Evapotranspiration Dewatering Effect On CT Deposits By Grasses

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ABSTRACT
Greenhouse experiments were conducted to assess the feasibility of using five grass species to dewater composite / consolidated tailings (CT) via evapotranspiration. Selected plant species were directly seeded via modified broadcast seeding, hydro-seeding with mulch, and fresh discharged CT slurry seeding techniques. A dimensionless parameter, the plant dewatering ratio (α), was introduced to evaluate the capacity of uptaking water via plant evapotranspiration. The testing results indicated that Slender wheatgrass and Northern wheatgrass were the best candidates for use in CT deposits with highest germination rates and fair growth performance. CT discharged from the Suncor Oil Sands operation plant is not phytotoxic for these two native plant species. Seeding via modified broadcast and slurry discharge resulted in higher germination. Slender and Northern wheatgrass also have higher α values (15% to 25%). Evapotranspiration during one growing season was higher for Slender wheatgrass and Northern wheatgrass resulting in average solids content increases of 87.6 to 90.5% from the 65% initial solids content. Grass species were able to uptake water from high water content tailings and to increase the solids contents resulting in enhanced tailings strength.

RÉSUMÉ
Des expériences en serre ont été menées pour évaluer la faisabilité de l'utilisation de cinq espèces de graminées afin de germer dans et assécher des résidus CT (Consolidated Tailings) par évapotranspiration en croissant directement dans les CT. Les résultats de début de croissance des végétaux sélectionnés qui ont été semés : 1) directement par diffusion de semences en plein et recouvrement d'une mince couche de CT fraîchement libérés; 2) hydro-ensemencement d'un mélange d'eau de bassin de résidus avec du paillis, et ; 3) le semis direct dans une boue de décharge de résidus indiquent que les espèces, l'agropyre à chaumes rudes et l'agropyre du Nord, sont les meilleurs candidats pour la réhabilitation des résidus CT. L'ensemencement par la diffusion et le semis à même la décharge permettent de distribuer les graines résultant en une plus grande faculté germinative. Un nouveau paramètre sans dimension, le ratio d'àssèchement (α), défini comme le ratio de la capacité d'assèchement des plantes à la quantité d'eau disponible dans le sol, a été créé. L'agropyre à chaumes rudes et l'agropyre du Nord ont également une valeur α supérieure (valeur de 15% à 25%), ce qui indique que ces espèces de plantes sont en effet capables d'absorber l'eau de résidus à haute teneur en eau et d'en augmenter le contenu solide. Le taux d'évapotranspiration au cours d'une saison de croissance est également plus élevé pour l'agropyre à chaumes rudes et l'agropyre du Nord résultant en une augmentation de la teneur moyenne de solides à 87,6 - 90,5%, d'une valeur initiale de 65%.

1 INTRODUCTION

Annually, the Clark Hot Water Extraction (CHWE) of bitumen from oil sands produces significant amounts of tailings consisting of water, sand, fines and residual bitumen. These tailings are deposited hydraulically in the impoundment areas. Upon deposition, sand segregates from tailings slurry, leaving fine tailings of silt and clay with 5% solids content which flows into the settling pond. These fine tailings gradually settle and undergo self-weight consolidation to form mature fine tailings (MFT) with approximately 30% solids content after about two years. MFT is an unstable material with extremely low strength and will take centuries to dewater via self weight consolidation. Since about 1995, gypsum based CT technology has been used by mixing MFT with a stream of cyclone underflow (tailings sand) and the appropriate amount of gypsum to produce non-segregating composite / consolidated tailings (CT) with solids content of 65%. At this solids content, CT is a semi-plastic, but weak slurry (Qiu and Sego, 2001). CT needs to be dewatered to over 85% solids content for its shear strength to be sufficient to support equipment traffic that allows reclamation activities to proceed (Johnson et al. 1993).

The mechanism of biological processes to dewater oil sands tailings has been identified by many researchers. Laboratory and field experiment results (Johnson et al. 1993; Stahl, 1996; and Silva, 1999) have indicated that suitable plant species are able to transpire water through their leaves depleting water from tailings and enhancing its shear strength. The plant root system provides fiber reinforcement, which also contributes to increasing bearing capacity within the rooted tailings zone.

During the past decade, non-native introduced plant species were preferred for dewatering high water content CT since many are tolerant of the high salinity CT materials and have strong growth and survival characteristics (Johnson et al., 1993; Silva et al., 1998; Naeth et al., 1999; Renault et al., 2003; 2004). The aggressive characteristics that make these non-native species successful also result in their dominance and competitive exclusion of slower growing native plant species. Past use of non-native plants on revegetated sites in Alberta has resulted in the exclusion of native species. The loss of these important native plant species may negatively impact ecosystem development and function (Lyster et al. 2001).

Native plant species are now often favoured in reclamation because they have grown over time under local soil conditions and are well adapted to annual climate fluctuations. Native plants often have low insect attack and perform satisfactorily without supplementary irrigation or maintenance (Alberta Environment, 2003).

For dewatering CT purposes, cool season grasses were considered because of the short growing season and requirement in these local climates. These grasses often have a higher germination rate, require little maintenance, and more economical seeding techniques can be employed. Effective dewatering can thus begin in the first growing season. Since these grasses are not overly aggressive, other local native plant species may encroach once they are established and natural processes of dewatering the high water content tailings can lead to successful site reclamation.

This greenhouse experiment was carried out to study plant capacity for dewatering CT deposits. The objective of this study was to estimate the water loss from CT via plant evaportranspiration in the equivalent of one growing season. Seeds of these plant species were directly seeded using modified broadcast seeding, hydro-seeding with Fibramulch™, and fresh discharged slurry seeding techniques.

2 BACKGROUND

Plants have been widely used in civil engineering to enhance slope stability, erosion prevention and landscape reclamation (Schiechtl, 1980; Bache and MacAskill, 1984; and Coppin and Richards, 1990). Pioneering and practical applications of plants to dewater lacustrine and marine sediment were carried out in polder reclamation (Public Relations and Information Department of the Netherlands, 1959; Volker, 1982). Plants applied in polder reclamation accelerated the drying process via evapotranspiration. Ocean bottom sediments have an extremely high water content, low hydraulic conductivity and low bearing capacity which is similar to oil sands tailings in their physical and engineering properties.

The influence of plants on dewatering high water content materials has been observed in the reclamation of tailings. Based on the research and reclamation work carried out on tailings disposal areas in northeastern Canada, Leroy (1972) highlighted that a fully vegetated acre will transpire from 4.5 to 9.0 mm water daily. He summarized the basic guidelines of soil amenity, fertilizer application, seeding and mulching for successful and acceptable reclamation of mine tailings.

Dwatering fine grained mine tailings and CT by natural processes has been documented by Stahl (1996) and Johnson et al. (1993). Laboratory and field experimental results concluded that suitable plant species are capable of increasing surface stability by increasing cohesion and friction angle of the reinforced soil mass. Plants growing in tailings can remove the water via evapotranspitation to increase the solids content.

Greenhouse experiments performed by Silva (1999) evaluated the response of introduced plant species: Altai wildrye (*Elymus angustus*); Creeping foxtail (*Alopecurus arundinaceus*); Red top (*Agrostis stolonifera*); Reed canarygrass (*Phalaris arundinacea*); and Streambank wheatgrass (*Agropyron riparian*). The seeds of these species germinated in a nursery, then were transplanted into CT and grown in a greenhouse. He found CT was not phytotoxic to those non-native species. After one growing season, the solids content of the upper layer of CT increased from 68% to 95% by evapotranspiration.

3 THEORETICAL MODEL FOR ESTIMATING PLANT EVAPOTRANSPIRATION

Evapotranspiration is a crucial component of the water balance. The rate of water uptake from soil through the plant root-stem-leaves system in a crop with a uniform but incomplete canopy may be limited by soil, plant and atmospheric factors. Evaporation from a wet soil surface is primarily influenced by the energy available. When the plants are in an early growth stage with little vegetative cover, the evapotranspiration rate from the entire field surface is dominated by the soil evaporation rate. As the surface dries, evapotranspiration becomes more important and depends on the hydraulic properties of the near surface soil. As the plant canopy increases, transpiration becomes more dependent on leaf area and ability of the root system to supply water (Penman et al. 1967).

An empirical relationship presented by Ritchie (1972) is widely used to predict plant transpiration in which evaporation from a soil surface and transpiration from a plant surface are considered separately. Then evapotranspiration (E) is distributed into soil evaporation (E_s) and plant transpiration (E_p).

$$E = E_s + E_p \quad [1]$$

The plant transpiration under incomplete cover condition can be expressed as:

$$\begin{aligned} E_p &= 0 && LAI < 0.1 \\ E_p &= E_0\,(-0.21 + 0.7LAI^{1/2}) && 0.1 \le LAI \le 2.7 \\ E_p &= E_0 && LAI > 2.7 \end{aligned} \quad [2]$$

The potential evaporation (E_0) is calculated from measured actual evaporation (E_s) as:

$$E_0 = E_s / K_{evap} \quad [3]$$

Where, K_{evap} is an evaporation limiting factor. For CT deposits, accounting for hydraulic properties and salt crust formation, the surface evaporation rate drops to about 0.6 of potential evaporation after approximately 10 days (Qiu and Sego, 2001).

A dimensionless parameter α representing the ratio of dewatering by plants defined as plant dewatering capacity over initial soil water storage ($(E\text{-}P')/M_{w0}$ in percentage) was introduced in this greenhouse study to estimate plant transpiration. According to the Ritchie (1972) model that plant transpiration is a function of LAI.

$$\alpha = \frac{(E - P')}{M_{w0}} = f(LAI)$$

[4]

Where, E is evapotranspiration, P' is precipitation, M_{w0} is initial water mass in the soil.

4 MATERIAL AND LABORATORY EXPERIMENT DESIGN

4.1 Composite Tailings (CT)

CT was prepared by mixing sand, mature fine tailings (MFT), pond water and gypsum ($CaSO \cdot 2H_2O$), provided by Suncor Energy Inc. in Fort McMurray. The amount of gypsum added was approximately 1200 g/m^3. The CT mixture had an initial solids content of 65% and contained 20% fines (< 44 μm, # 325 sieves). In the laboratory, the CT mixture was prepared in several batches to produce a homogenous material.

The CT mixture used in this study had a pH of 7.48 and sodium adsorption ratio (SAR) of 10.4. Based on the combined value of SAR and pH, CT can be classified as a slightly salinity soil (Wu, 2009).

4.2 Plant species

Through screening of native plant species listed in references (Alberta Agriculture, 1981; Hardy BBT Ltd, 1989; Johnson et al. 1993; Naeth et al. 1999; Native Plant Working Group, 2001), four native grass species: Bluejoint (*Calamagrostis canadensis*), Hairy wild rye (*Elymus innovatus* Beal), Northern wheatgrass (*Agropyron dasystachyum*), and Slender wheatgrass (*Agropyron trachycaulum*) and one non-native grass Creeping red fescue (*Festuca rubra*), were selected for this greenhouse experiment. Seeds were seeded into CT using different techniques as outlined in Wu (2009).

4.3 Greenhouse experiments

Ninety (90) four-liter (4L) plastic pails having a diameter of 218 mm and a height of 145 mm were used as containers during the experiment. The container was filled with CT to 130 mm depth. Self-weight consolidation was allowed to occur and expressed water was siphoned from the surface. Three replicates were prepared for each plant species and each different seeding treatment; three samples were left unplanted as a control.

The pails were placed in a controlled environment greenhouse at 22 ^{0}C average air temperature with 15 hours of light and 9 hours darkness, simulating the typical growing climate condition in Fort McMurray in June. Mercury and sodium vapor lights (400 W) acted as supplemental light to complement the low light intensity in the greenhouse during late fall and winter when the tests were carried out. Plants were placed randomly rather than placing all the plants with a particular seeding method together to minimize the effect of any environmental differences.

Distilled water was added twice a week on the surface of CT soil to simulate the average precipitation (9.8 mm per week) from May through September. Since the standing water would float the seeds out of the soil causing germination rate to decrease, the amount of distilled water added was approximately 89% of the average precipitation.

Fertilizer 20-8-20 (nitrogen-phosphorus-potassium) was added biweekly after the initial germination study (week 1 to 8) was completed to compensate for the nutrient deficiency measured in the CT soil. Application rate was 100 ppm. Treatments presented in this paper were modified broadcast seeding and seeding in 5 mm of fresh discharge CT slurry.

5 MEASUREMENTS

5.1 Plants

Plant density was determined by counting the plant shoots, then expressed as plants per m^2. Weekly plant height measurements began 7 days after seeding and continued for 15 weeks to monitor plant growth during one complete growing season (about 105 days). At the end of the experiment, leaf area was measured using UCPE-leaf area measurement program (The University of Sheffield, UK). The total leaf area was determined by multiplying the area of the subsample by the total number of leaves. These leaf areas were then used to calculate the leaf area index (LAI, dimensionless), which is defined as the area of one side of leaves per unit of soil surface (Jensen et al. 1990).

After fifteen (15) weeks, plants were harvested; gently cleaned with soft paper towel and weighed to measure the wet plant weights. Plants were then washed three times with distilled water, the samples bulked for three (3) days, allowed to air dry and weighed, then oven dried overnight at 65 ^{0}C to determine dry plant weight.

One random soil sample for each plant species was used to determine root weights of selected grass species. Samples were submerged in a pail of water, then lose soil and the roots removed. Roots were washed using distilled water and paper towel dried. The samples were air dried for three (3) days and weighed to determine the wet weight of roots, then oven dried overnight at 65 ^{0}C and dry weights determined. Plant dry biomass (mg dry wt.) above and below ground was calculated.

5.2 Solids content profile

Solids contents were measured by taking soil samples using a 37.65 mm diameter thin walled tube sampler at depth of 0-15 mm, 15-30 mm, 30-45 mm, 45-60 mm, 60-75 mm to obtain a profile on solids contents resulting from evapotranspiration in the planted samples and evaporation in the unplanted control samples.

5.3 Evapotranspiration and evaporation

Water lost by plant evapotranspiration and evaporation was measured weekly by weighing the planted samples and unplanted sample containers, respectively (Ritchie and Burnett, 1968). The dimensionless parameter α was calculated for estimating plant dewatering capacity.

6 RESULTS AND DISCUSSIONS

Grass species germinated reasonably well in CT deposits when using different seeding techniques. With broadcast seeding, Slender wheatgrass and Northern wheatgrass produced the highest plant density, 1167 plants/m^2 and 1008 plants/m^2, respectively, followed by Creeping red fescue, 583 plants/m^2. Hairy wild rye and Bluejoint had the lowest plant density as summarized in Table1.

Table 1. Average plant density in with broadcast seeding

Plant species	Plant density (Plants/m^2)	Total Plant leaves	Plant Leaf Area (mm^2)
Hairy wild rye	201.7	97	2,737.5
Northern wheatgrass	1,008.5	501	12,660.2
Creeping red fescue	583.9	219	5,137.1
Slender wheatgrass	1,167.7	556	26,841.3
Bluejoint	21.2	3	--

Average plant growth height versus time curve as shown in Figure1 indicated that the average plant height reached the maximum after approximately 15 weeks. The heights of Slender wheatgrass and Northern wheatgrass reached 30.4 cm and 23.9 cm, respectively, at 15 weeks in broadcast seeding treatment (Figure1 (a)). Fertilizer added biweekly after 8 weeks enhanced plant growth. Under the fertilized condition, Slender wheatgrass and Northern wheatgrass would likely have grown higher if the experiment continued. However, it appears that the growth of Hairy wild rye and Bluejoint was dramatically delayed. Creeping red fescue presented a stunted growth. Similar observations can be made when the seeds were spread using the fresh CT discharge slurry to assist with seeding (Figure1 (b)). The initial waterlogged conditions, slightly saline soil, and the climate conditions likely contributed to lower growth in treatment-4.

Leaf area index (LAI) of each plant species for each treatment was calculated from measured leaf area (Table 2). LAI was greatest for Slender wheatgrass in all treatments followed by Northern wheatgrass. Hairy wild rye and Bluejoint produced lowest LAI because of low germination rate, plant density and stunted plant growth in the treatments.

Slender wheatgrass and Northern wheatgrass species produced the highest shoot and root dry weights (Table 3); Creeping red fescue, Hairy wild rye and Bluejoint produced the lowest shoot and root dry weights. Slender wheatgrass and Northern wheatgrass produced the higher root to shoot ratio (1.05 and 1.49, respectively), followed by Creeping red fescue (0.79) and Hairy wild rye (0.67).

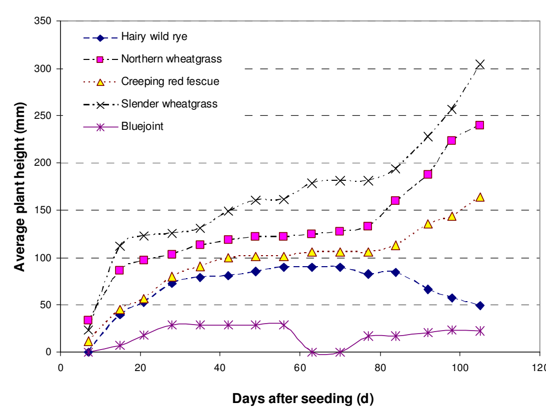
Table 2 Plant shoots and roots dry weight and wet weight with broadcast seeding

Plant Species	Shoots wet weight (mg)	Shoots dry weight (mg)	Roots wet weight (mg)	Roots dry weight (mg)	Root: Shoot ratio
Hairy wild rye	490	157.4	333.45	236.1	0.67
Northern wheatgrass	2600	1249	1870.1	835.8	1.49
Creeping red fescue	740	265.5	594.5	336.1	0.79
Slender wheatgrass	5760	2421.7	1997.8	2306.4	1.05
Bluejoint	2.1	1.8	--	--	--

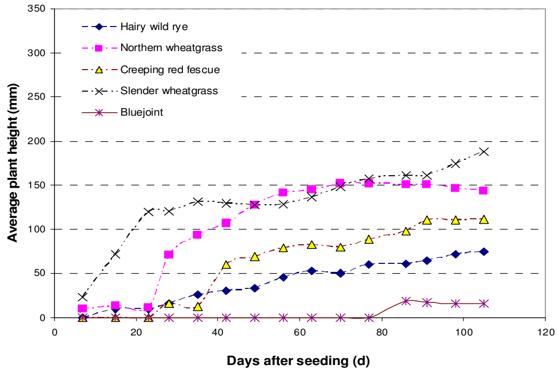
Table 3 Leaf Area Index with broadcast seeding and CT slurry seeding

Plant species	Broadcast (15 weeks)	CT slurry (15 weeks)
Hairy wild rye	2.91	0.65
Northern wheatgrass	13.44	9.31
Creeping red fescue	5.45	3.76
Slender wheatgrass	28.30	19.44
Bluejoint	--	--

With broadcast seeding, after 15 weeks, dry biomass (Figure 2 (a)) ranged from 1.05 mg to 2306.4 mg below ground, from 1.8 mg to 2421.7 mg above ground, and from 2.85 mg to 4728.1 mg for total biomass. Slender wheatgrass produced the highest total dry biomass followed by Northern wheatgrass.



(a)

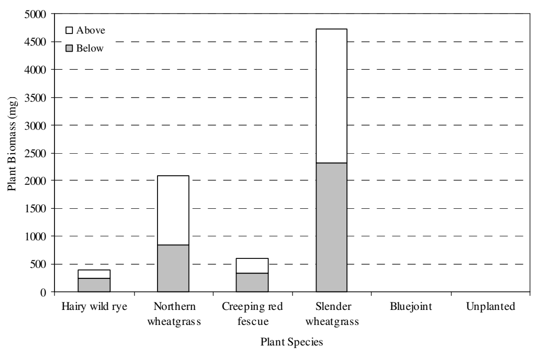


(b)

Figure 1 Average plant growth height versus time in different seeding treatments

(a) Broadcast seeding;

(b) 5 mm fresh discharge CT slurry seeding.



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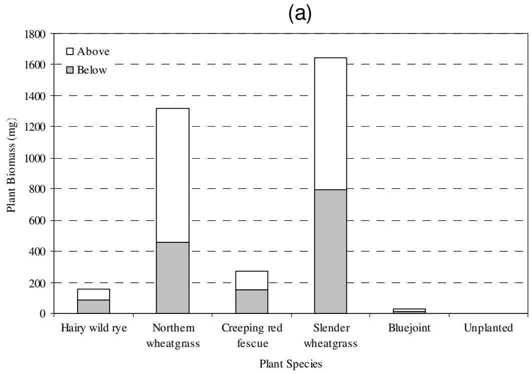


(b)

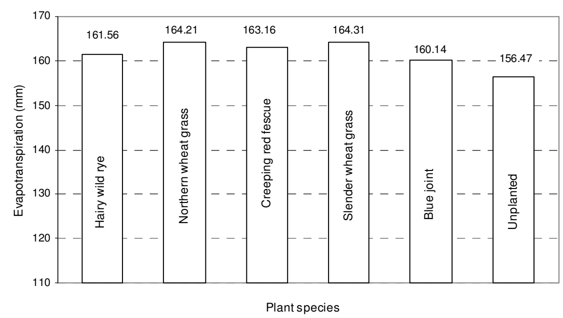
Figure 2 Plant biomass above and below ground

(a) Broadcast seeding;

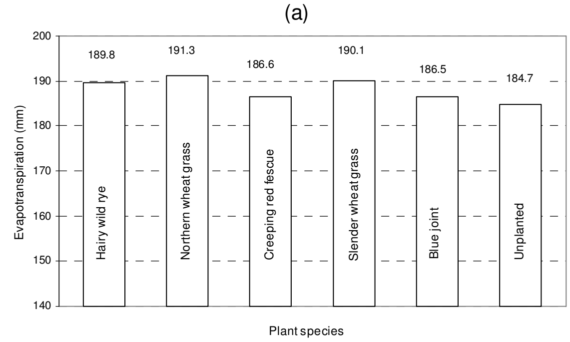
(b) 5 mm fresh discharge CT slurry seeding

The total amount of water lost from soil through evapotranspiration or by evaporation alone in the case of unplanted samples after 15 weeks of plant growth is schematically illustrated in Figure 3. The plant species with the highest dewatering capability were Northern wheatgrass (164.2 mm with broadcast seeding and 191.3 mm with CT slurry seeding) and Slender wheatgrass (164.3 mm with broadcast seeding and 190.1 mm with CT slurry seeding). Evaporation from the CT mixture surface in the unplanted samples was 156.4 mm and 184.7 mm, with broadcast seeding and with CT slurry seeding, respectively. Bluejoint transpired little water than the other plant species because of its poor germination and physiological state.

In Figure 3, at the end of the experiment, water loss in all planted samples was higher than in unplanted samples, indicating water loss via plant evapotranspiration was greater than via soil surface evaporation. Selected native plants have the capacity to uptake water from CT. Very little difference in dewatering was observed between individual plant species and the unplanted samples which can be explained as follows. Plant evapotranspiration testing followed emergence testing, plant density was too low to uptake a significant amount of water from CT materials. When simulated precipitation water was added, free water stood on the surface in the unplanted samples which resulted from salt crust formation and prevented water from soaking into the CT. In this condition, the tests were similar to pan evaporation tests. However, plant root channels guided water into the CT (Figure 4). The free pan evaporation rate was much greater than CT surface evaporation (Johnson, 1993).



(a)



(b)

Figure 3 Evapotranspiration of CT after 15 weeks plant growth

(a) Broadcast seeding;

(b) 5 mm fresh discharge CT slurry seeding

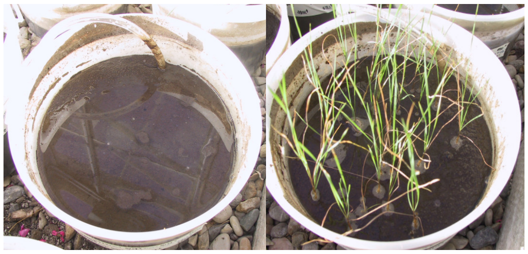
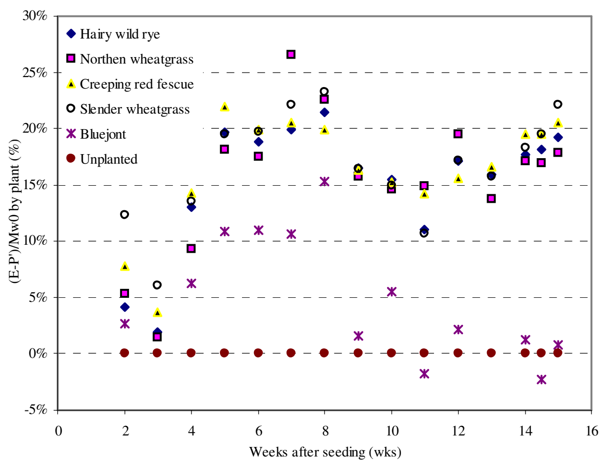


Figure 4 Free water in unplanted sample and plant channels in planted samples

Using the dimensionless parameter α to present plant evapotranspiration is shown in Figure 5, In broadcast seeded and CT slurry seeded treatments, most α values were greater than zero. All plant species that grew in CT materials did uptake more water by plant transpiration than CT surface evaporation. Northern wheatgrass and Slender wheatgrass had higher plant dewatering capacity ratios α.



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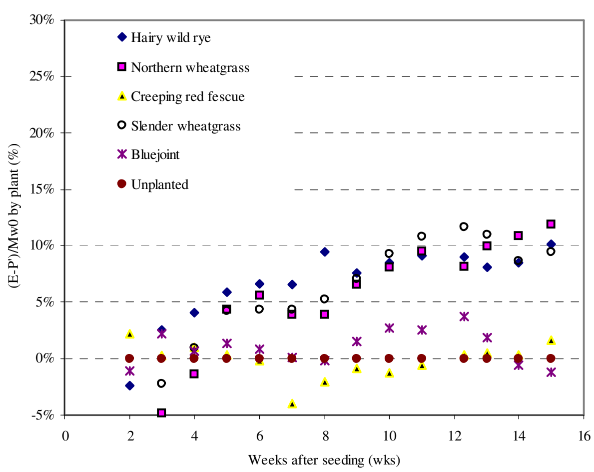

(b)

Figure 5 Parameter α by native plant species in treatments (a) broadcast seeding, (b) CT slurry seeding

Figure 6 shows trend lines between parameter α and LAI for Northern wheatgrass and Slender wheatgrass. The dewatering capacity parameter, α, generally increased when LAI increased. Based on the limited data obtained, it is difficult to find an accurate formula to represent the relationship between parameter α and LAI. In this study, the test data were used to develop a linear trend. R-square values of those curves were obtained as 0.72 and 0.016 for Northern wheatgrass and Slender wheatgrass, respectively, indicating the inaccuracy of those two trend lines. Further research is required to obtain an accurate relationship between dewatering capacity parameter α and LAI to simulate the prediction of plant dewatering capacity.

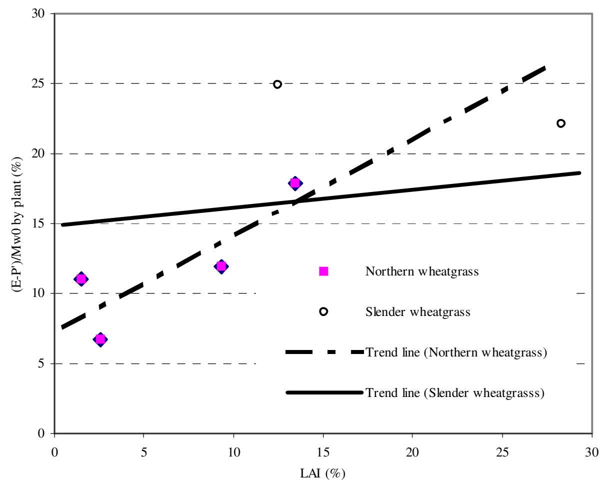

Figure 6 α versus. LAI and trend lines

As water evapotranspired or evaporated from the surface, a moisture gradient was established that directly reflected the solids content profile at the end of the experiment (Figure 7). The average solids contents in all planted samples increased to 87.6% to 90.5%. Slender wheatgrass increased the solids content of the CT mixture from 80% to 90.5% at the end of the experiment. For all plant species, solids content generally decreased with depth, averaging 84.6% to 87.3% at the bottom of the profile and 92.4% to 94.5% at the top of the profile. Evaporation alone (unplanted), increased solids content from 80% to 87% at the end of the experiment. The salt accumulations and the presence of the crust on the unplanted samples reduced dewatering via surface evaporation.

The fitted curve shown in Figure 8 indicated that the grass species transpiration from the CT mixture increased slightly as the LAI increased in this experiment. Native plant transpiration was dependent on LAI. Compared to the prediction presented by Ritchie (1972), the actual transpiration of native plant species growing in CT soil would be vastly over predicted. The source of the inaccuracy in using this model was the low plant density and the fact that the water supply to the plant roots was limited during this test period. The accuracy of leaf area measurement also affects the results. The model used the standard local rainfall and solar radiation to calculate the potential evaporation (E_0) and E_s was calculated as if the surface was freely evaporating. However, in this experiment, to avoid standing water floating the seeds out of the slurry which may decrease the germination rate, the water added to the CT mixture was only 89% of the average local precipitation.

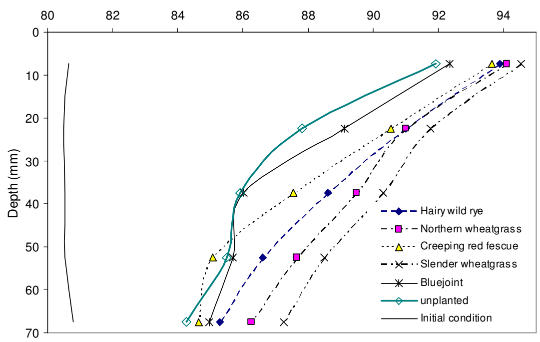

Figure 7 Solids Content Profile in broadcast seeding treatment

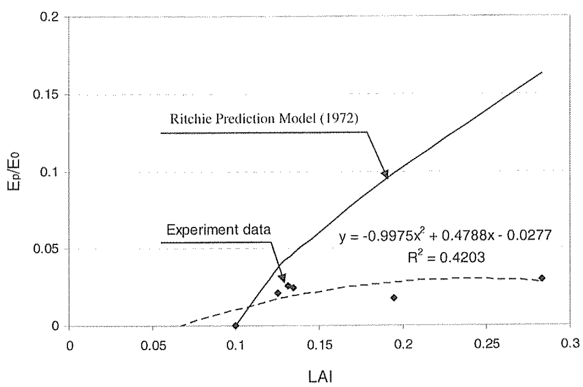

Figure 8 Native plant transpiration E_p influenced by LAI

7 Conclusions

A greenhouse experimental program was conducted to identify suitable grass species for dewatering and reclamation of composite / consolidated tailings (CT). Based on the measurement of plant height, dry biomass, and leaf area, native plant species can germinate and grow in CT mixture. The native grasses, Slender wheatgrass and Northern wheatgrass produced the highest dry biomass and leaf area index which indicated that CT can be reclaimed directly using native plant species to dewater CT deposits and increase surface bearing capacity. Slender wheatgrass and Northern wheatgrass had the highest evapotranspiration in one growing season.

The dimensionless parameter α can be used to indicate the plant dewatering capacity when soil water storage quantity is limited. Slender wheatgrass and Northern wheatgrass also have higher plant dewatering ratio α. which indicated that grass species were able to uptake water from high water content material and increase the solids content and therefore its bearing capacity. Plant dewatering capacity increased when its leaf area increased. More greenhouse experiments and field tests should be carried out to determine the relationship between dewatering capacity parameter α and LAI to increase the accuracy of the dewatering capacity prediction for each selected plant species.

Slender wheatgrass and Northern wheatgrass proved to be the best candidates for further field research using different seeding techniques and in high plant density to dewater the CT mixture. Field tests, to evaluate practical seeding techniques capable of distributing seeds widely on fresh CT deposits, should be carried out.

ACKNOWLEDGEMENTS

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