper at the 15 cm depth in tailing soil material were gradually decreased by leaching and natural weathering.

Average moisture content from field capacity to the permanent wilting point decreased more rapidly in tailing soil material than it did in tailing-overburden, overburden, and desert soil materials. Tailing soil material may be improved as a medium for plant growth by the addition of organic matter, fertilizer, and supplemental irrigation water. Careful selection of adapted plant species will increase the success of any revegetation and stabilization program on copper mine tailing disposal berms.
INTRODUCTION

Environmental pollution is one of the most important problems currently facing people throughout the world. Federal and state agencies have already enacted legislation and are considering possible laws for more effective pollution control. Cities, governmental agencies, industries, livestock operations, and mineral mining return sewage, garbage, manure, and other forms of waste to the environment. Present interest in pollution control has directed attention to the accumulation of mine, mill, and smelter wastes that present potential air, water, and environmental pollution hazards. Pollution hazards associated with copper milling may possibly be reduced or eliminated by effective stabilization and revegetation of copper mine tailing disposal berms. Pima Mining Company, Tucson, Arizona is taking the lead in effective control of copper mining and milling pollution. Since Pima Mining Company has adopted the foresighted policy of improving the environment in the copper mining industry, from both a physical and public point of view, Pima Mining Company has made financial resources available for this study. The primary objectives were to (a) make copper mine tailing disposal berms aesthetically acceptable, (b) facilitate revegetation of tailing disposal berms, (c) study the problems of soil structure and the
chemical composition of the soil materials in mining wastes that may affect revegetation, and (d) eliminate possible environmental pollution problems.
LITERATURE REVIEW

The mining industry contributes greatly to the general economy of Arizona, the United States, and many other areas throughout the world. This literature review summarizes environmental pollution and orients the individual for a meaningful understanding of the Environmental Pollution Control Program conducted by Pima Mining Company, Tucson, Arizona.

Environmental Pollution

Environmental pollution is caused by the improper disposal of waste material. Wastes may be solids, liquids, or gases, singly, or in combinations. Pollution destroys air and water resources, creates accident hazards, decreases land values, becomes a public nuisance, and interferes with normal community life and development. Failure to control pollution results in unnecessary waste and the depletion of natural resources (11).

Pollution Sources

Congress described solid waste pollution in the Solid Waste Disposal Act of 1965 as the disposal of agricultural, mineral, urban, industrial, and federal wastes (8).
Traditionally, urban refuse disposal has been concerned only with wastes collected from households. For example, Vaughn (37) reported that in 1970 an average of 2.75 pounds of waste was collected from each person in the United States, as a result of his daily activities. It is estimated that by 1980 per capita waste collection in the United States will be eight pounds per day. This increase will be due to single-use containers, non-returnable bottles, and other disposable conveniences that industry has created in the past and will continue to produce in the future. Steimle and MacDonald (36) revealed that increased use of plastics has decreased the degradability of refuse. Non-returnable containers have decreased combustibility of refuse and marred the appearance of the countryside. Sanitary landfills offer the most efficient means of disposing urban wastes.

Industrial

Bonar and Hefy (6) reported that industrial solid wastes were any discarded solid materials resulting from an industrial operation or derived from an industrial establishment. They include processing, general plant packaging, shipping, office, and cafeteria wastes. In many instances, industry is forced to store solid waste on the company's property, which results in a solid waste management and
environmental pollution problem. Heaney and Keane (17) found that land-disposal costs for industrial wastes were about $4.50 per ton. The idea that the ocean is a gigantic sink that will absorb an infinite amount of pollution has now been discarded (25).

Agricultural

The principal agricultural wastes in the United States are animal manures, vineyard and orchard prunings, crop harvesting residues, animal carcasses, greenhouse wastes, and disposable pesticide containers. It has been reported that agricultural wastes in the United States total more than 2,000,000,000 tons annually (13). Sorg and Hickman (34) observed that the production of farm animals has become big business in the United States, which has resulted in large quantities of manure and solid wastes that cannot be readily disposed of in the soil.

Federal

Solid wastes produced at federal installations, particularly those associated with the military, require special considerations in disposal (26). For example, the disposal of defective bombs and contaminated military material require special handling and storage. Improper disposal of military wastes disrupts efficient forest production and related agricultural operations.
Vaughn (38) reported that during the past 30 years over 20,000,000,000 tons of mineral solid wastes have been generated in the United States. Frey (15) noted that by 1980 the nation's mineral industries will be generating between 2,000,000,000 and 4,000,000,000 tons of solid wastes annually. Mineral wastes are, for the most part, barren overburden or submarginal grade ore from open-pit or surface-mines. These mountains of waste, often hundreds of feet high and covering extensive land areas, accumulate over the landscape adjacent to mining operations. Witt (39) reported that of the 100 pounds per day per capita of solid wastes, 89 pounds are mine tailing. According to Engelahl (12), solid wastes differ from air and water pollutants in that they remain at the point of origin until a management decision is made for disposal. Smith (31) noted that mineral wastes disposed of in the ocean may act as fertilizers and increase the productivity of the sea. Smith and Brown (32) revealed that 4,690,500 tons of industrial wastes were disposed of at sea in 1968.

Peterson and Monk (28) demonstrated that mine and mill waste accumulations detract from the aesthetic appearance of the natural landscape. Finely ground mill tailing contribute to air and water pollution. Research is being conducted to develop procedures for the stabilization and beautification of solid waste accumulations. Knabe (21)
reported that reclamation was regarded as an integral part of mining. Aynes and Coates (1) revealed that correct land use was the first step toward effective agronomy and erosion control. Conservationists suggested that correct land use was the utilization of each area according to its capability for sustained and economic production.

**Stabilization of Mineral Wastes**

The Environmental Protection Agency of the United States Department of Interior has requested that all mining interests stabilize mineral wastes.

**Types of Wastes**

Peckering (27) observed that the piles of mineral wastes, regardless of their location, can be categorized from the standpoint of the various problems created.

1. Those that **cause public health and safety hazards**, i.e., tailing banks that generate dust near populated areas and wastes that tend to pollute water courses.

2. Those that **cause economic problems** by retarding industrial or urban development and contribute to the depression of local land values, i.e., spoil banks and tailing piles.

3. Those which **have intrinsic value but are not immediately usable** because of technological or economic problems, i.e., iron mine rejects with high
carbon content and other types of wastes with appreciable mineral content.

4. Those that are of little significance from the standpoint of economic mineral value but are important or potentially important as industrial raw materials, i.e., slags and chat piles useable for road ballasts, lightweight block aggregate, and concrete aggregate.

5. Those having little or no economic value but which are substantial enough in volume that they cover a large area and are located in populated areas or at sites visible to the public, i.e., spoil banks and tailing piles adjoining urban centers, primary road systems, or frequently visited locations.

6. Those having little or no economic value, located in remote or untraveled areas but which are nevertheless aesthetically objectionable, i.e., gold dredger tailing and coal strip mine wastes.

Climate

Climate influences the stabilization of mineral wastes (22). Water erosion is a serious problem in mineral wastes located in humid climates, and mineral wastes are eroded by air movement in semi-arid and arid environments.
Location

Bitterling, Humble, and Morris (5) reported that solid wastes are deposited adjacent to or within short distances from mining and/or processing operations. Because of the high transportation costs, waste problems in the mining industries are largely local in nature (4). Bailey (2) pointed out that mineral waste management problems vary from location to location.

Physical

Sorg and Hickman (33) revealed that typical solid waste physical stabilization can be accomplished by the use of off-specification products, byproducts, filter cake, and other waste from plant surroundings, including plant trash, tires, hose, gasket material, cable reels, railroad ties, demolition debris, and overburden waste material.

Chemical

Harpaz, Shanon, and Tadmor (16) observed that a 1:5:25 emulsion of rubber in oil in water (approximately 3% rubber) produced an effective rubber crust over sand, and that the rubber mulch was sufficiently durable for temporary sand dune stabilization.

Vegetation.

Child and Smith (9) noted that seedlings of silk oak were usually raised in nurseries and transplanted to areas
of concern including mine dams and sand dumps. Holz (18) reported that a number of South Africa's gold mines were planting their slimes, dams, and sand dumps with grass and other vegetation. McClennan (24) revealed that there appears to be a definite shortage of plant nutrients in most tailing waste material.

Pollution Control

Stabilization and pollution control of mineral wastes may be accomplished using physical, chemical, and vegetative methods. Rosenbaum (30) found that the Department of Interior was given the responsibility for supervising research to control pollution from mineral waste. Barsick (3) suggested that what was needed on a national scale was a method for interrelating and coordinating pollution control research.

The status of present solid waste technology is not adequate to meet the needs as they exist today. Pollution control and stabilization of mineral waste should go hand in hand. Limstrom (23) observed that a research and development program was highly recommended to devise solid waste management systems for treating and redepositing coal mine stripping wastes concurrent with mining to continually restore the land in accordance with a preplanned use.

Francis (14) found that it was important to evaluate and characterize tailing wastes to determine potential
industry or commercial outlets for different mineral components. Chenik (7) noted that one must develop economically, competitive processes for utilizing tailing as construction raw materials and building blocks, or in the production of glass, ceramics, aggregate, and a multitude of other items of commerce. Dean, Havens, and Valdez (10) reported that investigations of better methods of impounding tailing to minimize desecration of land were in progress throughout the mining areas of the world.
MATERIALS AND METHODS

Vegetation requires soil to develop properly and in which to grow. Waste products of the mining operations, at best, contain disturbed soil materials. Any program of pollution control or revegetation of copper mine tailing disposal berms must begin with a fundamental understanding of the soil materials, both physically and chemically. Minor elements may prove toxic to plant life and limit revegetation, just as more favorable conditions may support or enhance plant growth.

The objectives of research at Pima Mining Company were to study physical wastes of copper mining and milling, and to investigate ways of making waste products more aesthetically acceptable and useful to the mining industry. To accomplish these objectives, research was initiated to study the physical and chemical characteristics of mine tailing berms.

The physical and chemical properties of tailing waste materials vary according to the milling operation. Jones (19) observed that mine dump material contained no organic matter, no microflora other than bacteria that oxidize iron and sulphur, and no nitrogen detectable by chemical analysis. Studies by Keen (20) also revealed that great nutritional deficiencies existed among various mine
and mill wastes and that mill tailing had high temperatures and excess salinity. Mineral wastes were deficient in available nutrients and they had poor physical conditions, which resulted in poor aeration and improper water relations.

Experiments were conducted over a three-year period (1970 through 1972) at the Pima Mining Company, Tucson, Arizona to compare differences in the average organic matter, bulk density, pH, total soluble salts, nitrogen, phosphorus, sodium, and potassium at two depths in four soil materials. In copper mine tailing disposal berms these factors were studied for their potential effect on revegetation of plant life. Average acid extractable iron, magnesium, zinc, manganese, and copper were determined for possible toxic levels of these elements. Available iron, magnesium, and copper were also noted. Moisture percentages at several soil tensions (1/3, 1, 5, 10, and 15 atm.) were recorded for fresh wet tailing, fresh oven-dried tailing, and old natural-weathered tailing (approximately 6-8 months) to study water holding capacity and physiologic responses. The experimental design for collection of these data was a randomized complete block with four replications and eight treatments.

Soil samples were taken from four soil materials consisting of tailing, tailing-overburden, overburden, and desert at two depths (0-15 and 15-91 cm). The approximate times that these materials had been in place were 3 and 11
years for tailing and overburden, respectively. The tailing-overburden resulted from the addition of old, natural-weathered tailing to overburden, which had been stockpiled from previous excavation. Adding overburden to tailing resulted in some mixing of the two materials on the tailing berm slope; however, no attempt was made to uniformly mix these materials. The following average data were recorded from soil samples obtained in 1972: (a) organic matter, (b) bulk density, (c) pH, (d) total soluble salts, (e) nitrate nitrogen, (f) extractable potassium, (g) available phosphorus, and (h) extractable sodium. Additional data recorded consisted of total extractable iron, magnesium, zinc, manganese, and copper. Available iron, magnesium, and copper were determined because it was hypothesized that the availability of these elements was more important than the extractable amounts, when toxicity was considered.

Samples were oven-dried at 80 C until they reached constant weight to assure equal moisture contents for the analytical determinations. Except for bulk density and pH determinations, all analyses were run on oven-dried soil. Per cent organic matter was determined by weight-loss on ignition at 500 C for four hours. Bulk density was expressed in grams per cubic centimeter and determined by weighing a known volume of sample. The pH was determined on
all samples from a soil paste made with distilled water, having an initial pH of seven with a standard pH meter.

Total water soluble salts were determined on the extract of a one-to-five soil-to-distilled water suspension by determining electrical conductivity at 60 C and then converting to ppm salts from standard tables. Carbonic acid extractable nutrients were determined by aerating the one-to-five soil suspension used in the total salt determination with compressed carbon dioxide for 15 minutes and then filtering the suspension to obtain a clear extract. Nitrate nitrogen (NO₃-N) and phosphate (P) were determined by the colometric phenodisulfonic acid and ammonium molybdate methods, respectively. Potassium (K) and sodium (Na) were determined on a flame spectrophotometer.

Extractable trace elements were determined by atomic absorption spectrophotometry on a 0.075 N acid mixture (0.05 N HCl/0.025 N H₂SO₄) soil extract. Available trace elements were extracted by 1% disodiumethylene-diaminetetra-acetate. Individual cations were determined by atomic absorption spectrophotometry on the filtered extract.

All moisture retention values for the four soil materials were determined as described by Richards (29).

All data were analyzed using the standard analysis of variance and means were compared using the Student-Newman-Keul test as described by Steel and Torrie (35).
RESULTS AND DISCUSSION

Average organic matter bulk density, pH, total soluble salts, nitrogen (NO$_3$-N), phosphorus (P), sodium (Na), and potassium (K) at two depths in four soil materials in copper mine tailing disposal berms are reported in Table 1. Soil organic matter content was higher at the 15 cm depth than at the 91 cm depth. With one exception, tailing and desert soil materials contained more organic matter than did tailing-overburden and overburden. At the 15 cm depth, tailing and desert soil materials contained more organic matter than did tailing-overburden and overburden. At the 91 cm depth tailing soil material contained more organic matter than did tailing-overburden, overburden, and desert. Since the organic matter contents of all soil materials in copper mine tailing berms were very low, it will probably be necessary to incorporate straw or other forms of organic material into the surface of these tailing berms in order to obtain satisfactory plant growth.

Bulk density of soil materials was not influenced by depth of sample. The average bulk density of tailing-overburden was higher than the bulk density of tailing, overburden, and desert. All soil materials had similar bulk densities at the 15 cm depth. At the 91 cm depth, tailing-overburden had a higher bulk density than did tailing,
Table 1. Average organic matter, bulk density, pH, total soluble salts, NO$_3$-N, available P, extractable Na, and extractable K at two depths in four soil materials in copper mine tailing disposal berms at Pima Mining Company, Tucson, Arizona, 1972.

<table>
<thead>
<tr>
<th>Soil material</th>
<th>Depth of sample (cm)</th>
<th>Organic matter (%)</th>
<th>Bulk density (g/cm$^3$)</th>
<th>pH</th>
<th>Total soluble salts (ppm)</th>
<th>Elements (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailing</td>
<td>15</td>
<td>0.21 a</td>
<td>1.35 b</td>
<td>7.75 a</td>
<td>355 c</td>
<td>22 a 31 b 66 b 51 a</td>
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<tr>
<td></td>
<td>91</td>
<td>0.18 a</td>
<td>1.31 b</td>
<td>7.88 a</td>
<td>271 c</td>
<td>7 a 48 a 55 b 35 a</td>
</tr>
<tr>
<td>Tailing and overburden</td>
<td>15</td>
<td>0.11 b</td>
<td>1.34 b</td>
<td>7.78 a</td>
<td>2869 b</td>
<td>7 b 26 b 189 a 25 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>0.11 b</td>
<td>1.40 a</td>
<td>7.55 b</td>
<td>2808 b</td>
<td>8 a 1 b 104 a 39 a</td>
</tr>
<tr>
<td>Overburden</td>
<td>15</td>
<td>0.14 b</td>
<td>1.29 b</td>
<td>7.85 a</td>
<td>2452 b</td>
<td>7 b 2 b 135 a 15 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>0.14 b</td>
<td>1.28 b</td>
<td>7.56 b</td>
<td>2896 b</td>
<td>8 a 2 b 107 a 20 b</td>
</tr>
<tr>
<td>Desert</td>
<td>15</td>
<td>0.18 a</td>
<td>1.37 b</td>
<td>7.45 b</td>
<td>3182 a</td>
<td>6 b 1 b 63 b 17 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>0.13 b</td>
<td>1.27 b</td>
<td>7.44 b</td>
<td>5540 a</td>
<td>3 b 1 b 55 b 21 b</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td></td>
<td>26</td>
<td>4</td>
<td>19</td>
<td>73</td>
<td>57 59 47 43</td>
</tr>
</tbody>
</table>

Significance of differences:
1. Between soil depths * ns * ** ** ns ** ns
2. Between soil materials** * ** ** ** **

Legend: ns = not significant at 5%, * = significant at 5%, ** = significant at 1%.

Means followed by the same letter, within soil depths, are not different at the 5% level of significance (Student-Newman-Keul test).
overburden, and desert. The bulk densities of the soil materials studied were representative of those normally found for mineral soils. They do not indicate any serious problems in the movement of air and water or root growth.

Desert soil pH was lower than tailing, tailing-overburden, and overburden at the 15 cm depth. Tailing soil had a higher pH at the 91 cm depth than did tailing-overburden, overburden, and desert. The pH values in all soil materials in copper mine tailing berms were mildly alkaline. The availability of most plant nutrients is influenced by soil pH. Essential elements for grass plants are readily available at pH values normally present in most copper mill wastes.

With one exception, total soluble salts were higher at the 91 cm depth than they were at the 15 cm depth. Soil materials differed significantly in total soluble salts. Desert soil material contained the highest concentration of soluble salts, followed by overburden, tailing-overburden, and tailing soil material, in decreasing order. At both soil depths, desert soil material contained more soluble salts than did overburden, tailing-overburden, and tailing. Preliminary observations indicated that grass plants grew best in desert soil material, which had the highest soluble salts, followed by overburden, tailing-overburden, and tailing, in decreasing order. It is obvious that the total soluble salt contents of tailing, tailing-overburden, and
overburden soil materials were low enough to permit satisfactory plant growth of relatively non-salt tolerant plants in order to allow for vegetative stabilization and aesthetic environmental improvements.

Nitrogen (NO$_3$-N) was higher in the tailing at the 15 cm depth than tailing-overburden, overburden, and desert. Desert soil contained lesser amounts of NO$_3$-N at the 91 cm depth than did tailing, tailing-overburden, and overburden. The NO$_3$-N levels in all soil materials were too low for normal plant growth. Therefore, NO$_3$-N fertilization is essential in the revegetation of copper milling wastes.

No differences in P were observed between soil depths. Tailing had a higher content of P at the 91 cm depth than did tailing-overburden, overburden, and desert. It has been observed that with sufficient applications of NO$_3$-N forage crops grow well in all soil materials in tailing disposal berms, without additional applications of P. Phosphorus, therefore, does not appear to be a limiting plant nutrient in the revegetation of copper mine wastes.

Tailing-overburden and overburden contained more Na at both the 15 cm and 91 cm depths than did tailing and desert soil materials. No reports were found in the literature to suggest that Na has been a problem in the revegetation of mineral wastes. Generally the quantity of Na found in these soil materials was not considered high enough to be
considered detrimental to plant growth or to cause soil dispersion.

Both soil depths contained similar concentrations of K. Potassium content was higher in tailing at the 15 cm depth than it was in tailing-overburden, overburden, and desert. Tailing and tailing-overburden soil materials were higher in K at the 91 cm depth than were overburden and desert. As a general rule, K is present in adequate amounts in mineral soils in the Southwest and this observation also holds true for the soil materials normally present in copper mine tailing disposal berms.

Acid extractable iron (Fe) was higher at the 15 cm depth than it was at the 91 cm depth (Table 2). Soil materials differed in acid extractable Fe. At the 15 cm depth, tailing soil material contained the highest concentration of acid extractable Fe, followed by tailing-overburden, desert, and overburden, in decreasing order. The amount of Fe found in the tailing and tailing-overburden may appear excessively high when compared to desert and overburden material. It should be remembered that Fe in the form of iron balls is used in the milling operation of the copper ore which produces the tailing and, therefore, adds free iron to the material. The ore removed from the open-pit also contains high concentrations of pyrite (and other minerals containing lesser quantities of iron). The mixing of tailing and overburden would only dilute the Fe
Table 2. Average acid extractable Fe, Mg, Zn, Mn, and Cu; and copper at two depths in four soil materials in copper mine tailing disposal berms at Pima Mining Company, Tucson, Arizona, 1972.

<table>
<thead>
<tr>
<th>Soil Material</th>
<th>Depth of sample (cm)</th>
<th>Acid extractable</th>
<th>Available</th>
<th>C.V. (%)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Fe</td>
<td>Mg</td>
<td>Zn</td>
</tr>
<tr>
<td>Tailing</td>
<td>15</td>
<td>16215 a</td>
<td>7028 a</td>
<td>187 a</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>14678 a</td>
<td>3758 c</td>
<td>74 b</td>
</tr>
<tr>
<td>Tailing and overburden</td>
<td>15</td>
<td>13013 b</td>
<td>6016 b</td>
<td>110 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>11188 b</td>
<td>3520 c</td>
<td>63 bc</td>
</tr>
<tr>
<td>Overburden</td>
<td>15</td>
<td>6113 d</td>
<td>3131 d</td>
<td>67 c</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>5828 c</td>
<td>2938 d</td>
<td>54 bc</td>
</tr>
<tr>
<td>Desert</td>
<td>15</td>
<td>7255 c</td>
<td>3984 c</td>
<td>64 c</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>4683 d</td>
<td>3555 c</td>
<td>40 c</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td></td>
<td>43</td>
<td>34</td>
<td>55</td>
</tr>
</tbody>
</table>

Significance of differences:
1. Between soil depths ** ** ** ** ** ** * **
2. Between soil materials ** ** ** ** ** ** **

Legend: ns = not significant at 5%, * = significant at 5%, ** = significant at 1%.

Means followed by the same letter, within soil depths, are not different at the 5% level of significance (Student-Newman-Keul test).
concentration as evidenced by the parts per million concentration of the Fe ion, compared to the tailing soil material. The acid extractable Fe was higher in the 15 cm depth desert samples than in the overburden and this could be expected. There are two possible explanations:

1. Overburden is all the soil material from 170-220 meters in depth, whereas, the desert soil is the top 15 cm. Overburden is composed of unweathered soil material and it does not possess any appreciable accumulation of Fe.

2. Desert soil is the top 15 cm of soil material in which weathering has taken place. Since Fe is fairly immobile in soil, leaching tends to leave accumulations of Fe near the surface.

The 91 cm depth had the same pattern as did the 15 cm depth in which tailing soil material contained the most acid extractable Fe, followed by tailing-overburden, overburden, and desert, in decreasing order (Table 2).

Acid extractable magnesium (Mg) was also higher at the 15 cm depth than it was at the 91 cm depth (Table 2). Tailing soil material contained the highest concentration of acid extractable Mg at the 15 cm depth, followed by tailing-overburden, desert, and overburden, in decreasing order. At the 91 cm depth, overburden contained less extractable Mg than did the other soil materials. There is no explanation
related to the milling process as to why the Mg should be highest in the tailing soil material.

Tailing soil material had the highest concentration of zinc (Zn) at the 15 cm depth and, therefore, contained the most acid extractable Zn. Acid extractable Zn (ppm) follows the same pattern as Fe and is related to the concentrating of the ore in that Zn is used as a filler between the ball and rod liners used in the milling process. Zinc present in the ore as sphalerite also explains why such high concentrations of Zn are found in tailing. This increases the concentration of Zn in tailing soil material. The remaining soil materials were similar in extractable Zn.

Desert and tailing soil materials had similar concentrations of manganese (Mn) at the 15 cm depth (Table 2). The other two soil materials contained smaller amounts of Mn. The four soil materials contained smaller amounts of extractable Mn at the 91 cm depth than they did at the 15 cm depth.

Acid extractable copper (Cu) was higher for tailing at the 15 cm depth than tailing-overburden, overburden, and desert (Table 2). The same results existed at the 91 cm depth for acid extractable Cu. Because the removal of Cu is the ultimate objective of the milling process, it might be expected that the concentration of Cu would be higher in those materials that contained waste products from copper milling. Since 100% recovery of Cu is impossible from the
milling operation, high amounts of Cu are therefore found in tailing soil material.

Available iron (Fe) found in the tailing and tailing-overburden was significantly higher than in the other soil materials at both soil depths (Table 2). As was explained for acid extractable Fe, the amount of available Fe concentration found in the tailing soil material may logically be related to the Fe used in the milling process. Acid extractable Fe and available Fe both appear to be immobile and are not leached into overburden, at least to depths of 170-220 meters under arid conditions.

Tailing and tailing-overburden had higher concentrations of available magnesium (Mg) at the 15 cm depth than did overburden and desert (Table 2), whereas, tailing had the highest available Mg at the 91 cm depth, followed by tailing-overburden, overburden, and desert. Available Mg concentrations in tailing soil materials are directly related to the concentrations of other mineral elements found in copper ore bodies.

Total available copper (Cu) was higher in tailing than tailing-overburden, overburden, and desert at the 15 cm and the 91 cm depths (Table 2). It is obvious that high concentrations of available Cu in copper milling wastes, apparently, are related to the milling operation and not to their distribution in undisturbed soil materials. The significant points in Table 2, available Fe, Mn, and Cu are
the most important considerations from an agronomist's point of view, because in a revegetation program toxicity from any one of these elements may hinder the effective stabilization of copper mine tailing disposal berms. Available Mg appears to be more readily leachable from copper milling soil materials than does available Fe and available Mn, because it is found in similar concentrations in both surface and subsurface soil materials. The fact that Mg may be leached easily from the plant root zone could be a desirable factor in the establishment of vegetation on copper mine tailing disposal berms. The remaining two extractable ions evaluated (Zn, Mn) were not studied from the standpoint of their availability because they were present in low concentrations and their availability was considered unimportant, especially at the pH values encountered in this study. This was particularly true for the Mn ion, since it was relatively constant in all soil materials.

Average organic matter, bulk density, pH, total soluble salts, NO₃-N, P, Na, and K at two depths in three treatments of a soil material in copper mine tailing disposal berms are presented in Table 3. Organic matter content was highest in fresh, oven-dried tailing, followed by fresh, wet tailing, and old natural weathered tailing, in decreasing order. The addition of organic matter to soil material reduces its bulk density. Organic matter can be
Table 3. Average organic matter, bulk density, pH, total soluble salts, NO$_3$-N, available P, extractable Na, and extractable K at two depths in three treatments of a soil material in copper mine tailing disposal berms at Pima Mining Company, Tucson, Arizona, 1972.

<table>
<thead>
<tr>
<th>Treatments of a soil material</th>
<th>Depth of sample (cm)</th>
<th>Organic matter (%)</th>
<th>Bulk density (g/cm$^3$)</th>
<th>pH</th>
<th>Total soluble salts (ppm)</th>
<th>Elements (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh, wet</td>
<td>15</td>
<td>0.89 b</td>
<td>1.51 a</td>
<td>10.39 a</td>
<td>3427 a</td>
<td>1 b 1 b 196 b 75 ab</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>1.29 b</td>
<td>1.61 a</td>
<td>10.20 a</td>
<td>2165 b</td>
<td>1 b 1 b 72 a 45 b</td>
</tr>
<tr>
<td>Fresh, oven-dried tailing</td>
<td>15</td>
<td>1.71 a</td>
<td>1.08 a</td>
<td>8.19 b</td>
<td>4059 a</td>
<td>1 b 2 ab 158 a 138 a</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>2.36 a</td>
<td>1.18 a</td>
<td>8.20 b</td>
<td>3483 b</td>
<td>1 b 3 ab 114 a 71 b</td>
</tr>
<tr>
<td>Old, natural-weathered tailing</td>
<td>15</td>
<td>0.21 c</td>
<td>1.35 a</td>
<td>7.75 b</td>
<td>355 b</td>
<td>22 a 3 a 66 c 51 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>0.18 c</td>
<td>1.31 a</td>
<td>7.88 b</td>
<td>271 b</td>
<td>7 a 5 a 55 a 35 b</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td></td>
<td>74</td>
<td>18</td>
<td>13</td>
<td>84</td>
<td>169 84 105 63</td>
</tr>
</tbody>
</table>

Significance of differences:
1. Between soil depths ** ns ns ns ** ns **
2. Between soil treatments** ** ** ** ** **

Legend: ns = not significant at 5%, * = significant at 5%, ** = significant at 1%.

Means followed by the same letter, within soil depths, are not different at the 5% level of significance (Student-Newman-Keul test).
provided by growing an annual crop or by transporting plant residue to the site for incorporation.

Bulk density of the three treatments of tailing soil material was not influenced by depth of sample. All treatments of tailing soil material had similar bulk densities at both the 15 cm and 91 cm depths.

The pH of the three treatments of tailing soil material was not influenced by depth of sample. Fresh, wet tailing had a higher pH than did fresh, oven-dried tailing and old, natural-weathered tailing. Since lime is added to the copper milling operation, the pH of fresh, wet tailing would be expected to be high. As tailing material is weathered under natural environmental conditions its pH is gradually decreased.

Depth of sample did influence total soluble salts. Fresh, oven-dried tailing contained the highest concentration of total soluble salts, followed by fresh, wet tailing and old, natural-weathered tailing, in decreasing order. Old, natural-weathered tailing had the lowest total soluble salts, probably because leaching had occurred since its deposition in the tailing pond.

Average NO$_3$-N content was higher at the 15 cm depth than it was at the 91 cm depth only in the old, natural-weathered tailing, which had a higher NO$_3$-N content than did fresh, wet tailing and fresh, oven-dried tailing.
Average available P contents for the three treatments of tailing soil material were not influenced by depth of sample. Old, natural-weathered tailing had the highest available P content, followed by fresh, oven-dried tailing, and fresh, wet tailing, in decreasing order, but in amounts so low as to have no value for plant life. Old, natural-weathered tailing contained more available P than did fresh, wet tailing at both soil depths.

The extractable Na content was higher at the 15 cm depth than it was at the 91 cm depth. Fresh, oven-dried tailing contained more Na than did fresh, wet tailing and old, natural-weathered tailing. At the 15 cm soil depth fresh, oven-dried tailing contained the most Na, followed by fresh, wet tailing, and old, natural-weathered tailing, in decreasing order.

The concentration of K was higher at the 15 cm soil depth than it was at the 91 cm depth. Fresh, oven-dried tailing, and fresh, wet tailing contained more K than did old, natural-weathered tailing. At the 15 cm soil depth fresh, oven-dried tailing contained a higher concentration of K than did old, natural-weathered tailing.

The four elements: N, P, Na, and K, usually considered important in plant growth, were present in the three treatments of tailing soil material in relatively low concentrations. This observation verified the original decision to eliminate these elements from detailed chemical
analyses, particularly from the aspect of availability, because they were present in concentrations too low to be toxic to vegetation. The foregoing elements may be added as fertilizer amendments, together with organic matter, to provide a soil material suitable for supporting economical plant growth.

The concentration of acid extractable Fe was higher at the 15 cm soil depth for all treatments of tailing soil material than it was at the 91 cm depth (Table 4). Old, natural-weathered tailing contained more extractable Fe than did fresh, oven-dried tailing and fresh, wet tailing. At both the 15 cm and 91 cm soil depths, the concentration of acid extractable Fe was highest in old, natural-weathered tailing, followed by fresh, oven-dried tailing and fresh, wet tailing, in decreasing order, respectively. The high concentration of Fe in old, natural-weathered tailing can not be explained from the existing data supplied in this thesis.

In general, the concentration of extractable Mg was higher at the 15 cm soil depth than it was at the 91 cm depth (Table 4). Old, natural-weathered tailing and fresh, oven-dried tailing contained more exchangeable Mg than did fresh, wet tailing. At the 15 cm soil depth, old, natural-weathered tailing contained the most Mg, followed by fresh, oven-dried tailing and fresh, wet tailing, in decreasing order, respectively. The high concentrations of acid
Table 4. Average total extractable Fe, Mg, Zn, Mn, and Cu; and available Fe, Mg, and Cu at two depths in three treatments of a soil material in copper mine tailing disposal berms at Fima Mining Company, Tucson, Arizona, 1972.

<table>
<thead>
<tr>
<th>Treatments of soil material</th>
<th>Depth of sample (cm)</th>
<th>Acid extractable</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fe (ppm)</td>
<td>Mg (ppm)</td>
</tr>
<tr>
<td>Fresh, wet tailing</td>
<td>15</td>
<td>1896 c</td>
<td>2123 c</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>1538 c</td>
<td>2279 c</td>
</tr>
<tr>
<td>Fresh, oven-dried tailing</td>
<td>15</td>
<td>3560 b</td>
<td>4000 b</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>2745 b</td>
<td>3800 b</td>
</tr>
<tr>
<td>Old, natural-weathered tailing</td>
<td>15</td>
<td>16215 a</td>
<td>7028 a</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>14678 a</td>
<td>3758 b</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td></td>
<td>94</td>
<td>44</td>
</tr>
</tbody>
</table>

Significance of differences:
1. Between soil depths ** ** ** ** ns ns ns ns
2. Between soil treatments** ** ** ** ns ns ns

Legend: ns = not significant at 5%, * = significant at 5%, ** = significant at 1%.

Means followed by the same letter, within soil depths, are not different at the 5% level of significance (Student-Newman-Keul test).
extractable Mg at the 15 cm soil depth cannot be explained from the existing data.

The concentrations of total extractable Zn, Mn, and Cu were usually higher at the 15 cm soil depth than they were at the 91 cm depth (Table 4). In most instances, the concentrations of Zn, Mn, and Cu were highest in old, natural-weathered tailing and lowest in fresh, wet tailing.

Available Fe, Mg, and Cu were not influenced by soil depth in all treatments of tailing soil material (Table 4). Highest concentrations of available Fe, Mg, and Cu were found in fresh, oven-dried tailing, followed by fresh, wet tailing and old, natural-weathered tailing, in decreasing order, respectively. Concentrations of available Fe, Mg, and Cu were higher at the 91 cm soil depth than they were at the 15 cm depth in fresh, wet tailing and also in old, natural-weathered tailing. In contrast, concentrations of extractable Zn, Mn, and Cu were higher at the 15 cm soil depth than they were at the 91 cm depth for all treatments of tailing material. Since the concentrations of available Fe, Mg, and Cu at the 15 cm soil depth may be gradually decreased over time, because of leaching and natural weathering, tailing disposal berms that will not support plant life when they are first constructed, may provide a suitable media for plant growth after a period of years. Leaching and natural weathering will probably decrease the
total amount of available Fe, Mg, and Cu at the 15 cm soil depth with time and provide a suitable soil medium.

Average atmospheres of tension, per cent moisture, and available water for four soil materials in copper mine tailing disposal berms are reported in Table 5. At the time of collection and analysis, overburden soil material contained more moisture at all tensions studied than did tailing-overburden, tailing, and desert soil materials. Available water was highest in tailing soil material, followed by tailing-overburden, overburden, and desert soil materials, in decreasing order, respectively. Tailing soil material had a higher available water holding capacity for plant growth than did the other soil materials because it has a fine texture, a high porosity, it is loosely compacted, it contains no clay minerals, and it is devoid of organic matter, but it will not retain the water for a long period of time. Under proper management, tailing soil material would require more irrigations for suitable plant growth and economical vegetative stabilization than other materials. One means of improving tailing soil material as a medium for plant growth is by the addition of organic matter. The addition of organic matter to any soil, generally, increases its water holding capacity, decreases the frequency of irrigations, insulates the soil surface from both heat and cold, increases germination and seedling emergence, decreases the erosive power of falling water, and provides
Table 5. Average moisture percentages for designated tensions and available water for four materials in copper mine tailing disposal berms at Pima Mining Company, Tucson, Arizona, 1972.

<table>
<thead>
<tr>
<th>Soil materials</th>
<th>Atmospheres of tension</th>
<th>Available water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/3 1 5 10 15</td>
<td></td>
</tr>
<tr>
<td>Tailing</td>
<td>10.2 7.1 3.6 2.6 2.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Tailing-overburden</td>
<td>9.4 7.6 5.0 4.1 3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Overburden</td>
<td>11.0 8.8 7.3 6.1 5.9</td>
<td>5.1</td>
</tr>
<tr>
<td>Desert</td>
<td>4.8 4.2 3.9 3.0 2.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>

\(^a\)Recorded as per cent moisture at each tension level.

additional nutrients for plant growth. An effective way to provide organic matter is to utilize annual crops, such as cereal grains, sorghum, perennial crops, and native vegetation. The objective would be to incorporate these plant materials into the soil when they contained the greatest amount of organic matter. This would reduce the bulk density of the soil material and increase the water holding capacity. Increasing the water holding capacity decreases the danger from the marginal toxicity of large quantities of elements normally found in copper mine tailing disposal berms. As the total soluble salt concentration in a soil decreases the amount of available water for plant growth increases; therefore, in copper mine tailing berms as the
concentration of soluble salts decrease from leaching and natural weathering, more water becomes available for plant growth and the potential for successful revegetation of copper milling wastes improves with time.

Moisture tension curves for tailing, tailing-overburden, overburden, and desert soil materials are presented in Figure 1. The average moisture content from field capacity to five atmospheres tension decreased much more rapidly in tailing soil material than it did in tailing-overburden, overburden, and desert soil materials.

This is related to the uniform size of the tailing material. Overall, the tailing had a higher water holding capacity than did the other three soil materials.
Figure 1. Tension curves for the four soil materials in copper mine tailing disposal berms at Pima Mining Company, Tucson, Arizona, 1972.
SUMMARY

Research was conducted from 1970 through 1972 at Pima Mining Company, Tucson, Arizona to study the physical and chemical properties of four soil materials found in copper mine tailing disposal berms. The primary objectives were to: (a) make copper mine tailing disposal berms aesthetically acceptable, (b) facilitate revegetation of tailing disposal berms, (c) study the problems of soil structure and the chemical composition of the soil materials in mining wastes that may affect revegetation, and (d) eliminate possible environmental pollution problems.

Average concentrations of acid extractable and available mineral elements were higher in tailing soil material than they were in tailing-overburden, overburden, and desert soil materials. Since iron rods and balls are used in the copper milling operation, unusually high concentrations of the iron ion are concentrated in the surface areas of fresh tailing material.

In general, old, natural-weathered tailing contained more extractable iron, magnesium, zinc, manganese, and copper in both the surface and subsurface areas than did fresh, oven-dried tailing and fresh, wet tailing. The foregoing condition was probably due to the leaching of
heavy metals from the surface of fresh, wet tailing down to the subsurface layers of old, natural-weathered tailing.

The concentrations of iron, magnesium, and copper at the 15 cm depth in tailing soil material were gradually decreased by leaching and natural weathering. Tailing disposal berms that would not support plant life when they were first constructed, because the foregoing elements were present in toxic amounts, will usually support vegetation after a period of years.

The average moisture content from field capacity to the permanent wilting point changed more rapidly in tailing soil material than it did in tailing-overburden, overburden, and desert soil materials. This characteristic indicates that tailing had a higher water holding capacity than did the other three soil materials.

Data in this thesis and observations of plant growth in other studies at the Pima Mine have illustrated that tailing soil material may be improved as a medium for plant growth by the addition of organic matter, fertilizer, and supplemental irrigation water. The addition of organic matter and commercial fertilizer to tailing soil material increases the water holding capacity, insulates the soil surface, increases germination and seedling emergence, and provides additional nutrients for plant growth. Careful selection of adapted plant species will, no doubt, increase
the success of any revegetation program on copper mine tailing disposal berms.
CONCLUSIONS

This thesis was designed to study the physical and chemical properties of soil materials found in copper mine tailing disposal berms at the Pima Mining Company near Tucson, Arizona. Results obtained from the study suggest the following conclusions:

1. Tailing disposal berms contain sufficient nutrients to sustain plant growth but need amendments of nitrogen, phosphorus, and potassium for satisfactory revegetation.

2. The minor elements in copper mine wastes are present in low concentrations and do not present toxicity problems for plant growth.

3. Water holding capacity of all soil materials in copper mine wastes can be improved by the incorporation of organic matter.

4. Bulk density of milling wastes can be reduced by the addition of crop residue and other forms of organic material.

5. There is no obvious reason why tailing disposal berms cannot be stabilized with the utilization of plant vegetation.
6. Copper mine tailing disposal berms can be made more aesthetically pleasing to the eye by the use of plant vegetation.

7. The use of plant life to revegetate and stabilize copper mine tailing disposal berms blends these structures into the low desert environment in the Southwestern United States.
Atmospheres of tension. The pressure required to remove moisture from any substrate greater than evaporation from a free water surface.

Desert soil. Undisturbed surface soil. (15 cm = surface)

Environmental pollution. Is caused by the improper disposal of waste materials.

Field capacity. The amount of water a soil will hold after free drainage has taken place or at 1/3 atmospheres of tension used in this thesis.

Overburden. Non-ore material above an ore body. This material may include soil materials from all soil horizons including bedrock to depths of 220 meters in the Pima Mine.

Tailing. Waste material from an ore concentration process.

Tailing berm or dike. A bank thrown up to construct a barrier around the periphery of an impounding area constructed of soil material excavated from within the dried tailing pond.

Tailing pond. An area for deposition of tailing material from the milling process.
LITERATURE CITED


