PLANT SELECTION FOR DEWATERING AND RECLAMATION OF TAILINGS[1]

by

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Abstract: A two-phase greenhouse experiment was conducted to identify the most suitable species for dewatering and reclamation of Composite Tailings (CT) from Alberta oil sands operated by Syncrude Canada Ltd. and Copper Mine Tailings (CMT) from the Kennecott site in Utah. A total of 15 and 9 plant species were selected for testing in CT and CMT, respectively. In Phase 1, distilled water was added weekly to simulate local precipitation. The initial solids contents were 80% and 76% and the electrical conductivities were 1.1 dS/m and 3.2 dS/m for CT and CMT, respectively. All plants survived after a ten-week period. In Phase 2 only process water was added weekly to provide a worst case scenario of no precipitation and water recharge due only to process water being released from within the tailings. The initial solids contents were 65% and 76% for CT and CMT, respectively. Surface (0 – 3") salinity increased dramatically due to the application of process water only: at the end of Phase 2 it had reached toxic levels of approximately 18.9 dS/m and 35.0 dS/m in CT and CMT, respectively. Many plants showed signs of stress due to the high salinity level. The plants which performed the best under both phases in Composite Tailings were creeping foxtail (Alopecurus arundinaceus), reed canarygrass (Phalaris arundinacea), Altai wildrye (Elymus angustus), and red top (Agrostis stolonifera); and in Copper Mine Tailings were Altai wildrye, smooth bromegrass (Bromus inermis) and creeping foxtail.

Additional Key Words: Alberta oil sands, Kennecott copper mine, salt tolerant plants, mine reclamation.

Introduction

Fine tailings are composed mainly of slow-settling fine mineral particles and a large amount of water. They have little or no sand and include phosphatic clays, bauxite red muds, fine taconite tailings, and slimes from the oil sands tailings (Vick 1983). These materials have very high moisture contents which leads to very low strengths. Thus the tailings must be stored behind a retaining structure capable of retaining heavy fluids. If the water can be removed, the strength of the material can be greatly enhanced, and the volume of water stored can be reduced potentially reducing the cost of the retaining structure.

There is a need to find innovative, environmentally acceptable, economic and technically feasible ways to dewater fine tailings, enhance their surface stability and reduce their volume to generate additional storage space for continued tailings deposition. The use of plants to dewater tailings has been identified as a mechanism which may economically enhance the surface stability of these weak deposits. Plants growing in fine tailings will have the ability to remove the water through evapotranspiration, increasing the matric suction in the deposit. This results in an increase in the shear strength and bearing capacity in the rizhosphere. Furthermore, the plant root system may provide a fiber reinforcement, which should also contribute to the increased bearing capacity of the rooted tailings. Once tailings are stabilized, reclamation activities will be facilitated when the impoundment reaches full capacity.

Plant species for dewatering of tailings must adapt to the particular chemical and physical conditions of the growth medium, and to the macro-

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and microclimates. Species lists of potential dewatering plants must be developed on a regional basis to take general climatic effect into account, but additional screening programs will be necessary to determine the response of proposed species to special soil conditions. As suggested by Ripley et al. (1978) and supported by Stahl (1996) the ultimate selection of species must remain site specific; that is, the choice will have to be made at each individual mining site based on greenhouse experiments and/or field trials.

This paper presents the results of a two-phase greenhouse experiment conducted to identify the most suitable plant species for dewatering and reclamation of Composite Tailings (CT) from Alberta oil sands operated by Syncrude Canada Ltd. and Copper Mine Tailings (CMT) from the Kennecott site located in the State of Utah. The selected species will be used in a future greenhouse experiment to quantify the improvement in tailings deposit behavior due to the plant dewatering mechanism.

Both tailings are not phytotoxic as demonstrated by experiments conducted by Johnson et al. (1993) on oil sands tailings and from information provided by Neilson and Peterson (1978) and Barth (1986) on vegetation established on copper mine tailings.

Background

Plant Dewatering

The use of plants to dewater high water content materials is an inexpensive technique which has been accomplished for many years by the Dutch to dewater lacustrine and marine sediments (Public Relations and Information Department of the Netherlands 1959, Shelling 1960, Volker 1982). This drying of wet soils to shallow depths in short time periods is called polder reclamation. The ocean bottom sediments with which polder formation begins have an extremely high water content, are low in hydraulic conductivity, and have a low bearing capacity (Rijniersce 1982). The plants accelerate the dewatering process in polders by using large amounts of water and developing deep root systems. Evapotranspiration by plants allows the construction of thicker polders, whereas when relying only on surface evaporation the maximum thickness will be about 8" (20 cm), because the formation of a desiccated crust will inhibit further evaporation. Wuerz (1986) found that roots of alfalfa (Medicago sativa) penetrated more than 6.5' (2 m) into the soil in the polders, thereby loosening the soil and forming air channels, which accelerated drainage and consolidation.

Plant dewatering has also been used in dewatering sludge from wastewater treatment facilities, termed reed beds, which were initially built in Austria and southern Germany (Neurohr 1983). In addition, studies conducted by Lee et al. (1976) demonstrated the feasibility of using selected vegetation to dewater and consolidate fine textured dredged materials.

The dewatering capabilities of plants have also been observed in the reclamation of tailings. Barth (1986) recognized that vegetation transpires large quantities of water, thus reducing water entry into tailings and subsequent seepage. He concluded that vegetation is the most effective and least costly means to stabilize tailings against wind and water erosion.

Dean and Havens (1973) compared the cost of different methods for stabilization of tailings. The principal methods included physical, chemical and vegetative. They reported that the vegetative method was the most economical and recommended that wherever applicable it should be a preferred method.

At present, vegetation is the most common and usually preferred stabilization option for tailings impoundments. If a self-perpetuating vegetative cover can be established, not only can wind and water erosion be minimized, but the impoundment can be returned to some semblance of its original appearance and land use (Vick 1983, Ludeke 1973). Leroy (1973) estimated that a fully vegetated acre of tailings will transpire from 5,000 to 10,000 gallons of water daily (45 to 90 m^3/hectare/day), and eliminate all previous erosion brought about with every precipitation. Presnell (1988) reported that when alfalfa was planted in phosphate tailings in Florida, the clay began to dry out further and significant cracking and splitting of the soil were evident as the soil moisture was withdrawn by the plants. Chosa and Shreton (1976) established a test on abandoned mined mill wastes from an iron mining process. The species tested were cattails (Typha latifolia), reed canarygrass transplants, and willow cuttings (Salix sp.). Of the three local species studied for the stabilization of iron mine slime tailings, willow cuttings proved to be most effective. Their extensive root and branching habit helped to increase water removal from the slimes allowing planting of herbaceous vegetation.

Although plant dewatering of tailings has been recognized for a long time, it was not until recently that researchers showed interest in studying the mechanical effects that plants have on the tailings. Oil sands tailings from northeastern Alberta at 50% solids were planted with reed canary grass in trial pits. The tailings were dewatered to 80% solids in one growing season at which they had a shear strength of 2,505 psf (120 kPa) (Johnson et al. 1993). Stahl and Sego (1995) studied changes in surface stability of a 45 acre (18.2 hectare) coal tailings impoundment undergoing reclamation activities since reaching full capacity in 1989. Natural enhancement processes including dewatering through evaporation, evapotranspiration, and fiber reinforcement of plant root systems increased the shear strength of the surficial soils. Bearing capacity and surface stability of the coal tailings within the impoundment also increased. In some cases, the bearing pressure of the rooted tailings were 50-60% greater than that of the unrooted tailings at equivalent strain or relative settlement levels.

The formation of root-bound surfaces causes as much stabilization of weak soils as does the loss of water by evapotranspiration. Therefore, the increase of surface stability and bearing capacity of fine tailings cannot be predicted by only considering the net loss of water as the plants develop.

Evaporation only has been used to dewater tailings of the Florida phosphate industry (McFarlin et al. 1989) and Alberta oil sands (Cuddy and Lahaie 1993, Johnson et al. 1993, Li and Feng 1995). As soil surfaces desaturate with evaporation, the evaporative flux decreases and the depth of soil enhancement through dewatering becomes limited. Newson et al. (1996) reported that the depth of influence of evaporative flux on shear strength of saline gold tailings was limited to 4" (10 cm), and Burns et al. (1993) highlighted that effective dewatering of oil sands tailings can only occur if thin layers (4" to 8")(10 to 20 cm) are placed. However, because of the slow consolidation rate of tailings, this method requires a long period of time to reclaim the area and return it to a useful state (Bromwell 1982, McLonden et al. 1983, U.S. Bureau of Mines 1975). For consolidation of tailings to occur, substantial drying must take place. Furthermore, this drying must proceed to a considerable depth rather than be limited to the surface. Therefore dewatering by means of pure evaporation is generally not economically feasible because of the vast areas and quantities of tailings involved in land disposal operations.

Plant Species Selection

An ongoing debate among some reclamation specialists involves the selection of species, and in particular whether native or introduced plant species should be used. A variety of introduced species is available, allowing the selection of those plants that can quickly stabilize the surface by shallow soil-holding root systems, rapid growth rates, and high seed production. The use of introduced species also offers the opportunity for use of special salt-resistant or metal-resistant varieties; an important and sometimes crucial factor in attempts to revegetate the surface of toxic tailings directly without topsoiling (Bradshaw et al. 1978). Introduced species are often preferred because of flexibility in selecting those plant varieties that have characteristics compatible with initial impoundment soil and microclimate conditions. Johnson and Putwain (1981) provided several case histories of the use of semi-natural revegetation on iron, bauxite, manganese, nickel, copper, and other types of tailings demonstrating that revegetation with natural species, while often costly and difficult, can be successful in establishing a self-perpetuating cover. Native species often have sporadically low seed production and slower establishment rates, whereas species best suited to initial dewatering and stabilization should ideally have deep, water-seeking root systems, spreading roots, rapid growth, and high seed production.

The problem of selecting plant species for vegetating a tailings pond is complicated by the fact that the composition of all ponds is different, as are the climatic conditions. Harwood (1979) described the reclamation criteria that plant species must conform to: potential survival in the local climate; suitability to the soil conditions on the surface; rapid growth; soil conditioning capability; forage quality and aesthetics.

Barth (1986) reported that at a copper tailings impoundment in Utah, Japanese millet (Echinochloa crus-galli) was used as a cover crop in wet areas followed by perennial species including salt cedar (Tamarix sp.) and reedgrass (Phragmites australis), while in drier areas annual rye (Secale cereale) was used as a cover crop followed by perennial species that included ranger alfalfa and tall wheatgrass (Agropyron elongatum). At a taconite tailings impoundment in Minnesota, a mixture of smooth bromegrass, red top, perennial ryegrass (Lolium perenne), alfalfa, and birdsfoot trefoil (Lotus corniculatus) is often used to revegetate the drier coarse tailings products while rye grain, sweet clover (Melilotus alba), alfalfa, and red top are used to revegetate the wetter fine tailings products (Barr Engineering Company 1980). Other factors often important in species selection include drought tolerance, rooting depth, hardiness, propensity to accumulate metals, palatability, availability of seed, frost resistance, ease of propagation, and longevity of established plants. Commonly, field trials are necessary to determine which species are adapted to the particular substrate and climatic conditions at the site and to what degree the growth medium must be changed chemically and physically to support the desired species.

Fertilization of Tailings

When infertility restricts plant growth, appropriate fertilizers may dramatically improve growth. Berg (1972) measured a seven-fold increase in grass yields and a six-fold increase in herbaceous ground cover following nitrogen fertilization of gold tailings from telluride ores. When infertility is extreme, fertilization rates are high. Dickinson (1972) and Sidhu (1979) found that over 1,000 lb/acre (1,100 kg/hectare) of nitrogen, phosphorous and potassium fertilizer was required for successful tailings revegetation. Leroy (1973) used a rate of 1,000 lb/acre (1,100 kg/hectare) in reclamation of tailings in Eastern Canada. Based on greenhouse experiments, Meecham and Bell (1977) recommended that 355 lb of phosphorous per acre (400 kg/hectare) be applied to alumina tailings. However, over-fertilization must be avoided. Michelutti (1974) reported that excess fertilizer stunted plant growth and was more harmful than no fertilizer in sulfide tailings. Nitrogen in quantities of more than 45 lb per acre (50 kg/hectare) seriously hampered legume germination (Dean and Havens 1973). As little as 100 ppm N, 30 ppm P, and 150 ppm K were sufficient to achieve optimal reed canary grass growth on pure sludge from oil sands in Alberta. However, 300 ppm N was excessive, causing a decrease in biomass and general lack of vigor in the plants (Johnson et al. 1993).

Materials and Methods

A two-phase greenhouse experimental program was conducted to identify the most suitable plant species for dewatering and reclamation of Composite Tailings (CT) and Copper Mine Tailings (CMT). Phase 1 was formulated to identify the most suitable plant species for dewatering mine tailings and to examine which species would be suitable for use in reclamation of these two surface deposits. Phase 2 had the purpose of identifying the plant species which would be tolerant to high levels of salinity and any toxic compounds in the tailings release water.

Plant Material

A wide range of plants are available for use in dewatering of tailings. Because potentially large areas need to be managed, seeds should be readily available from suppliers or grown in the area. The seeds should have a high viability and germinate quickly at low temperatures to get an early start when temperatures rise.

A literature review was conducted to screen for plant species that might adapt themselves to the local climatic conditions of the two sites and to the tailings as growth medium. The criteria used for the selection of possible candidates were: survival in the local climate, rapid growth, soil conditioning capability, and tolerance to flooding, drought, high pH and high level of salinity. The most practical and complete guides to plant selection for critical environments on the Canadian prairies and in the northern boreal forests were consulted (Alberta Agriculture 1978, Best and Looman 1979, Hardy BBT Limited 1989, Smoliak et al. 1976, Watson et al. 1980). A total of 15 and 9 plant species were selected for testing in CT and CMT, respectively (Table 1).

Tailings Material, Release and Process Water

In the fall of 1996, CT and CMT materials and CT release and CMT process water were shipped to the University of Alberta from Syncrude and Kennecott sites, respectively. Two representative samples were taken from each tailings to determine nutrient status, pH and electrical conductivity (EC) (Table 2). In CT nitrate, phosphate and potassium levels were deficient, sulfate was optimal for plant growth. In CMT nitrate and phosphate levels were deficient. Potassium and sulfate were at marginal and optimum level, respectively.

Results of micronutrient analyses are shown in Table 3. In CT, levels of iron, boron and manganese were adequate for plant growth. Zinc and copper levels were marginal and deficient, respectively. Chloride was in excess. The calculated value of Sodium Adsorption Ratio (SAR) was 1.9, which is less than 13 (Miller and Donahue 1990), therefore CT can be classified as a non-sodic soil. Based on the combined values of SAR and EC, CT can be classified as a normal soil (non-saline and non-sodic). In CMT, iron, manganese and zinc were adequate for plant growth.

Boron was deficient, chloride in excess and copper may be toxic. SAR for CMT was 1.0. SAR and EC also classifies CMT as a normal soil.

Chemical compositions of CT release water and CMT process water are shown in Table 4. Both waters have high EC, which could cause severe problems to plant growth. In CT release water sodium was extremely high, giving a high SAR of 43.1. This makes the water unsuitable for irrigation. SAR for CMT process water was 6.6, which is not critical. However, its high EC also makes it unsuitable for plant watering.

Amount of Fertilizer

To avoid over-fertilization the amount of fertilizer was based on optimum levels of macronutrients required by agronomic species. For CT the fertilizer was added to give an equivalent of 134 lb N/acre (150 kg N/hectare), 71 lb P_2O_5/acre (80 kg P_2O_5/hectare), and 94 lb K_2O/acre (105 kg K_2O/hectare) for non-leguminous species; and 9 lb N/acre (10 kg N/hectare), 67 lb P_2O_5 /acre (75 kg P_2O_5/hectare), and 125 lb K_2O/acre (140 kg K_2O/hectare) for leguminous species. For CMT the fertilizer was added to give an equivalent of 129 lb N/acre (145 kg N/hectare), 58 lb P_2O_5 /acre (65 kg P_2O_5/hectare), and 27 lb K_2O/acre (30 kg K_2O/hectare) for non-leguminous species; and 9 lb N/acre (10 kg N/hectare), 49 lb P_2O_5/acre (55 kg P_2O_5/hectare), and 13 lb K_2O/acre (15 kg K_2O/hectare) for leguminous species.

Methods

Twenty liter plastic buckets were used as lysimeters with no drainage at the bottom to prevent any water loss other than evapotranspiration. The lysimeters were filled with tailings to a depth of about 12" (30 cm) and settlement was allowed to take place. Any expressed water was siphoned off and extra tailings was added to restore the initial level.

Fifteen plants were placed in each lysimeter. Three replicates were used for each treatment and one treatment was left unplanted as a control. The lysimeters were placed in the greenhouse in two randomized complete block designs, one for each type of tailings. Air temperature and hours of light per day were set at 72 °F (22 °C) and 15 hours, respectively.

Phase 1. In Phase 1, CT was used as received from the site, with a solids content of about 80%. The initial solids content of CMT was reduced from 87%, as received from the site, to about 76% by adding process water. Plants were started from seeds in root trainers and transplanted to the lysimeters after 5 weeks. Distilled water was added weekly to simulate the average amount of local precipitation from June through August. CT and CMT were watered at a rate of 16 and 5.5 mm per week for the first four weeks and at 20 and 4.0 mm for the fifth week, respectively. From the sixth week to the end of the experiment the water added to each lysimeter had to be increased to about 29 mm per week to prevent a loss of plant turgor. Water loss due to evapotranspiration was measured weekly by weighing the lysimeters.

Phase 2. In Phase 2, the initial solids contents were 65% and 76% for CT and CMT, respectively. Plants were started in root trainers, but transplanted after 3 weeks to the lysimeters. CT release water was added to the CT at a rate of 7 mm per week for the first four weeks, after which the rate was increased to 14 mm. CMT process water was added to the CMT material at 14 mm per week.

Observations of stress symptoms, survival and tillering were conducted chronologically in both phases. Depth of root penetration and plant biomass were measured at the end of each phase. Also, samples of tailings selected at random from each block were analyzed for nutrient levels, pH and EC at the end of each phase.

Results

Phase 1

Composite Tailings (CT). Results of Phase 1 obtained from CT are presented in Figures 1 to 3. Water was lost from the lysimeters through evapotranspiration or by evaporation alone in the case of the controls. The total amount of water lost after 70 days of plant growth is schematically illustrated in Figure 1. The species with the highest dewatering capability were red top (258 mm), smooth bromegrass (250 mm) and Altai wildrye (248 mm). The evaporation in the unplanted treatment (control) was 166 mm.

The roots of all species reached the bottom of the lysimeters by growing along the sides of the pails where water was easier to access. However, only a few plants developed roots inside the tailings. Figure 2 shows the depths of the roots which grew inside the tailings. Altai wildrye, creeping foxtail and reed canarygrass had roots developed in the tailings to the bottom of the lysimeters (about 30 cm deep) and would likely have gone further if the tailings deposit had been deeper. Streambank wheatgrass developed roots to 23 cm, and both red top and smooth bromegrass grew roots to a depth of 18 cm.

Dry biomasses above and below ground are shown in Figure 3. Red top produced the highest above ground biomass followed by smooth bromegrass, western dock and reed canarygrass. However, reed canarygrass produced the highest below ground biomass.

Copper Mine Tailings (CMT). Results obtained are presented in Figures 4 to 6. Total evapotranspiration after 69 days of plant growth are shown in Figure 4. The plant species with the highest dewatering capability were Altai wildrye (190 mm), alfalfa (180 mm), creeping foxtail (180 mm), and smooth bromegrass (179 mm). The evaporation in the unplanted treatment was 133 mm.

The roots of all species behaved the same way as in the CT; they reached the bottom of the lysimeters along their sides. However, only a few plants developed roots inside the tailings. Figure 5 shows the depth of only the roots that grew inside the tailings. Altai wildrye was the only plant that developed roots to the bottom of the lysimeters. Western dock developed roots to 20 cm, and both creeping foxtail and smooth bromegrass grew roots to a depth of 10 cm.

Results of dry biomass are illustrated in Figure 6. Western dock produced the highest above ground biomass followed by reed canarygrass, Altai wildrye, and timothy. However, only Altai wildrye had a high root biomass, resulting in a high root to shoot ratio, whereas Timothy produced a low root biomass, giving a very low root to shoot ratio. Smooth bromegrass had the highest root biomass and the highest root to shoot ratio.

Phase 2

Nutrient status, pH, and EC of the tailings at the beginning of Phase 2 are shown in Table 5. Fertilizer was again added to the tailings to increase the macronutrients to optimum levels.

Composite Tailings (CT). Three week old plants were transplanted to CT with an initial solids content of 65%. All plants were flooded for three days with water that was being released from the tailings due to consolidation. A total of about 40 mm of water was siphoned off from each lysimeter leaving the CT with a solids content of approximately 73 %.

CT release water, with an electrical conductivity of 7.14 dS/m, was used to water the plants every week. The addition of this water increased the level of salinity of the CT to extremely toxic levels. At the end of Phase 2, samples of tailings were taken at the top and bottom of five treatments selected at random. The increase of EC was in the range from 15.2 to 27.0 dS/m at the surface, but it did not change significantly at the bottom (Table 6).

Figure 7 presents the total evapotranspiration for each plant species after 56 days of growth. Creeping foxtail caused the highest water loss (115 mm), followed by Altai wildrye (104 mm), red top (101 mm) and reed canarygrass (99 mm).

Altai wildrye, creeping foxtail and streambank wheatgrass developed roots to the bottom of the lysimeters (about 30 cm) (Figure 8). In Phase 2 water was applied at a lower rate and the preferential growth of roots along the sides of the lysimeters was prevented by pressing the material tightly against the wall. This avoided added water accumulating in the space between the tailings and the pail walls as occurred in Phase 1. In this manner plants were forced to developed roots inside the tailings.

Figure 9 shows plant biomass above and below ground. Red top produced the highest dry above ground biomass, followed by creeping foxtail, Altai wildrye and reed canarygrass. Creeping foxtail, Altai wildrye and reed canarygrass produced the highest below ground biomass.

Assessments of the plant response to salt increase were conducted at the beginning of the third week and the eleventh week after transplanting (Table 7). Altai wildrye presented the lowest change in symptoms. Creeping foxtail had the highest survival and very strong tillering (vegetative reproduction).

Copper Mine Tailings (CMT). CMT process water, with an EC of 6.04 dS/m, was used to water the plants every week. The salinity levels at the end of Phase 2 are shown in Table 8. The increase of the EC at the surface of the tailings ranged from 28.2 to 40.0 dS/m, but it did not change significantly at the bottom.

Figure 10 presents the amount of water removed from each treatment after 56 days of plant growth. Smooth bromegrass caused the highest water loss (119 mm), followed by Altai wildrye (117 mm), and creeping foxtail (112 mm).

Altai wildrye, creeping foxtail and smooth bromegrass developed the deepest root systems 28, 27 and 27 cm, respectively, followed by alfalfa (23 cm) and reed canarygrass (21 cm) (Figure 11).

Altai wildrye produced the highest total dry biomass, followed by smooth bromegrass and creeping foxtail (Figure 12).

Altai wildrye presented the lowest change in symptoms and had the highest survival and very strong tillering (Table 9).

Discussion

Phase 1

Fifteen plant species were initially selected for testing in Composite Tailings (CT) in Phase 1. All plants survived after a ten-week period. Many of the plants examined in this experiment showed signs of healthy growth, except cattails and willows, which did not grow well in the tailings. Seeds of cattails were not commercially available and plants were started from roots collected from the field. Willows were started from cuttings taken from the field. Both cattails and willows were shocked in the transplant and their growth was stunted during the whole period of Phase 1. In spite of that, the results obtained clearly demonstrate that CT is not phytotoxic and can be used as a medium for plant growth. This conclusion is supported by the low EC and SAR, which class CT as a normal soil.

All of the nine species tested in CMT grew reasonably well. The plants caused significantly less water loss than those in the CT. A higher EC and high levels of copper may have contributed to a decrease in plant performance. However, all plants presented a healthy growth during the ten-week period of Phase 1.

Phase 2

The successful results obtained in Phase 1 made all plants good candidates for future reclamation activities when the impoundments reach full capacity. Plants which had the lowest performance in Phase 1 were eliminated for testing in Phase 2.

The application of CT release water, with EC of 7.14 dS/m, increased dramatically the level of salinity at the surface of the CT (0 - 7.5 cm) reaching toxic levels in the range of 15.2 to 27.0 dS/m. The addition of process water to CMT increased its surface (0 - 7.5 cm) salinity in the range from 28.2 to 40.0 dS/m. The salinity level at the bottom of both tailings did not change significantly.

In Phase 2 many plants showed signs of stress due to the high salinity level reached in the tailings. The increase of salt content in the tailings caused a reduction in the osmotic potential of the pore water in the tailings, making this water unavailable for plant use. In this situation, the level of metabolic activity in the plants was reduced. This was accomplished by reducing their biomass through shedding their leaves, or by going into a dormant stage. These symptoms were observed at the end of Phase 2, where many plants had dry leaves with tips curled and dead, and with dying tillers. The high salinity level reached in the tailings subjected the plants to water stress, even though the tailings had still high water content, but the soil water was not available to them. Consequently the amount of evapotranspiration was significantly reduced.

Evaluation of Plant Performance

Plants with the highest evapotranspiration rates had the highest above and below ground biomass, deeper roots, highest survival, and lowest stress symptoms. This supports the statement that the dewatering capability of plants is closely linked to their growth and physiological condition. Plant performance was evaluated by using a percentage index based on the following four parameters: total evapotranspiration, root depth, above and below ground biomass for both study phases. The plant with the highest value in each parameter was assigned the index of 100. The indices for the other plants are fractions of 100 calculated from their relative values. Each parameter and each phase were assigned equal weights in the calculation of the final indices. Plants with the highest indices on CT were creeping foxtail (91%), reed canarygrass (88%), Altai wildrye (85%), and red top (84%). The rest of the plants had indices below 75%. In CMT the plants with the highest indices were Altai wildrye (97%), smooth bromegrass (78%), and creeping foxtail (70%). The rest had indices below 60%.

The final selection of the most suitable plants was based on a qualitative analysis of percentage index, symptom scale, survival, tillering and past performance.

The plants which performed the best under both phases in Composite Tailings were creeping foxtail, reed canarygrass, Altai wildrye, and red top; and in Copper Mine Tailings were Altai wildrye, smooth bromegrass and creeping foxtail.

Conclusions

A two-phase greenhouse experimental program was conducted to identify the most suitable plant species for dewatering and reclamation of Composite Tailings (CT) and Copper Mine Tailings (CMT). Based on values of Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) both tailings can be classified as normal soils (non-sodic and non-saline soils). Healthy plant growth obtained in Phase 1 of the experiment led to the conclusion that both tailings are not phytotoxic and plants can be used to implement future reclamation activities when the impoundments reach full capacity. Results obtained from Phase 2 were useful to identify plant species tolerant to high levels of salinity and any toxic component contained in the tailings water. Those plants adapted well to extremely toxic levels of salinity and are recommended for future field research for dewatering and reclamation of CT and CMT tailings.

In conclusion, four plant species proved to be the best candidates for future greenhouse and/or field research in CT: creeping foxtail, reed canarygrass, Altai wildrye, and red top. Three species are recommended for further studies in CMT: Altai wildrye, smooth bromegrass and creeping foxtail.

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Table 1. Plant species selected for testing

Common Name	**Scientific Name**	**CT**		**CMT**	
		Phase		**Phase**	
		1	**2**	**1**	**2**
Alfalfa	Medicago sativa	✓	✓	✓	✓
Alsike clover	Trifolium hybridum	✓	✓		
Altai wildrye	Elymus angustus	✓	✓	✓	✓
Common cattail	Typha latifolia	✓			
Creeping foxtail	Alopecurus arundinaceus	✓	✓	✓	✓
Indian ricegrass	Oryzopsis hymenoides	✓			
Kentucky bluegrass	Poa pratensis	✓	✓		
Northern wheatgrass	Agropyron dasystachyum	✓	✓	✓	✓
Red top	Agrostis stolonifera	✓	✓		
Reed canarygrass	Phalaris arundinacea	✓	✓	✓	✓
Smooth bromegrass	Bromus inermis	✓	✓	✓	✓
Streambank wheatgrass	Agropyron riparian	✓	✓		
Timothy	Phleum pratense	✓	✓	✓	✓
Willow	Salix bebbiana	✓		✓	
Western dock	Rumex occidentalis	✓	✓	✓	✓

Table 2. Chemical analyses of CT and CMT samples

Analysis	**CT**		**CMT**		**Optimum***
	Sample 1	**Sample 2**	**Sample 1**	**Sample 2**	
pH	9.5	9.6	8.1	8.1	6-8
EC (dS/m)	1.1	1.1	3.0	3.3	<1
Nitrate (ppm)	<1	<1	<1	<1	100 – 279
Phosphate (ppm)	1	2	7	9	8 – 13
Potassium (ppm)	39	45	149	163	150 – 249
Sulfate (ppm)	>20	>20	>20	>20	10 - 12

* Warncke 1979

Table 3. Micronutrient status of CT and CMT

Element	CT (ppm)	CMT (ppm)
Ca	392	2660
Na	151	190
Mg	58	200
Fe	11	24
Cu	0.23	78.14
Zn	0.7	1.5
B	2.24	0.12
Mn	6.7	3.4
Cl	>50	>50

Table 4. Chemical composition of CT release water and CMT process water

Parameters and Units	CT	CMT
pH	8.15	6.51
EC (dS/m)	7.14	6.04
Ca (mg/L)	54	580
Mg (mg/L)	38.5	155
Na (mg/L)	1700	698
K (mg/L)	38.7	68.1
SO_4 (mg/L)	2360	1920
Nitrate and Nitrite (mg/L)	<0.05	<0.05
PO_4 (mg/L)	<0.05	<0.05
SAR	43.1	6.6

Table 5. Chemical analyses of CT and CMT samples at beginning of phase 2

Analysis	CT	CMT
pH	7.5	7.4
EC (dS/m)	1.6	2.5
Nitrate (ppm)	<1	7
Phosphate (ppm)	3	12
Potassium (ppm)	44	170
Sulfate (ppm)	>20	>20

Table 6. Chemical analyses of five CT samples at end of phase 2

Analysis	Sample 1		Sample 2		Sample 3		Sample 4		Sample 5	
	Top	Btm	Top	Btm	Top	Btm	Top	Btm	Top	Btm
pH	9.0	8.4	8.8	8.5	9.0	9.0	8.9	8.9	9.1	8.8
EC (dS/m)	19.0	1.7	17.3	1.8	27.0	1.5	15.8	1.5	15.2	1.3
Nitrate (ppm)	>75	<1	>75	<1	>75	<1	>75	<1	>75	<1
Phosphate (ppm)	25	17	27	18	32	20	24	20	24	18
Potassium (ppm)	351	59	320	71	548	87	396	80	267	65
Sulphate (ppm)	7	>20	>20	>20	16	>20	>20	>20	>20	>20

Table 7. Summary of plant behavior assessment for CT-phase 2

Plant Species	Symptom Scale		No. of Tiller				Tillering Observed
	3rd Week	11th Week	3rd wk		11th wk		
			Live	Dead	Live	Dead	
Alfalfa	4	3.5	15	1	8	4	No
Alsike clover	4	4	9	7	0	All	No
Altai wildrye	2	2	19	0	23	1	Yes
Creeping foxtail	2	3	29	0	38	0	Yes
Kentucky bluegrass	3	3	24	0	31	2	Yes
Northern wheatgrass	2.5	3	22	1	18	5	Yes
Red top	1	2.5	47	0	54	6	Yes
Reed canarygrass	2	3	24	0	20	11	Yes
Smooth bromegrass	2.5	3.5	18	0	18	5	Yes
Streambank wheatgrass	2.5	3	20	1	25	7	Yes
Timothy	2.5	4	24	0	9	15	No
Western dock	1.5	3.5	14	0	4	3	No

Note: tiller means total number of plants and tillering is the ability to develop new plants

Symptom scale is based on degree of plant health.

1 Very healthy, lush, a few older leaves dying, maybe a few tips browning.

2 Fairly healthy, many first leaves dying, some symptoms evident, tips dying, a bit of chlorosis.

3 Looking stressed, dry leaves, chlorosis and necrosis very evident, tips curled and dead, perhaps stunted.

4 Very stressed, dry, dying tillers.

Note: dying refers to mortality

Table 8. Chemical analyses of four CMT samples at end of phase 2

Analysis	Sample 1		Sample 2		Sample 3		Sample 4	
	Top	Btm	Top	Btm	Top	Btm	Top	Btm
pH	7.2	8.0	7.3	8.1	7.6	8.1	7.6	8.1
EC (dS/m)	35.2	4.9	28.2	4.3	40.0	4.5	36.5	4.8
Nitrate (ppm)	>75	49	>75	43	>75	41	>75	64
Phosphate (ppm)	25	23	21	16	17	17	26	15
Potassium (ppm)	>600	235	>600	198	>600	253	>600	197
Sulphate (ppm)	>20	>20	>20	>20	>20	>20	15	>20

Table 9. Summary of plant behavior assessment for CMT-phase 2

Plant Species	Symptom Scale		No. of Tiller				Tillering Observed
	3rd Week	11th Week	3rd wk		11th wk		
			Live	Dead	Live	Dead	
Alfalfa	4	3.6	4	10	1	6	No
Altai wildrye	2	2	19	0	22	0	Yes
Creeping foxtail	2.8	3	27	0	24	2	Yes
Northern wheatgrass	2.3	3.7	17	0	9	9	Yes
Reed canarygrass	2.5	4	30	0	0	18	No
Smooth bromegrass	2.7	3.5	16	1	10	5	No
Timothy	2.3	4	27	0	3	24	No
Western dock	1.5	3.7	6	6	2	5	No