Geotechnical characterization of peat-based landfill cover materials

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ABSTRACT

Natural methane (CH4) oxidation that is carried out through the use of landfill covers (biocovers) is a promising method for reducing CH4 emissions from landfills. Previous studies on peat-based landfill covers have mainly focused on their biochemical properties (e.g. CH4 oxidation capacity). However, the utilization of peat as a cover material also requires a solid understanding of its geotechnical properties (thermal, hydraulic, and mechanical), which are critical to the performance of any biocover. Therefore, the objective of this context is to investigate and assess the geotechnical properties of peat-based cover materials (peat, peat–sand mixture), including compaction, consolidation, and hydraulic and thermal conductivities. The studied materials show high compressibility to the increase of vertical stress, with compression index (Cc) values ranging from 0.16 to 0.358. The compressibility is a function of sand content such that the peat–sand mixture (1:3) has the lowest Cc value. Both the thermal and hydraulic conductivities are functions of moisture content, dry density, and sand content. The hydraulic conductivity varies from 1.74 × 10−9 m/s to 7.35 × 10−8 m/s, and increases with the increase in sand content. The thermal conductivity of the studied samples varies between 0.54 W/(m K) and 1.41 W/(m K) and it increases with the increases in moisture and sand contents. Increases in sand content generally increase the mechanical behavior of peat-based covers; however, they also cause relatively high hydraulic and thermal conductivities which are not favored properties for biocovers.
demonstrated that peat materials show a high CH$_4$ oxidation rate (Stein and Hettiaratchi, 2001; Einola et al., 2009) have experimentally observed that the CH$_4$ oxidation rate of peat (up to 90%) is close to that of compost (up to 100%) and much higher than that observed in other types of biocover materials (loam soil, topsoil, agricultural soil, and sand). However, for the peat biocover material to be of interest, aside from a high CH$_4$ oxidation rate (Table 1), the material should demonstrate its geotechnical properties that are comparable to or better than those of existing biocover materials (particularly compost) used in construction practices. The geotechnical properties (mechanical, hydraulic, and thermal) of biocover materials are of prime importance for design, construction and maintenance of any biocover as will be discussed later. Absence of a proper understanding of the geotechnical properties of cover materials may lead to inaccurate biocover design and consequently, construction of inefficient biocovers. However, to date, the geotechnical characteristics of peat-based biocover material are not well understood. Therefore, the goal of this paper is to provide insight into the geotechnical properties of peat-based biocover materials and assess their suitability for use as biocover media from a geotechnical point of view.

2. Materials and methods

2.1. Material selection and characterization

Mixing potential biocover materials with sand minimizes the settlement and compaction of biocovers (Powelson et al., 2006; Philopoulos et al., 2009; Schetz et al., 2009a; Khoshand and Fall, 2014). Compaction is especially important when consideration is given to any field installations, as there will be some traffic on the surface of the medium (e.g. maintenance) (Philopoulos et al., 2009). Therefore, laboratory investigations have been conducted in this study on peat and peat–sand mixture samples with ratios of 1:3, 1:1 and 3:1 (w/w). The aforementioned ratios are recommended inPokhrel et al. (2011), a study on the CH$_4$ oxidation capacity of different mixtures of potential biocover materials.

Ottawa sand, obtained from Unimin Canada Ltd. is used in this study. The sand was oven-dried prior to use in the experiments in order to eliminate any methanotrophic bacteria that may be present in the sand. Also, the sand was free of organic content based on the results of laboratory tests performed in accordance with ASTM D2974-14 (2014). The peat soil samples were collected from the Moose Creek Bog in Moose Creek, Canada, which is owned and operated by Lafleche Environmental Inc. The peat samples were transported to a laboratory and stored at a temperature of 3 °C before further characterization.

The mineralogical compositions of the peat material and peat–sand mixtures were determined by X-ray diffraction analyses and the results are presented in Table 2. The selected geotechnical properties of all the samples were determined in accordance with the procedures described by ASTM standards. A grain size analysis was performed in accordance with ASTM D422-65 (1998). It can be seen in Fig. 1 that all of the samples have a grain size that ranges from 0.07 mm to 5 mm and the grain size distribution becomes coarser as the sand ratio is increased.

The grain size distribution of the peat samples indicates that the percentage of grains that pass through the sieves Nos. 10, 40 and 100 is 79%, 22% and 7%, respectively. The pure peat sample in this study is classified as organic SW (well graded sand) and the rest of samples are organic SP (poorly graded sand) based on the Unified Soil Classification System (USCS). However, this classification system is not suited for organic soils because samples are only considered as peat when the organic content is more than 75%. Therefore, a classification system proposed by Wüst et al. (2003), based on the ash and organic contents of peats, is also used in this study. Based on this classification, peat and peat–sand mixture with a mix ratio of 3:1 are considered as peat, while peat–sand mixtures with mix ratios of 1:1 and 1:3 are considered as muck. A summary of the properties and pH value of the samples are shown in Table 3. The pH value of the peat sample is 6.72, which falls within the range quoted by Cola and Cortellazzo (2005).

2.2. Methods

2.2.1. Compaction test

In order to experimentally determine the values of the optimum moisture content and corresponding maximum dry density of the studied materials, standard Proctor compaction tests were performed in accordance with ASTM D698-12 (2012).

2.2.2. Consolidation test

Conventional consolidation tests were performed on the samples at the dry side of the optimum moisture content and the optimum moisture content in accordance with ASTM D2435/D2435M-11 (2011) to determine the consolidation characteristics of the peat and its mixture samples. The dried samples were moistened and compacted to reach the desired densities for specific moisture contents that correspond to standard Proctor compaction test results. Each test consisted of five increments of loading (5 kPa, 10 kPa, 20 kPa, 40 kPa and 80 kPa) and the duration of each loading was 24 h to ensure that the long-term compressibility of the samples was properly simulated (Moo-Young and Zimmie, 1996). Each test was repeated twice.
2.2.3. Hydraulic conductivity test

Hydraulic conductivity tests were performed on all of the samples in accordance with the procedures that are outlined in ASTM D5084-10 (2010). Hydraulic conductivity was measured by using a flexible wall permeameter on the samples (with dimensions of 115 mm in height and 50 mm in diameter) at the optimum, dry side of the optimum, and wet side of the optimum moisture contents and related densities based on the compaction curves. In order to prevent anomalies during the flow rate measurements, a low hydraulic gradient (approximately 10) was maintained in all of the tests (Benson and Othman, 1993). Also, for each sample, hydraulic conductivity tests were repeated until three values were derived which fell within ±10% of each other (minimum three and maximum five replicates for each sample). The average value was considered as the saturated hydraulic conductivity of the sample tested.

2.2.4. Thermal conductivity test

The materials were first air-dried and then kept dry for 10 d to reach thermal equilibrium. Afterwards, the samples were moistened and compacted to reach the desired densities in accordance with the compaction curves. The thermal conductivity of the samples was determined based on the non-steady state method under isothermal conditions by using the KD2 device (Decagon Devices, Inc., 2006). Each thermal conductivity test was performed two to four times to ensure the repeatability of the results.

### Table 2

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical compositions (w/w %)</th>
<th>LOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO$_2$</td>
<td>Al$_2$O$_3$</td>
</tr>
<tr>
<td>Peat</td>
<td>11.7</td>
<td>2.49</td>
</tr>
<tr>
<td>Peat—sand (3:1 w/w)</td>
<td>31.51</td>
<td>3.25</td>
</tr>
<tr>
<td>Peat—sand (1:1 w/w)</td>
<td>51.2</td>
<td>3.97</td>
</tr>
<tr>
<td>Peat—sand (1:3 w/w)</td>
<td>70.79</td>
<td>4.71</td>
</tr>
</tbody>
</table>

Note: LOI is the loss in ignition (%).

### Table 3

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial moisture content, w (%)</th>
<th>Organic content (%)</th>
<th>pH (in H$_2$O)</th>
<th>Specific gravity, $G_s$</th>
<th>Dry bulk density (kg/m$^3$)</th>
<th>WHC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat</td>
<td>195.48</td>
<td>69.73</td>
<td>6.72</td>
<td>1.65</td>
<td>375.4</td>
<td>218.86</td>
</tr>
<tr>
<td>Peat—sand (3:1 w/w)</td>
<td>145.43</td>
<td>51.92</td>
<td>6.75</td>
<td>1.9</td>
<td>659.5</td>
<td>166.67</td>
</tr>
<tr>
<td>Peat—sand (1:1 w/w)</td>
<td>98.63</td>
<td>35.35</td>
<td>6.81</td>
<td>2.15</td>
<td>943.7</td>
<td>137.08</td>
</tr>
<tr>
<td>Peat—sand (1:3 w/w)</td>
<td>48.93</td>
<td>19.12</td>
<td>6.91</td>
<td>2.4</td>
<td>1227.8</td>
<td>94.41</td>
</tr>
</tbody>
</table>

Note: WHC is the water holding capacity.
density value in comparison to the other mixtures which can be attributed to its lower specific gravity (1.65). During the compaction process, samples with lower sand content required the addition of more water but were still compactable while those with higher sand content required less water and were less compactable. Compared to pure peat, the peat–sand mixtures have lower optimum moisture contents and are less compactable (Stone and Ekwue, 1993).

In biocovers, the CH4 oxidation rate is significantly influenced by oxygen penetration. The parameters that can control oxygen penetration and therefore the CH4 oxidation rate are related to the free air space (FAS) and the degree of saturation ($S_r$) of biocover media. The diffusivity of biocover media is regulated by the degree of saturation ($S_r$) (Gebert et al., 2011) because saturation creates water menisci which cause discontinuous diffusion pathways (Moldrup et al., 2001). Therefore, by varying the FAS and $S_r$ with moisture content for the studied materials, the significance of these parameters is taken into account, as shown in Fig. 3. This figure shows that increases in moisture content reduce the FAS to a value close to zero at the wet side of the optimum moisture content. Consequently, the air phase in the pores becomes occluded (Nagaraj et al., 2006) and the gases have to diffuse in the liquid phase. The gaseous diffusion in the liquid phase is much less than that in air (Gebert et al., 2011), which slows the diffusive migration of oxygen through the biocover media and greatly reduces the CH4 oxidation rate. The O2 consumption rate reaches the maximum value when the FAS is between 20% and 35% (Haug, 1993). So, it can be concluded from Fig. 3 that the maximum O2 consumption rate (and thereby the highest CH4 oxidation rate) in the peat and peat–sand samples with mix ratios of 3:1, 1:1 and 1:3 should be expected when the moisture content is 85%–110%, 70%–85%, 80%–95% and 65%–75%, respectively. It can be clearly observed that the range of moisture content associated with the maximum rate of O2 consumption in the studied samples generally decreases with the increase in sand content.

3.2. Consolidation characteristics

Consolidation can significantly change the porosity of biocovers. The gas transport process in biocovers (e.g. advection flux of CH4 (upward) and diffusion flux of oxygen (downward) into the CH4 oxidation zone) and consequently the performance (CH4 oxidation capacity) of biocovers is strongly affected by their porosity (Pedersen et al., 2011). Moreover, the strain due to consolidation could also translate into crack development in the biocovers which can affect their physical stability (Bajwa, 2012) as well as the amount of CH4 emitted into the atmosphere. These cracks may provide the preferential pathways for the escape of CH4 into the atmosphere. Thus, there is a need to understand the consolidation characteristics of peat-based biocover materials. Here, the compressibility of the studied materials is categorized as primary consolidation and secondary consolidation (Mesri and Ajlouni, 2007).

3.2.1. Primary consolidation

Primary consolidation is defined by the variation of the void ratio and a logarithm of the consolidation pressure as shown in Fig. 4. It is clear from Fig. 4 that the void ratio of samples is reduced when there is an increase in the moisture content and consolidation pressure. The lowest void ratio values (2.57, 1.87, 1.61 and 1.11 for peat and peat–sand mixtures with mix ratios of 3:1, 1:1 and 1:3, respectively) can be observed at higher moisture contents and a consolidation pressure of 80 kPa.

The calculation of the coefficient of consolidation ($C_v$) was carried out based on the square root of time (Taylor’s) method. It is evident from Table 4 that there is a significant reduction in the $C_v$ value of the samples with an increase in consolidation pressure, and this reduction is more pronounced in the samples with less sand content. The compression index ($C_s$) and recompression index ($C_e$) values are presented in Table 5. The $C_v$ value, which reflects the compressibility of the materials, ranges from 0.358 to 0.134 in this study. This is a lower range compared with those obtained by Kazemian et al. (2011) and Ulusay et al. (2010) because the pre-compaction of the studied materials had a lower density value in comparison to the other mixtures which can be attributed to its lower specific gravity (1.65). During the compaction process, samples with lower sand content required the addition of more water but were still compactable while those with higher sand content required less water and were less compactable.

Compared to pure peat, the peat–sand mixtures have lower optimum moisture contents and are less compactable (Stone and Ekwue, 1993).
peat material to the dry side of the optimum moisture content has significantly reduced its initial void ratio, which is significantly lower than that of the peat material investigated in previous studies (e.g. Ulusay et al., 2010; Kazemian et al., 2011).

The primary consolidation and associated settlement can be explained in terms of the $C_c$ value, in that a higher $C_c$ value results in larger primary settlement. It can be clearly observed from Table 5 that there is a general trend of $C_c$ decreasing with increasing sand content. The $C_c$ value of the peat samples is the highest among all of the studied materials ($C_c$ of the peat samples is up to 124% higher than that of peat–sand samples) (Table 5) and subsequently, the peat samples experience larger primary settlement that could increase the risk of crack formation and/or significantly reduce the FAS, and thereby reduce the efficiency of CH$_4$ oxidation. It is clear from Table 5 that the $C_c$ values generally increase with an increase in initial moisture content because the high moisture content of peat is related to more water in the pores (Huat et al., 2011). However, the pore water can be easily dissipated during consolidation due to the increase in vertical stress. As shown in Table 5, the $C_r$ values of the samples show that the swelling potential of the materials is low for the studied materials. These $C_r$ values are also consistent with those reported by Mesri and Ajlouni (2007). It is also clear that the $C_r$ value decreases as the sand content is increased, which means that the samples with a higher sand content have less swelling potential.

### 3.2.2. Secondary consolidation

Secondary consolidation is the ratio of the coefficient of the secondary consolidation ($C_a$) to $C_c$ (Mesri and Ajlouni, 2007). The variations in $C_a/C_c$ for peat and peat–sand mixtures at different stress levels (5–80 kPa) are shown in Fig. 5, which indicates that the values of $C_a/C_c$ for the studied samples decrease when the consolidation pressure is increased. Ulusay et al. (2010) also reported similar observations for peat materials. However, most of the previous studies obtained $C_a/C_c$ values of 0.06 ± 0.01 or even
Biocovers should also have an appropriate hydraulic conductivity to minimize rainfall infiltration and subsequent biocover saturation, which can result in a drastic reduction in the CH4 oxidation rate (Pokhrel, 2006; Scheutz et al., 2009a, b; Khoshand and Fall, 2014). Therefore, changes in the hydraulic conductivity of biocovers have important effects on the CH4 oxidation rate and water intrusion. Fig. 6 shows the test results of saturated hydraulic conductivity for peat and its mixtures in the current study. It can be observed that the hydraulic conductivity values range from 1.74 × 10⁻⁹ m/s to 7.35 × 10⁻⁹ m/s while the moisture contents vary in an approximate range of 45%–132%. As illustrated in Fig. 6, the hydraulic conductivity of the specimens is reduced when the moisture content and dry density are increased until reaching the optimum moisture content and the maximum dry density. Afterward, the hydraulic conductivity is increased for moisture contents that exceed the optimum one. The minimum hydraulic conductivities (1.74 × 10⁻⁹ m/s, 2.62 × 10⁻⁹ m/s, 4.45 × 10⁻⁹ m/s and 6.26 × 10⁻⁹ m/s for peat and peat–sand mixtures with mix ratios of 3:1:1:1 and 1:3, respectively) were achieved at the optimum moisture content. Moo-Young and Zimmie (1996) studied the geotechnical behavior of potential landfill covers and reported a similar trend in the variation of the hydraulic conductivity with moisture content. The hydraulic conductivity of peat is a function of the void ratio and the size and shape of the flow channels (Mesri and Ajlouni, 2007). The grains of peat are naturally porous and subsequently have a large pore size which results in a high initial hydraulic conductivity at low dry density (Huat et al., 2011). The dry density is increased due to compaction until the maximum dry density is obtained. This causes smaller pores and tortuous flow channels through the samples which eventually result in a significant reduction in the hydraulic conductivity to a comparable value of clay soils (Huat et al., 2011).

The hydraulic conductivity of peat varies in the range of 1.74 × 10⁻⁹–2.33 × 10⁻⁹ m/s while the hydraulic conductivity of higher (up to 0.1) for peat materials (Mesri and Ajlouni, 2007; Ulusay et al., 2010). Duraisamy et al. (2007) reported even lower values of Cₐ/Cₑ (0.027 and 0.038) for some of their peat samples. In the current study, the values of Cₐ/Cₑ for the peat samples range from 0.048 to 0.061, so the obtained values are close to those of Mesri and Ajlouni (2007). The values of Cₐ/Cₑ for different geotechnical materials vary in a narrow range of 0.01–0.1 (Ulusay et al., 2010). The magnitude of Cₐ/Cₑ can be used to explain the deformability and compressibility of soils (Mesri and Ajlouni, 2007). In the current study, the peat samples consist of deformable grains and thereby are highly compressible and have the highest values of Cₐ/Cₑ. Increases in the sand content result in a lower range of Cₐ/Cₑ values because granular sand materials such as sands are less deformable, with Cₐ/Cₑ = 0.02 ± 0.01 (Mesri and Vardhanabhuti, 2009).

Secondary compression not only has a negative effect on the gas exchange process and thereby the CH4 oxidation potential of biocovers, but also affects the pore structure (Bajwa, 2012) and consequently the physical stability of biocovers. Based on the obtained values of Cₐ/Cₑ in the current study, the peat experiences more secondary settlement among the studied materials which could increase the risk of the physical failure of peat biocovers mainly due to crack development and changes in the pore structure.

### 3.3 Hydraulic conductivity

Fig. 5. Variations in Cₐ/Cₑ with consolidation pressure for the studied peat and peat–sand mixtures.

Fig. 6. Hydraulic conductivity versus moisture content.
peat—sand mixture with a mix ratio of 1:3 ranges from $6.29 \times 10^{-9}$ m/s to $7.35 \times 10^{-9}$ m/s. The hydraulic conductivity of peat is controlled by the physical and structural arrangement of the constituent grains (Edil, 2003), which can affect the pore size distribution and the size and shape of the flow channels. Increasing the sand content of the samples causes larger void ratios, pores and straight flow channels through the samples, which result in higher hydraulic conductivity. The interlinked fibrous structure of pure peat, which has a clogging effect (Edil, 2003), is another possible reason accounting for the lower hydraulic conductivity of peat in comparison to that of peat—sand mixtures. However, an increase in sand content increases the hydraulic conductivity and consequently promotes the gas exchange process within peat-based biocovers. Nevertheless, the hydraulic conductivity of biocovers needs to be low enough to prevent water infiltration.

3.4. Thermal conductivity

Knowledge of the thermal conductivity of the biocover material is essential for assessing and predicting the evolution and distribution of temperature in biocovers. The simultaneous variation of thermal conductivity and dry density with moisture content is shown in Fig. 7. The thermal conductivity of the peat samples varies from 0.54 W/(m K) to 0.71 W/(m K) when the moisture content ranges from 60% to 132% (Fig. 7). The obtained results are close to those reported by Dissanayaka et al. (2012) for pure peat in wet conditions (0.1–0.6 W/(m K)). It can be seen in Fig. 7 that the thermal conductivity of the studied peat-based materials is influenced by the moisture content such that the thermal conductivity consistently increases as the moisture content increases. It can also be seen from Fig. 7 that the minimum thermal conductivities (0.54 W/(m K), 0.7 W/(m K), 0.87 W/(m K) and 1.17 W/(m K) for peat and peat—sand mixtures with mix ratios of 3:1, 1:1 and 1:3, respectively) are obtained at the minimum moisture contents because the thermal conductivity of water (0.59 W/(m K)) is more than 20 times greater than that of air (0.025 W/(m K)) (Holman, 2002). By increasing the moisture content, the volume fraction of air is decreased and the proportion of the pore spaces filled with water is increased (Ahn et al., 2009). So the water films completely surround the soil grains and improve the contact between them which results in increases in thermal conductivity (Abu-Hamdeh and Reeder, 2000). A similar trend in the variation of the thermal conductivity with moisture content has been reported in previous studies (Ahn et al., 2009; Chandrakanthi et al., 2005).

Furthermore, Fig. 7 shows that the thermal conductivity increases with the increases in dry density of the samples because generally, when the density of the soil samples increases to the maximum dry density due to compaction, the degree of inter-particle contact increases and contact between the individual grains becomes more intimate (Al Nakshabandi and Kohnke, 1965), which facilitates heat movement through the soil and results in an increase in thermal conductivity. After the maximum density is reached, the excess water causes higher pore water pressure that results in less compactability and subsequently a reduction in density (Ekwue et al., 2011). However, as the density is reduced, the moisture contents still increase and there is less contact between the individual grains due to the presence of water between the soil grains. Whereas water has a thermal conductivity greater than that of air and considerably lower than that of mineral soil particles (e.g. 2.9 W/(m K) for silt and clay, 3 W/(m K) for sandstone, and 3.8 W/(m K) for dolostone (Ramires et al., 1995; Côté and Konrad, 2005)), so the thermal conductivity continues to increase slightly after the optimum moisture content is reached (Fig. 7). Ekwue et al. (2011) also reported that the effect of density variation on the thermal conductivity is considerably less than that of moisture variation.

Fig. 7. Changes in thermal conductivity and dry density with water content: (a) peat; (b) peat—sand (3:1 w/w); (c) peat—sand (1:1 w/w); and (d) peat—sand (1:3 w/w).
The optimal moisture content of the peat-based materials varies from 64% to 96% while the maximum dry density ranges from 64% to 96% with moisture contents varying in the range of 45%–132%. The hydraulic conductivity values range from 1.74 × 10⁻⁹ m/s to 7.35 × 10⁻⁷ m/s while the moisture contents vary in an approximate range of 45%–132%. The minimum hydraulic conductivity is achieved at the optimum moisture content and decreases when the moisture content is increased to the wet side of the optimum moisture content.

The thermal conductivity increases with increasing bulk density, and moisture and sand contents. However, the effect of the variation in bulk density on thermal conductivity is considerably less than that of the moisture content variation. It is found that pure peat materials can provide better temperature insulation and consequently a more stable temperature within biocovers than the peat–sand biocover materials due to their low thermal conductivity which is particularly important in cold climates.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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