Mechanical characteristics and behavior of compost-based landfill cover

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ABSTRACT:
Landfilling is one of the most common disposal methods for municipal solid waste in many countries. However, landfills are considered to be one of the largest sources of anthropogenic methane (CH_4) emissions to the environment. One of the most promising biocover materials to oxidize CH_4 is compost. Most of the previous research on landfill compost-based cover is centered on the methane oxidation capability and/or hydraulic conductivity of the compost materials. Technical data on the mechanical properties and behavior, such as shear strength parameters, deformation and consolidation behavior of the compost is quite limited. Hence, a research program is conducted by the above authors to study the mechanical characteristics and behavior of compost biocover. A detailed direct shear and Oedometer testing program has been conducted to study the mechanical properties and behavior of compost cover materials with various initial water contents and dry densities. Laboratory tests have also been performed to determine the particle size distribution and geotechnical index properties of the compost materials. Valuable results are obtained with regard to the shear resistance and settlement of compost cover material. Furthermore, conclusions of practical interests are derived from the obtained results.

RÉSUMÉ:
L'enfouissement des déchets est une des méthodes de gestion les plus communes pour les ordures solides municipales dans beaucoup de pays. Pourtant, on considère que ces enfouissements sont une des plus grandes sources anthropogéniques d'émission de CH_4 dans l'environnement. Un des matériaux de couverture le plus prometteur pour oxyder le CH_4 est le compost. La plupart des recherches précédentes sur les couvertures à base de compost étaient axées sur la capacité d'oxydation de méthane et/ou la conductivité hydraulique du compost. Les données techniques sur les propriétés et le comportement mécanique, tels que les paramètres de résistance au cisaillement, la déformation et la consolidation du compost sont particulièrement limitées. C'est pourquoi, un programme de recherche est accompli par les susdits auteurs pour étudier les propriétés et le comportement mécaniques du compost comme matériau de bio-couverture. Un programme extensif d'essais de cisaillement et de consolidation sur des échantillons de compost de différentes teneurs en eau et densité sèches initiales a été conduit. Des essais de laboratoire ont été aussi effectués pour déterminer la distribution granulométrique et les propriétés géotechniques physiques du compost. Des résultats de valeur sont obtenus en ce qui concerne la résistance au cisaillement et la consolidation du compost comme matériau de couverture. En outre, les conclusions d'intérêt pratique sont tirées des résultats obtenus.

1 INTRODUCTION

The concentration of methane (CH_4) in the atmosphere has increased in the past several decades principally due to the great increase in anthropogenic emissions (IPCC 2001). It is now estimated that as much as 19% of the CH_4 anthropogenic emissions into the atmosphere can be attributed to landfills (IPCC 2001). CH_4 is 62 times more potent as a greenhouse gas than CO_2 on a per mass basis. Figure 1 shows the US contribution to the anthropogenic supply from CH_4 emissions in 2001 from different sources. According to Figure 1, landfills are generating 33% of the total CH_4 into the atmosphere in the US.

A biocover is a cover system that optimizes environmental conditions for biotic CH_4 consumption. Research is currently being carried out to introduce the most effective cover design to mitigate CH_4 generation.

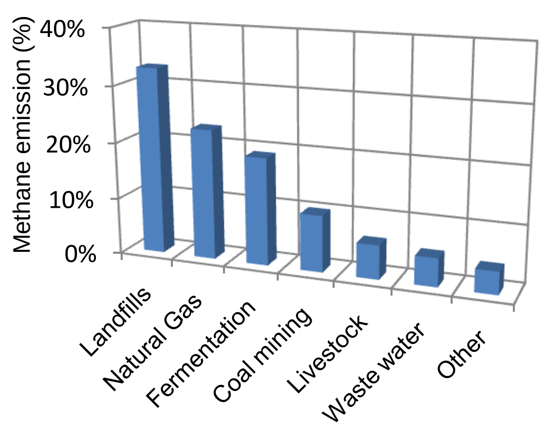

Figure 1: Distribution of anthropogenic sources in 2001 in the USA (Yuan L, 2006)

The biocover essentially comprises of a gas distribution layer with high gas permeability to normalize landfill gas fluxes. This gas distribution layer is supplemented with an overlying oxidation layer to support the methanotrophic populations. The oxidation layer can be constructed from a variety of materials, depending upon their oxidation capability. The most commonly used materials are selected as composted waste materials such as municipal source separated organics (food waste, kitchen waste, leaf and yard waste, and carbon-based bulking agents). Compost is a stabilized and sanitized product from composting. Research shows that the compost not only works well as a soil conditioner, which is beneficial to plant growth, but also as a good CH_4 oxidation agent. It has high water retention capacity as compared to other materials, which plays an important role in increasing the microbial population for CH_4 oxidation purposes. Albana et al. (2007) revealed that the CH_4 oxidation rate increases as the microbial activity grows more in the cover medium. It is well understood from the research studies that stable and mature compost performs well with regard to CH_4 oxidation purposes. Humer et al (2009) confirmed that compost is the most promising cover material that provides suitable chemical and physical properties to methanotrophs under favourable conditions. However, the mechanical (shear and settlement) behaviour of compost is not well understood.

Settlement plays a very crucial role in determining the performance of landfill cover material as CH_4 oxidation potential is directly related to free air space. Tim (1993) added that the free air space from 20% to 35% in compost establishes the maximum oxygen consumption rate i.e., 95%. This criterion means that it is even more important to take into consideration, the settlement of landfill cover material in the design phase. High and/or differential settlement could result in a significant reduction of the free air space or development of cracks in the biocover.

Furthermore, the landfill cover should have sufficient strength to resist sliding, rotation and movement of the slope as the slope is considered to be the most critical component of a landfill cover system.

Many studies have shown that the water content of the biocover has significant influence on the structural stability and oxidation capability of the landfill biocover. Humer et al. (2009) reported that the water content play three important roles in the CH_4 oxidation: i) provides an optimum environment for methanotrophs (CH_4 oxidizing bacteria), ii) influences the diffusivity of oxygen (O_2) into the cover medium, which affects CH_4 oxidation. The diffusivity of O_2 reduces with increases in water content, and iii) is a major agent, which affects the gas fluxes through the cover medium. The flow of gas decreases with increases in water content due to the filling of the soil pores with water.

The objectives of the present study are:

- To investigate the shear behaviour and determine the shear strength parameters of compost biocover materials with different initial water contents.
- To investigate the consolidation behaviour of compost biocover materials with different initial water contents.
- To have a better understanding of the mechanical behaviour of compost and the effect of compaction degree on this behaviour.

2 EXPERIMENTAL STUDY AND RESULTS

2.1 Material used

Laboratory tests were carried out on a compost sample (Figure 2), obtained from Lafleche Inc. Canada. The compost consists of municipal source separated organics such as food waste, kitchen waste, leaf and yard waste, and activated carbon. The biodegradable feed stock was separated from multiple municipal, commercial and institutional sources at the Lafleche facility.

The above mentioned organic materials were mixed in an industrial-grade mixer in order to achieve a homogeneous blend of proper carbon to nitrogen ratio and moisture content. The compost feedstock and bulking agents were subjected to an active composting phase for a minimum of 25 days. The material was stored outdoors on a curing pad for 6 months at the Lafleche facility prior to laboratory analyses. A bulk quantity of the compost (1 m^3) was sampled from the industrial site and then stored in a cold room (2ºC) at University of Ottawa to preserve the compost properties for a longer period of time. A small quantity of compost in buckets was transferred to the Geotechnical laboratory of the University of Ottawa for each analysis

Figure 2: Laboratory compost sample.

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2.2 Compost characterization:

Water content was gravimetrically determined in accordance with the American Society for Testing and Materials (ASTM) procedure D 4959-07. The specific gravity of the compost was measured by following ASTM standard D 854–06.The Atterberg limits of the compost were determined by following the ASTM D4318-10 procedures for the liquid limit, plastic limit, and plasticity index of soils. The plastic limit could not be determined due to the brittleness of the material. The specimen split into pieces at a low water content, but stuck to the glass plate in the form of small clods at higher water content, when rolled onto the glass plate. The bulk density, void ratio and porosity were determined according to the conventional soil mechanical methods (McCarthy, 2007). Table 1 shows the index properties of the compost.

Table 1: Index properties of the compost

Parameters	Values	Parameters	Values
Water content (%)	68	Degree of saturation (%)	1.68
Bulk density (kg/m³)	520	Liquid limit (%)	88
Specific gravity (Gs)	1.68	Plastic limit	0
Void ratio	3.93	Plasticity index	88
Porosity (%)	80	Liquidity index	0.77

A liquid limit of 88% was determined for the compost. A liquidity index for the specimen was also determined and found to be 0.77. Benson and Othman (1993) reported that an attempt was made to determine the plastic limit of compost, but no results were attained.

The range and numbers of the various sizes of particles in the sample determine the shape of the grain size distribution plot. It also defines the grain size history. The uniformity coefficient (C_u) and coefficient of curvature (C_c) determine the range of particle sizes and type of soil. A grain size distribution analysis of the compost was carried out by following ASTM standard D 6913 - 04. Figure 3 shows the grain size distribution curve of the compost used

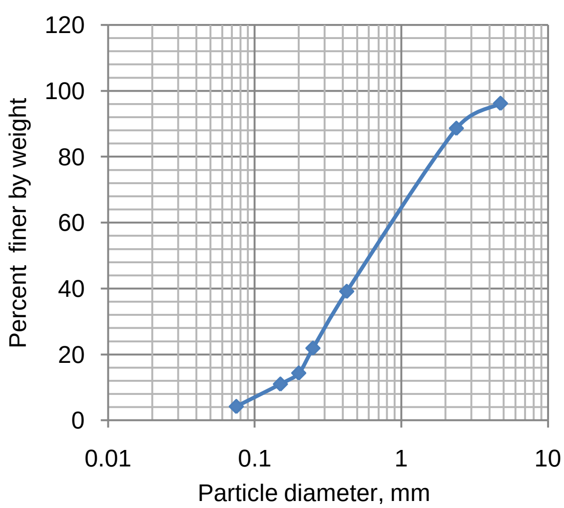

Figure 3: Grain size distribution curve of the compost

Figure 5 depicts that only 3% of the sample was retained on sieve # 4, and 90% were observed to fall in the range between 2.38 mm and 0.15 mm. Moreover, the C_u and C_c of the sample were also determined and found to be 6.07 and 0.86, respectively.

2.3 Mechanical characteristics of compost

Moo-Young et al. (1996) reported that normal stresses in a landfill cover fluctuate between 40 kPa and 60 kPa, and may reach up to 80 kPa in some circumstances. Benson and Othman (1993) commented that normal stresses in a landfill cover vary from 14 to 61 kPa. According to Rajesh and Viawanadhem (2009), a landfill barrier is subjected to an overburden pressure of 25 kN/m^2 that includes the self weight of the drainage layer and cover material. Cabrel et al. (2002) revealed that normal stresses in a landfill cover vary between 10-20 kPa. Therefore, a cover material may be characterized for these stresses to simulate field conditions. It is absolutely important to determine the shear strength parameters (c and Φ) and settlement behavior of the cover for different water contents and dry densities to determine the optimal water content with respect to structural stability and CH_4 oxidation potential.

2.3.1 Direct shear tests

A direct shear testing program was carried out at the University of Ottawa to study the shear strength parameters and behaviour of compost. The shear behaviour of compost is analysed by using the consolidated drained (CD) direct shear test which follows ASTM procedure D 3080-04.

First of all, a compost sample was thoroughly mixed with a specified quantity of water and particular dry density as set to the ASTM standard effort compaction test (ASTM D 698-07). After that, the sample was carefully transferred to the dissembled direct shear machine mold. The size of the direct shear machine mold was selected as 60x60x20 mm^3. For all samples, a compaction effort of 600 $kN\text{-}m/m^3$ was used. The normal force was kept constant during the testing. The specimen was compacted in three equal layers with a small square tamper to achieve the desired level of compaction for the specified water content. An equal number of blows to obtain the specified density were selected by trial and error. The mold which included the compacted sample was again assembled to the direct shear machine. The shear box was filled with water and the sample was left untested for two hours to attain equilibrium. The CD tests were carried out for wet of optimum, dry of optimum and optimal water contents for the compost samples. However, more tests were carried out for dry of optimum as this condition is more prevalent in landfill covers.

A very slow rate of shearing i.e., 0.0277 was selected to shear the specimen. The shear rate was calculated by the methods as prescribed in ASTM D3080 -04. It was ensured that excess of pore water pressure did not develop during the testing. Equation 1 was used to determine the shearing rate of the compost:

$$d_r = d_f / t_f \quad [1]$$

d_r = displacement rate (mm/min)
d_f = estimated horizontal displacement at failure (mm)
t_f = total estimated elapse time to failure (min)

The tests were carried out for each specified density and water content two to three times in order to ensure the repeatability and obtain accurate results.

2.3.2 Direct shear test results

Figure 4 shows the relationship between shear stress and relative shear displacement under different loading conditions i.e., 20, 40, 60, and 80 kPa for 59% water content.

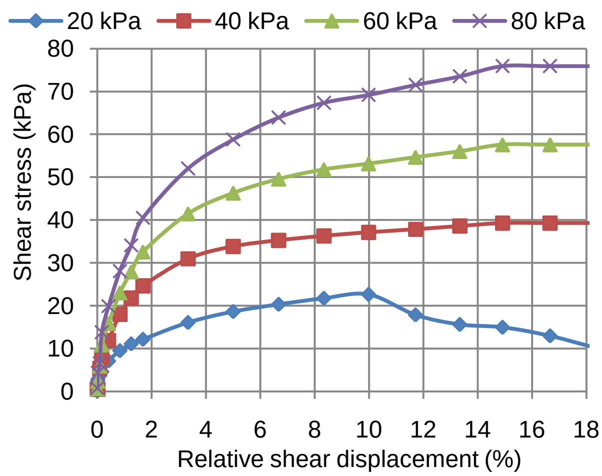

Figure 4: Shear stress vs relative shear displacement under different loading conditions for 59% water content

Figure 4 shows that the initial portion of all the curves is curvilinear and the shear stress gradually increases with relative shear displacement until it attains the maximum shear stress at a relative shear displacement of around 10% for 20 kPa and 14% for greater than 40 kPa loading conditions. After the peak value, the shear stress remains relatively constant or slightly decreases for normal stresses greater than 40 kPa per increases in relative shear displacement. As shearing is applied, 20 kPa normal stresses mobilize less frictional resistance in comparison to higher normal stresses as the specimen starts to dilate at relatively less shear displacement and fails earlier (Figure 6).

Figure 5 represents the relationship between shear stress and relative shear displacement for different water contents at a normal stress of 20 kPa. Figure 5 depicts that the shear stress gradually increases with relative shear displacement until it reaches the maximum shear stress at a relative shear displacement of 10% for the samples with lower water contents (46% and 59%) and around 14% for the samples with higher water content values (72% and 79%).

The peak shear stress is relatively similar for all water content values, except that it has a slightly higher peak for a water content of 46%. After the peak value, the curve suddenly drops, which shows highest drop for lower water content values. This observed higher relative shear displacement (14%) for the samples with higher initial water contents can be explained by the fact that at higher water contents, the compost particles are in close interaction to each other due to higher dry density or compaction degree, and mobilize consistent frictional resistance for relatively larger shear displacement, whereas at lower water content, the compost particles are not closely compacted due to a lower mass to volume ratio.

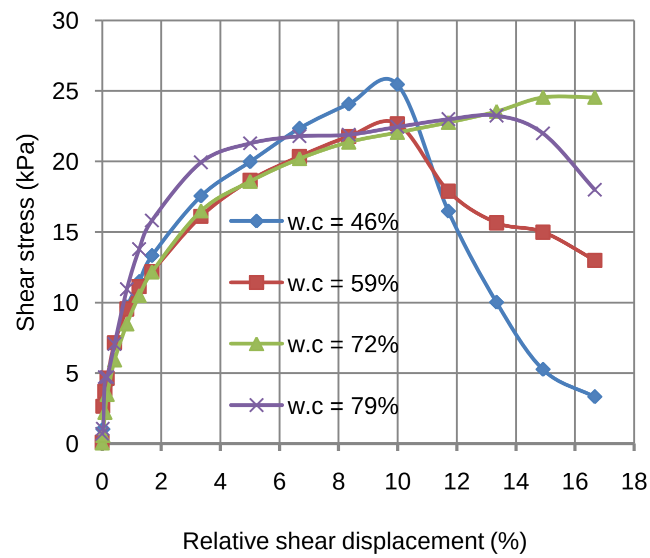

Figure 5: Shear stress vs shear displacement for different water contents under 20 kPa loading conditions

Figure 6 depicts the relationship between relative shear displacement and vertical displacement at water content of 59% under different loading conditions. It can be concluded from Figure 6 that the specimen compresses more at higher normal stresses in comparison to lower normal stress values. The fact is that a higher normal stress leads to a reduction in the local voids due to the compression of the compost material. In the beginning of the shear test, all the samples settled in the same way. However, the compost starts to dilate at a normal stress of 20 kPa at a relative shear displacement of 6 %.

For normal stresses of 40 and 60 kPa, the compost starts to dilate at a relative shear displacement of 10 %. However, dilation behaviour is not noted at a normal stress of 80 kPa. This means that high stress compresses the compost more.

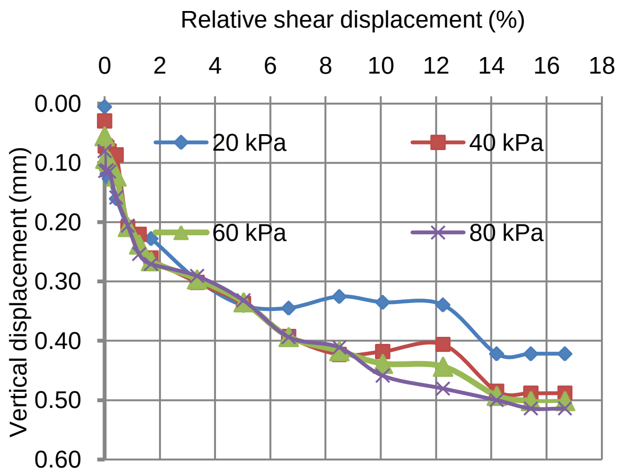

Figure 6: Vertical displacement vs relative shear displacement for water content of 59%

Figure 7 represents the Mohr-Coulomb strength envelope for shear strength parameters of the compost materials. The effective cohesion, c′, and effective angle of internal friction, Φ′, were also determined for the compost sample. The effective cohesion of compost varies from 4 to 5 kN/m^2. It has low cohesion due to its relatively brittle nature. Furthermore, it has an effective angle of internal friction of 45° that slightly varies by water content and dry density values under different loading conditions.

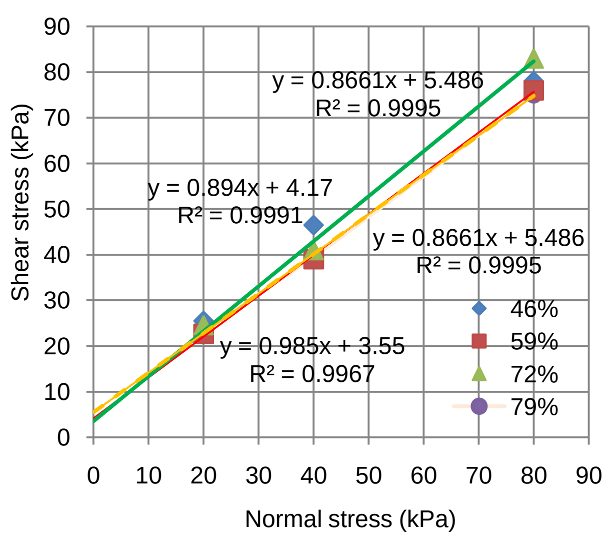

Figure 7: Shear stress vs shear displacement for different water contents under 20 kPa loading conditions

2.4 Settlement behavior of compost

2.4.1 Oedometer (consolidation) tests

The prediction of the settlement for the compost biocover material is complex and it is really important to analyze the settlement behavior prior using it as a landfill cover material. Various factors such as moisture content, depth and time of placement influence the consolidation properties of the cover material. These parameters contribute to changing the compost density with landfill depth and increasing the strain in the waste layers due to the weight of the overlying layers. The intermediate cover layer immediately settles due the placement of new layers above each other. The bottom layer has a higher density in comparison to the lower layers.

Therefore, a series of consolidation tests are performed to evaluate the consolidation behavior of compost for different water contents and dry densities. The consolidation test (Oedometer test) was carried out by following the method described in ASTM D 2435 – 04. First of all, the compost sample was thoroughly mixed with a specified quantity of water as set in a standard effort compaction test.

The sample was transferred to a consolidometer mold that is 62 mm in diameter. A circular base tamper was used to compact the specimen into the mold. The specimen was compacted into three equal layers in order to obtain the specified dry density and water content. The number of blows was set by trial and error method. The compacted sample was trimmed with a sharp knife to give it a proper shape and accurate dimensions. After that, the sample was carefully pushed into a consolidometer ring with a piston. The same procedure was applied to all the tested samples. Due to the sensitive nature of compost, the sample was sometimes broken into pieces while insertion into the ring and the test had to be repeated. This scenario was more prevalent in lower water content samples.

Each sample was soaked in the Oedometer cell throughout the testing. Consolidation pressure was applied in a normal manner, gradually rising from 2.5 kPa to 80 kPa as a load incremental ratio (LIR) with a multiple of 2.5, i.e., 2.5, 5, 10, 20, 40 and 80 kPa.

The samples were left under each loading for 24 hrs to reach their maximum consolidation capacity. However, most of the samples reached 50% consolidation in just 8 to 10 minutes. At the end of each test, the wet and dry weights of the sample were determined for further analyses. The compression and swelling indexes of the compost were estimated by using the liquid limit and plasticity index values, whereas the coefficient of compressibility was calculated by using the logarithm of time method.

2.4.2 Oedometer test results

Figure 8 shows the relationship between vertical deformation and consolidation pressure of the compost specimens evaluated at different water contents and dry densities. It can be seen that all the compression curves show almost the same nature for all the water content values. However, the compost swells more at higher water content in comparison to lower water content, and deforms up to 3.5 mm at 79% water content, with a maximum deformation for low water content (46%) at 2.6

mm, which is close to that for a water content value of 59%. This difference may be considered to be quite significant for a landfill biocover material with regard to fluid transport factors such as permeability, free air space and gas flux.

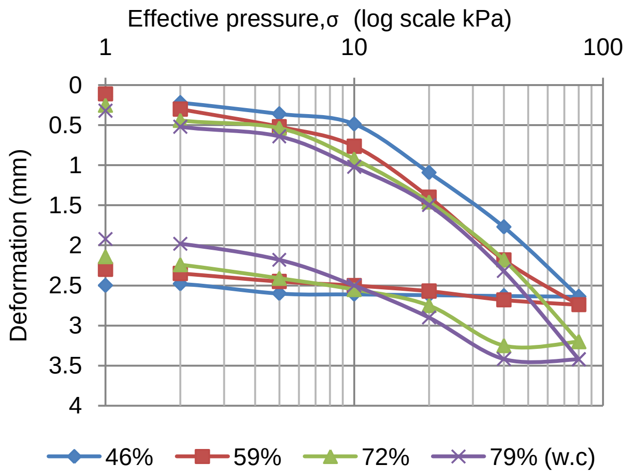

Figure 8: Relationship between deformation and normal stress for compost

The compost swells more as the water content increases irrespective of the dry density. The maximum dry density of the compost occurs at 79% water content, despite that the rebound curve shows a high peak for this particular water content in comparison to the other values. For low water content values, the compost shows low stress dilation behavior, and the rebound curve appears to look like a straight horizontal line.

Figure 9 represents the relationship between void ratios versus the logarithm of effective pressure. It shows that the void ratio of all the samples decreases with increases in effective pressure. However, the reduction rate in the void ratio for higher water content is relatively more in comparison to lower water content values under all loading conditions. The compost sample attains a low value of the void ratio (0.15) at 79% water content for an effective pressure of 80 kPa. This means that most of the voids are diminished or filled with water, and the sample may provide insufficient free space (f) for the movement of gas flux as a biocover material.

However, the rebound curve for higher water content samples shows more potential for swelling in contrary to low water content values. The expansion of the consolidated samples was calculated to be 5%, 15%, 35%, and 45% for water content values of 46%, 59%, 72% and 79%, respectively, during the unloading stage.

Despite the high swelling potential for high water content samples, the void ratio is still less than that of lower water content values at zero unloading conditions. So, it can be concluded from Figure 9 that the lower water content values could provide more favorable conditions for compost to be used as a landfill biocover material with regard to gas transport ability. The computed values of the compression index (C_c), and swelling index (Cs) are 0.20 and 0.04, respectively. The coefficient of consolidation (compressibility) was also estimated to be 8.4 x 10^{-4} cm^2/sec of the tested compost.

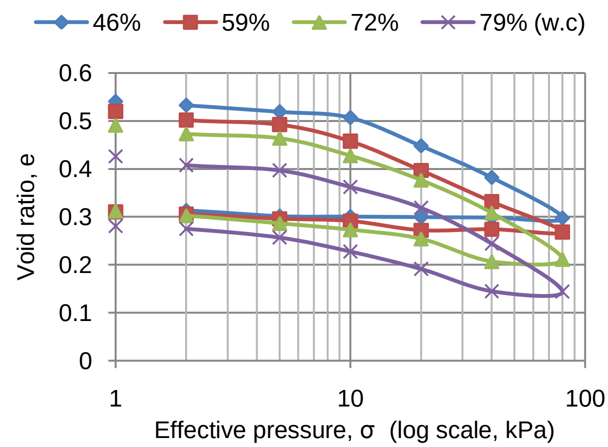

Figure 9: Relationship between the void ratio and effective pressure for compost

3 CONCLUSIONS

Mature compost can be used as landfill biocover material to obtain good results for CH_4 oxidation purposes. In this paper, experimental studies have been conducted on compost samples to investigate the mechanical behaviour of compost biocover, such shear behaviour, shear strength parameters and consolidation behaviour. Compost samples with different initial water contents or compaction degrees are adopted. The results obtained show that the compaction degree and initial water content can have a significant impact on the mechanical behaviour of compost. However, the shear strength parameters are only slightly affected by the initial water content and compaction degree. The compost shows more dilating behaviour at higher water content. However, it has a more consistent and stabilized nature at higher water contents in comparison to lower water contents. Compost settles more at higher water content and might provide insufficient free space for gas fluxes.

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