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Soil moisture and bulk density monitoring at Syncrude Canada Ltd.

B.L. Drozdowski *Alberta Innovates Technology Futures, Canada*

R.L. Faught *Alberta Innovates Technology Futures, Canada*

A. Underwood *Alberta Innovates Technology Futures, Canada*

Abstract

Soils disturbed by surface mining in the Athabasca oil sands region must be salvaged and replaced during reclamation in accordance with the current provincial legislation. Historical replacement strategies have been dependent on mining approval conditions, waste materials and targeted vegetation. To determine if the reconstructed soils provided adequate moisture for the post-reclamation vegetation community, a long-term monitoring study was established. Thirty-seven sites were established and monitored for soil moisture and bulk density in reclaimed soil covers and natural soils from 1994 to 2010. During the course of the study, the natural coarse textured Brunisolic (Cryochrepts and Dystrochrepts) soils had volumetric water content values ranging from approximately 3 to 10% and the finer textured Luvisolic (Boralf) soils had values ranging from 17 to 30% during the growing season. Reconstructed soils had moisture contents ranging between the Luvisolic and Brunisolic soils and the most seasonal variability occurred in the soil caps with the finer textured secondary layer and to a lesser extent the peat-mix over tailings sand cover. Based on laboratory derived available water holding capacity, all of the reconstructed soil covers were capable of holding more water in the upper metre of soil than the coarse textured natural soil and were variable (45–138%) compared to the fine textured natural Luvisolic soil. Bulk density of the reconstructed soil covers ranged from 1.4 to 1.7 Mg m^{-3} which was similar to the values for the finer textured Luvisolic soil. The underlying tailings sand had values of approximately 1.4 Mg m^{-3} which were similar to the values for the coarse textured Brunisolic soils. Results of the research indicate that current reclamation practices are appropriate for providing soil moisture to support vegetation covers.

1 Introduction

Reclamation practices associated with oil sands surface mining operations in the Athabasca oil sands region have evolved over time (Macyk and Drozdowski, 2008). Changes have been based on regulations, guidelines and overall government policy combined with research and experience gained through operational practice. In 1992 the Alberta Research Council (now part of Alberta Innovates Technology Futures) initiated a project to identify whether or not bison grazing was adversely affecting reconstructed soil properties. The project began with the evaluation of the changes in soil physical properties associated with bison grazing in areas with different soil reconstruction techniques compared to relevant control sites and included climate, soil moisture and density monitoring. This programme was subsequently expanded and the objective adjusted to compare the properties of the replaced soil covers with the undisturbed or naturally occurring soils in the region.

Soil capping research has been a major focus for Syncrude Canada Ltd. (Syncrude) and has included a range of soil capping prescriptions. One of the main reasons for placing soil covers or caps on land disturbed by surface mining is to provide adequate moisture for the post-reclamation vegetation community (Barbour et al., 2007). The bulk density and moisture dynamics in these replaced soil covers are a function of texture, organic matter content, soil shrinking and swelling characteristics and the number and nature of the layers, all of which interact with the climate and vegetation community to generate a soil moisture regime (Schmugge et al., 1980; Naeth et al., 1991; Barbour et al., 2007).

Available moisture is generally considered as moisture that is held between field capacity and wilting point. Available water holding capacity (AWHC) is defined as the volume of water, expressed as a depth of water that can be stored in the soil profile between field capacity (33 kPa for finer textured and 10 kPa for coarse textured soils) and wilting point (1,500 kPa) (Gardner, 1968; Barbour et al., 2007). The greater the clay content, in general, the greater the water retention at any particular suction pressure (Hillel, 1982). In a sandy soil most of the pores are relatively large and once these larger pores are emptied at a given suction only a small amount of water remains. In a soil rich in clay, the pore size distribution is more uniform and more water is absorbed so that increasing the matric suction causes a more gradual decrease in water content.

Bulk density is a basic soil quality indicator that relates to ecosystem function and can be used as a predictor of root system performance, especially in newly constructed soils. Bulk density, through its interrelationships with other soil properties such as porosity, water retention, strength, and hydraulic properties, affects plant growth (Naeth et al., 1991). Generally bulk densities exceeding 1.8 Mg m^{-3} are considered limiting to plant growth (Zimmerman and Kardos, 1961; Skopp, 2000). Decreases in porosity, water retention and air diffusivity result from increased bulk density. Furthermore pore size distribution will change towards a smaller proportion of large pores altering the soil moisture regime (Naeth et al., 1991). Changes in bulk density are dependent on disturbance type and are directly associated with soil type, especially texture and moisture content during soil salvage and replacement. In most development and management activities, soils are prone to bulk density increases from repeated high traffic and heavy construction equipment (Naeth et al., 1991). Brussler et al. (1984) found reclaimed soils had higher bulk density, lower porosity, lower permeability, higher coarse fragment and clay content, and lower AWHC than reference soils at comparable depths in Southwestern Indiana. Potter et al. (1988) compared soils constructed using similar methods with similar vegetation histories to each other and to an equivalent undisturbed soil in the western United States and found bulk density to be greater in the topsoil and subsoil materials of the constructed soils than in the undisturbed A and B horizons. In the mid-western United States, Albrecht and Thompson, (1982) found pre-mined bulk densities of 1.2 to 1.4 Mg m^{-1} and post-mined bulk densities of 1.7 to 1.8 Mg m^{-1}. In this long-term research programme, bulk density and soil water content have been monitored to compare the physical status and moisture regime of the reconstructed soil covers with natural soils in the area.

2 Methodology

2.1 Study area

Syncrude Canada Ltd. operations are located approximately 40 km north of Fort McMurray, Alberta. The area is characterised by a cool temperate climate with relatively long, cold winters and short, cool summers. Average annual precipitation is 342 mm rainfall and 156 mm snowfall with average potential evapotranspiration of 450 to 500 mm (Macyk et al., 2009).

Most of the area is underlain by cretaceous shales and sandstones. Glacial till is the most common surficial deposit and is comprised of an unsorted admixture of local bedrock and rock material from the Precambrian Shield (Turchenek and Lindsay, 1982). The typical mineral soils in the area are Luvisolic (Boralf) soils developed under mixed deciduous and coniferous vegetation (Turchenek and Lindsay, 1982). Brunisolic (Cryochrepts and Dystrochrepts), Gleysolic (Aquents, Aquepts, Argiaquolls), Regosolic (Entisols), and Organic (Histosols) soils also occur. The vegetation is characteristic of the Boreal Forest Region (Beckingham and Archibald, 1996).

2.2 Site establishment

Monitoring sites were established in 1992, 1994, 1995, 1996, 2000, and 2005 at locations where different soil reconstruction techniques were utilised (Macyk et al., 2009). Sites were established in natural coarse textured brunisolic soils and fine to medium textured luvisolic soils adjacent to the mine site and in reclaimed areas consisting of various materials such as secondary (Sec), peat, and /or peat-mix (PM) overlaying tailings sand (TS) or overburden (OB) (Table 1). The data were interpreted relative to five groups of similar reclamation strategies (Table 2). The undisturbed study areas include Sites 35, 37, and 18 and destroyed Sites 36, 7, 8, and 9. The second study area includes Sites 1 to 6 in 50 Sec/TS, Sites 10 to 15 in 20 cm PM/50 cm Sec/TS and Sites 31 and 32 in 20 cm PM and Sec incorporated 40 cm Sec/TS. A third major area is the 100 cm PM/OB which includes Sites 16 and 17 and destroyed Sites 18 to 21. The fourth area includes Sites 22 to 24, 33, and 34 located on Mildred Lake Settling Basin (MLSB) that have secondary, peat mix or windblown tailings sand for topsoil, and finally, the 80 cm Sec/TS which includes Sites 25 to 30. The effect of different vegetation types established on reclaimed soils was not measured in this study and therefore not included in the interpretation of the results.

Table 1 Description of materials used in reclamation at Syncrude Canada Ltd.

Material	Texture	Description
Tailings sand (TS)	>90% sand	Sand resulting from the extraction of bitumen from the McMurray oil sand formation; dominantly fine sand fractions (0.25 to 0.10 mm).
Overburden (OB)	Sandy clay loam to clay	Geologic materials overlying the oil sand layer that are removed and stored in-pit and in out of pit 'dumps'.
Secondary (Sec)	Sandy clay loam to clay	Salvaged subsoil or parent material (usually surficial geologic material of glacial origin); dominantly mineral material (i.e. organic matter content typically below 2%).
Peat-mix (PM)	Mineral material in mix - Sandy loam to Sandy clay loam	A mixture of peat and mineral materials resulting in a mineral soil with <17% organic carbon by weight.

2.3 Soil moisture, bulk density and available water holding capacity

A Campbell Pacific 501 moisture/density neutron probe was calibrated in the laboratory using soil reclamation materials from the Syncrude site under a range of moisture conditions. Neutron probe determination of water content is rapid, non-destructive and repeatable at the same sampling point (Naeth et al., 1991), thus a neutron access tube for measurement of soil moisture and bulk density was installed at each site (Table 2). The access tubes consisted of a 3.4 m length of Schedule 40 aluminium tubing with a tip to facilitate entry into the soil. The Campbell Pacific 501 moisture/density neutron probe was used to measure volumetric water content (%) and bulk density (Mg m^{-1}) to the 270 cm depth (15 cm depth increments to 120 cm and 30 cm increments to 270 cm) at each site and depth in the first or second week of each month from May to September inclusive for the duration of the study.

Soil bulk density is an indicator that must be measured in the field to relate laboratory measurements to field conditions (Doran and Parker, 1994). Soil samples were obtained to determine laboratory generated field capacity, wilting point and AWHC of the various reclamation materials. This data was then related to the data collected in the field with the neutron probe.

Table 2 Description of study sites

Site Number	Year of Reclamation	Year of Site Establishment	Number of Access Tubes	Soil Prescription/Cap
Undisturbed				
7	n/a	1994†	1	Brunisol; coarse textured
8 and 9	n/a	1994†	2	Luvisol; medium to fine textured
18	n/a	2009	1	
37	n/a	2006	1	
35	n/a	2005	1	Brunisol; coarse textured
36	n/a	2005‡	1	Luvisol; medium to fine textured
Reclaimed				
1, 2, 3, 4, 5, 6	1990	1992	6	50 cm Sec/TS
10, 11, 12, 13, 14, 15	1993	1994	6	20 cm PM/50 cm Sec/TS
31, 32	1997	2005	2	20 cm PM and Sec incorporated/ 40 cm Sec/TS
16, 17, 18, 19, 20, 21	1994	1995	6	100 cm PM/OB
25, 26	1997	2000	2	80 cm Sec/TS
27, 28	1997	2000	4	
33, 34	1991	2005	2	40 cm PM/TS
22	1985	1996	1	5 to 10 cm windblown TS/Sec/TS
23	1980	1996	1	20 to 30 cm PM/TS
24	1985	1996	1	10 cm windblown TS/30 cm PM/TS

† destroyed in winter 2006/07; ‡ destroyed in winter 2008/09; PM = Peat Mix; Sec = Secondary; TS = Tailings Sand; OB = Overburden

2.4 Meteorological properties

Campbell Scientific CR10X data logging systems were installed in the reclaimed area adjacent to Site 2, Site 33 and Sites 16 to 21 to measure total rainfall intensity, air temperature, solar radiation, wind speed and direction, and relative humidity in the study area on a continuous basis from 1993 to 2010.

3 Data

3.1 Meteorological properties

Annual rainfall data for 1993 to 2010 inclusive are provided in Figure 1. The highest total occurred in 2005 while 1998 and 1999 had the lowest totals. The highest monthly precipitation totals for the growing season generally occurred in July followed by June.

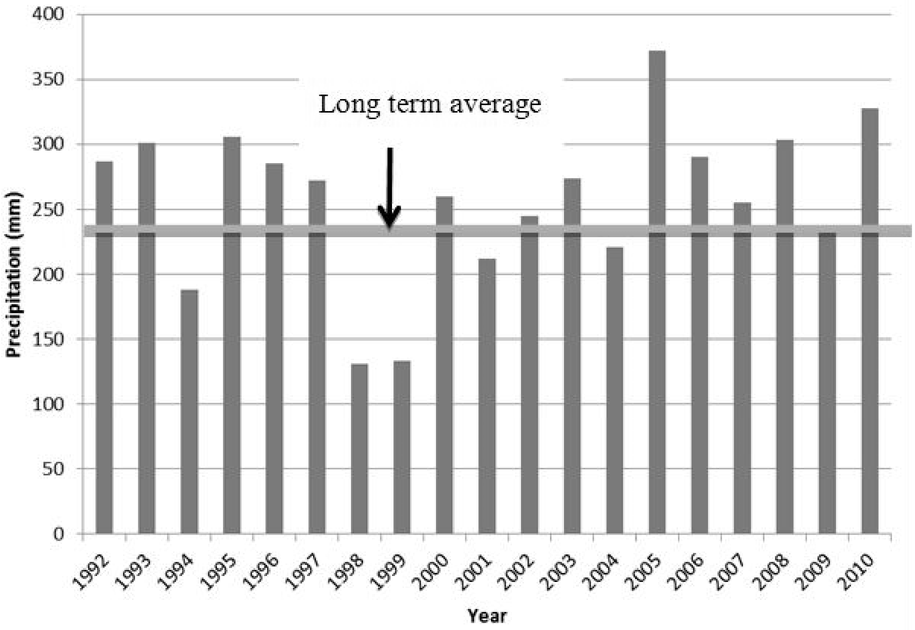


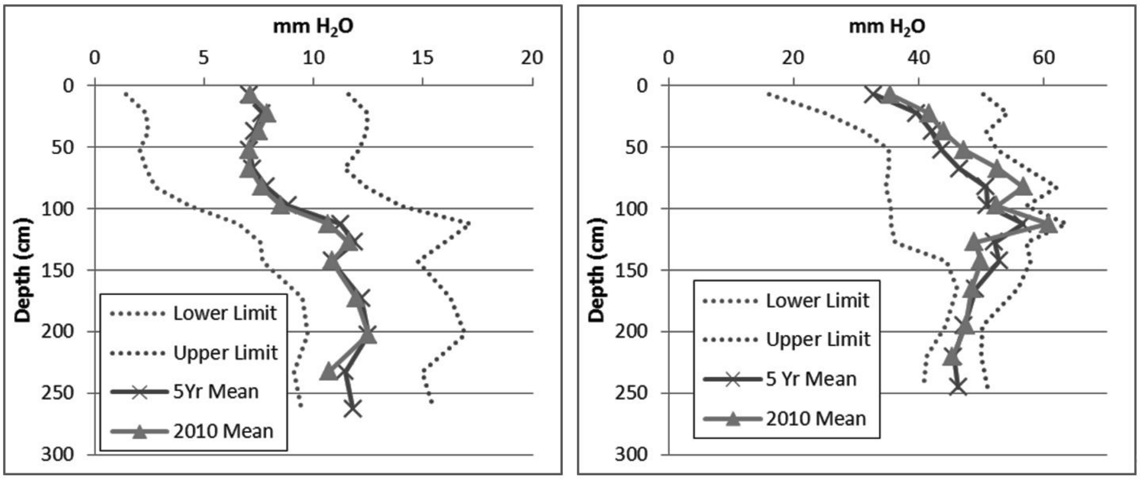
Figure 1 Annual rainfall data (mm) for 1992 to 2010 inclusive

3.2 Soil moisture and bulk density

The data for the soil moisture and density monitoring events completed in 2010 were compared to long-term ranges and are provided for selected sites. The moisture and density data were compared to monthly precipitation to evaluate soil moisture response to wetting and drying periods.

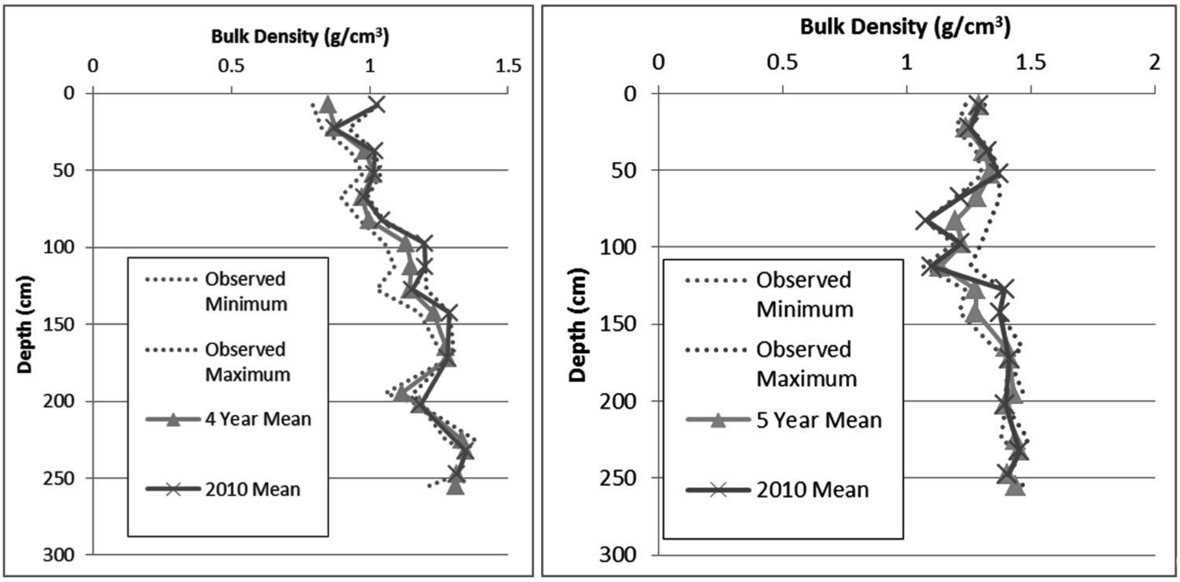
Soil water content varied relative to reclamation soil cover type and time of the year. Figure 2 illustrates moisture profiles at a coarse textured brunisolic natural control site and a medium to fine textured luvisolic natural control site and their associated long-term ranges. The most variability was observed in the upper 1 m at the Luvisolic control Site 37. The highest moisture values were generally recorded in May or June reflecting snowmelt and subsequent rainfall. Water content in the undisturbed fine textured Luvisolic soils ranged from 240 to 320 mm H_2O m^{-1} compared to the undisturbed coarse textured Brunisolic soil range of 45 to 70 mm H_2O m^{-1}. Due to the soil textures and AWHC of the various reclaimed soil profiles, the moisture contents range between the fine and coarse textured undisturbed soils. Bulk density values at the fine textured Luvisolic site and coarse textured Brunisolic site varied with depth and ranged between 1 and 1.5 g/cm^3 (Figure 3). In general, the Brunisolic controls (Site 35) were characterised by lower bulk density, especially near the surface.

Figures 4 and 5 provide moisture and density data, respectively, for the reclamation soil covers with 50 cm of Sec over TS (Sites 1 to 6), 20 cm of PM over 50 cm of Sec over TS (Sites 10 to 15), 20 to 40 cm of PM over TS (Sites 23, 24, 33 and 34), 100 cm peat/OB (Sites 16 to 21) and 80 cm Sec/TS (Sites 25 to 30) in comparison to the natural controls. The trends illustrated for the monitoring period was generally consistent throughout all the years of monitoring. The May moisture values which are largely attributed to snow melt were generally the highest for the growing season. The values for the remaining months were largely dependent on rainfall distribution. The most seasonal variability in the volumetric water content values occurred in the soil caps with the finer textured secondary layer and to a lesser extent the soil cap with the peat-mix over tailings sand. Figure 4 demonstrates the majority of the reclaimed soils have moisture contents ranging between the natural coarse textured Brunisolic control with low moisture contents and the natural fine to medium textured Luvisolic control with higher moisture content with the exception of the deep reclamation covers (80 cm Sec/TS and 100 cm Peat/OB). These deep soil covers are not practical reclamation solutions due to material availability and are not common reclamation scenarios. The low density of several of the reclaimed caps is due to the high organic content of the soil solum.



(a) (b)

Figure 2 Soil moisture at (a) natural brunisolic site 35 and (b) natural luvisolic site 37 with long-term range (dotted lines represent absolute maximum and absolute minimum observed moisture values of the pipe)



(a) (b)

Figure 3 Soil density at (a) natural brunisolic site 35 and (b) natural luvisolic site 37 with four year range (dotted lines represent absolute maximum and absolute minimum observed moisture values of the pipe)

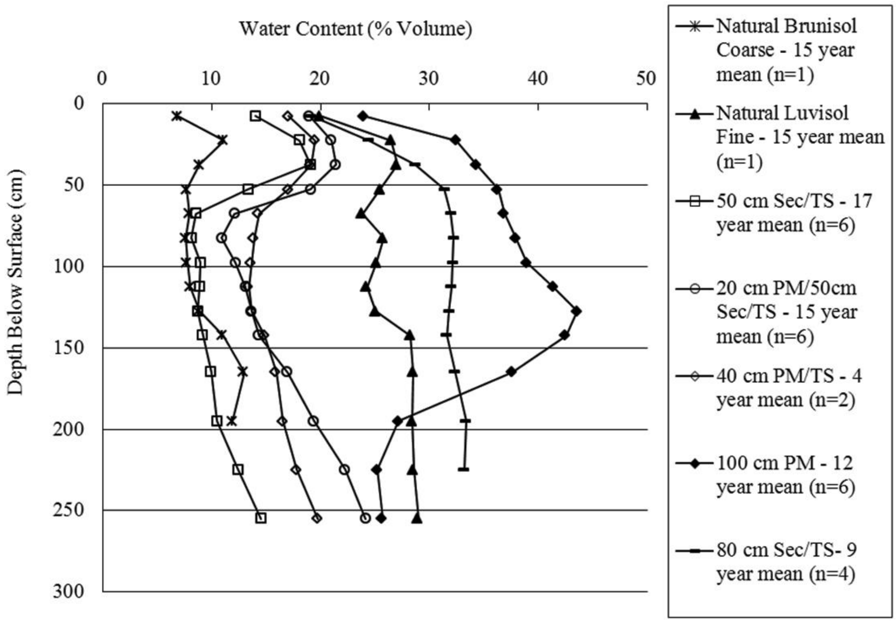


Figure 4 **Moisture data for the reclamation soil covers with 50 cm of Sec/TS (Sites 1 to 6), 20 cm of PM/50 cm of Sec/TS (Sites 10 to 15), 20 to 40 cm of PM/TS (Sites 23, 24, 33 and 34), 100 cm peat/OB (Sites 16 to 21) and 80 cm Sec/TS (Sites 25 to 30) in comparison to the natural controls**

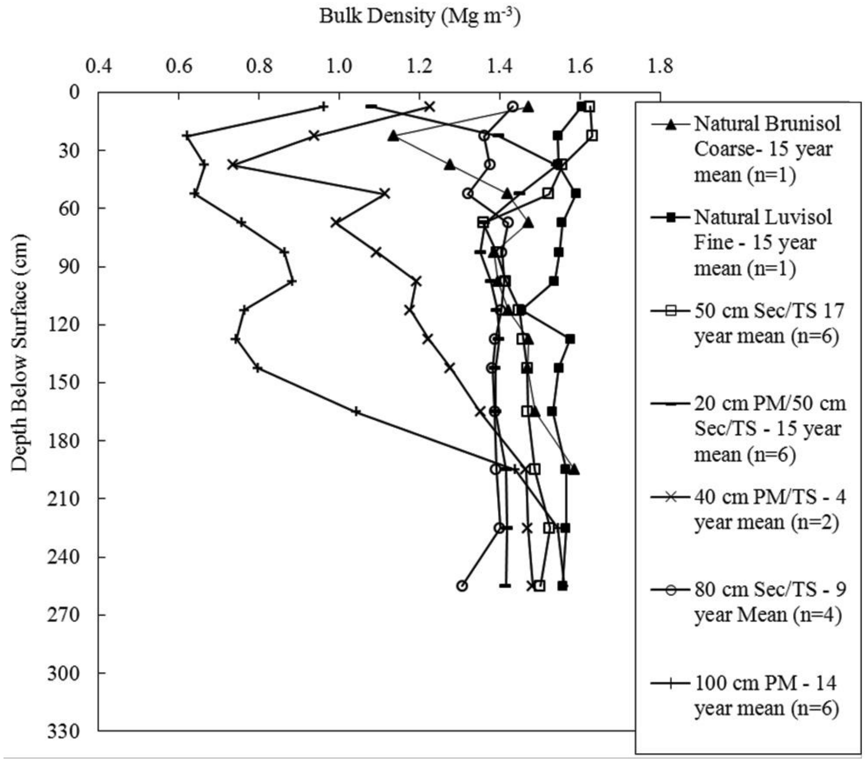


Figure 5 **Density data for the reclamation soil covers with 50 cm of Sec/TS (Sites 1 to 6), 20 cm of PM/50 cm of Sec/TS (Sites 10 to 15), 20 to 40 cm of PM/TS (Sites 23, 24, 33 and 34), 100 cm peat/OB (Sites 16 to 21) and 80 cm Sec/TS (Sites 25 to 30) in comparison to the natural controls**

3.3 Available water holding capacity

The dynamic nature of soil moisture in the soil covers and natural soils captured by the long-term monitoring of the project sites compared to laboratory generated AWHC is illustrated in Table 3. The values are reported in mm H_2O m^{-1}. The number of field measurement events and individual readings used to generate the mean values for each of the natural and reclaimed cover soil locations are included in the table. The yearly average values reflect the annual precipitation regimes presented previously. The consecutive drought years of 1998 and 1999 are reflected in the low annual average moisture values. The lowest annual values for all sites occurred in 1999.

The average field measured moisture values illustrate the differences between the natural soils and the different soil covers. For example, the coarse textured natural Brunisolic soil had the lowest average value while the medium to fine textured natural Luvisolic soil and the 80 cm Sec/TS treatment (SWSS) had the second highest average. The 50 cm Sec/TS cover (Sites 1 to 6) had a mean value similar to the cover with 40 cm PM/TS (Sites 33 and 34). Based on totals, all reclaimed soils investigated had a greater amount of available water compared to the coarse textured natural Brunisolic soil. When compared to fine textured natural Luvisolic soils, the reclaimed soils had lower values with the exception of the deeper capping soils (80 cm Sec/TS and 100 cm Peat/OB). The field measured average moisture values for the upper meter of soil are very similar or greater than the laboratory generated AWHC values for most of the sites evaluated.

Table 3 Laboratory generated available water holding capacity and annual field moisture values for the soil covers and natural soils

Soil Prescription/Cap	Site Number	Laboratory mm H20 m^{-1}			Field measured annual average mm H_2O m^{-1}									Average mm H_2O m^{-1}	N†
		WP	FC	AWHC	1992	1995	1998	1999	2001	2004	2005	2006	2008		
Natural															
Coarse - Brunisolic control	7	10.0	90.0	50.2	99	90	56	64	92	79	84	80	-	81	440
Fine to Medium Luvisolic control	8 and 9	100.0	280.0	140.0	303	281	212	214	235	228	238	242	280	248	821
Reclaimed															
50 cm Sec/TS	1 to 6	55.0	185.0	130.0	165	140	102	96	127	143	152	133	127	132	2158
20 cm PM/50 cm Sec/TS	10 to 15	68.0	232.0	164.0	-	232	144	126	145	157	170	151	159	160	2423
100 cm PM	16 to 21	120.0	420.0	300.0	-	434	362	300	329	327	341	319	275	336	2065
40 cm PM/TS	33, 34	81.4	153.4	72.0	-	-	-	-	-	-	150	122	143	138	587
80 cm Sec/TS	25 to 30	96.0	296.0	200.0	-	-	-	-	254	256	259	230	248	249	1375
20 to 30 cm PM/TS	23	42.5	123.2	80.7	-	-	106	82	114	130	119	89	109	107	806
10 cm WB TS/20 cm PM/TS	24	54.0	222.0	168.0	-	-	106.65	87.9	152	138	136	110	130	123	769
20 cm PM and Sec/40 cm Sec/TS	31, 32	68.0	232.0	164.0	-	-	-	-	-	-	-	149	155	152	-

N† - Number of readings; PM = Peat Mix; Sec = Secondary; TS = Tailings Sand; WB = Windblown; LFH = Lithic, Fibric, Humic; WP = Wilting Point; FC = Field Capacity; AWHC = Available Water Holding Capacity

4 Results

Long-term monitoring of volumetric soil water content and bulk density has been utilised to compare the physical status and moisture regime of the reconstructed soil covers with natural soils in the area. Evaluation of the long-term patterns in moisture and density of the reclaimed soil covers provides a measure of performance of the various capping prescriptions as the landscape matures and moisture demands increase. Soil moisture content varied relative to soil cover type and time of year. For the natural soils, the coarse textured Brunisols had volumetric moisture values ranging from approximately 3 to 10% during the growing season, whereas the finer textured Luvisols had values ranging from 17 to 30%. The reclaimed soils generally had moisture values in the range between the natural Brunisols and Luvisols. Greater amounts of secondary material in the reclamation cap resulted in less fluctuation during the growing season, however, greater amounts of peat in the reclamation cap resulted in higher amounts of water being stored in the root zone. Soil moisture at most sites evaluated fluctuated with the monthly precipitation.

Availability of soil water in reconstructed soil profiles is critical to reclamation success. As the vegetation at these sites reaches maturity in the next 50 years the water requirements will increase. Under the existing vegetative cover, water availability in all reconstructed soil profiles has been in the range between the undisturbed Brunisolic and Luvisolic forest soils. Several of the reclaimed sites are approximately 30 years old with nearly mature trees established and depending on climate the soil moisture has been adequate to support the water demand. This study was not designed specifically with the goal of comparative evaluation of capping techniques, which makes a conventional data analysis difficult. However, the data in Table 3 illustrate the relative benefit of the different components of the soil covers in terms of moisture retention. Adding a 20 cm peat-mix cap to the 50 cm secondary/tailings sand cover increases AWHC. Six cover scenarios in Table 3 demonstrate AWHC values that are higher than the coarse textured natural soil and one had values that are equivalent to or higher than the medium to fine textured natural soil.

The highest bulk density values were reported for the medium to fine textured Luvisol and the secondary material present in the various soil caps. The bulk density of the secondary material ranges from approximately 1.4 to 1.8 Mg m^{-3}, which is similar to the values for the soil solum and underlying parent material of the natural Luvisol. This is expected since the secondary materials in the reclaimed soil caps are derived from these medium to fine textured natural soils. The tailings sand component of the soil covers consistently had bulk density values in the range of 1.4 Mg m^{-3} which is similar to the values reported for one of the natural sandy Brunisolic sites. The data indicate that the soil covers all had bulk density values lower than 1.8 Mg m^{-3} which is considered limiting to root development (Zimmerman and Kardos, 1961) and were equivalent to or lower than the values for the fine textured natural Luvisolic soils.

The bulk density measurements indicated that there was no evidence of compaction in the reclaimed soil covers and therefore pose no limitation to root development which was consistent with previous research (Yarmuch, 2003). This supports other studies of reclaimed soils in the oil sands which compared depth of rooting and distribution of roots in the different reclamation soil covers to natural soils (Macyk and Richens, 2002).

5 Conclusions

The field measurements reflected the dynamic nature of soil moisture in the soil covers compared to the natural soils ranging from wet years such as 2005 compared to the drier years of 1998 and 1999. Bulk density regimes of the soil covers compared favourably with those of the natural soils. These results indicate that the reclaimed soil covers are capable of providing soil moisture to support the respective vegetation covers. The bulk density measurements indicated that there was no evidence of compaction in the reclamation soil covers and therefore pose no limitation to root development. Overall conclusions from this research are:

- Placement of peat mix and secondary material in soil caps results in AWHC values similar to natural soils.
- Placement of secondary material as part of the soil cap is critical to increasing AWHC values compared to tailing sand substrates.
- Current soil handling procedures such as winter striping, stockpiling, hauling and placement, limiting construction traffic and/or direct soil placement do not result in increased bulk density values.
- Current soil capping practices (reclaimed soil covers described in Table 2) are appropriate for providing soil moisture to support vegetation covers.

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