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An Assessment of the Potential Use of Compost Filled Plastic Void Forming Units to Serve as Vents on Historic Landfills and Related Sites

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Abstract

Much of the solid municipal waste generated by society is sent to landfill, where biodegrading processes result in the release of methane, a major contributor to climate change. This work examined the possibility of installing a type of biofilter within paved areas of the landfill site, making use of modified pervious paving, both to allow the escape of ground gas and avoid contamination of groundwater, using specially designed test models with provision for gas sampling in various chambers. It proposes the incorporation of an active layer within a void forming box with a view to making dual use of the pervious pavement to provide both a drainage feature and a ground gas vent, whilst providing an active layer for the oxidation of methane by microbial action. The methane removal was observed to have been effected by microbial oxidation and as such offers great promise as a method of methane removal to allow for development of landfills.

Keywords:
Landfills, Waste, Methane, Methanotrophs, Biodegradation, Biofilter, Pervious Pavement

1.0 Introduction: methane from refuse landfill processes

Whilst recent practices in some developed countries (such as the UK, USA, Canada and those in the EU) have reduced landfill disposal of biodegradeable material to some extent, much biodegradeable waste is still sent to landfill. Biodegrading processes with low oxygen availability inevitably produces methane, a greenhouse gas that contributes to climate change to a greater extent than the same mass of carbon, in the form of carbon dioxide (Woolf *et al*., 2010). Current practices such as active gas collection (incorporating electricity generation) are available where the gas has insufficient energy content to make electricity generation worthwhile. Active collection systems followed by flaring or actively ventilated biofilters are also effective at reducing both the potential health and safety hazards and achieving GHG reductions. However, the systems are not cost effective or environmentally sound for older landfills or other brownfield sites where lower, but unacceptable, concentrations of methane are present, inhibiting development. This is particularly important when ground gas concentrations are just above concentrations at which simple barriers in the floor slab would be effective.

One method that could address this issue would be to encourage the gas to vent passively from the site and in this case reduce climate change impact by the biological conversion of the methane to carbon dioxide. It would be more optimal to do this as the CO_2 was vented, something that has been actively pursued. Holmes *et al.* (1999), Einola *et al*. (2008) Scheutz *et al.* (2011) Schroth *et al.* (2012), reported that the use of bio-covers at older landfill sites was advantageous in terms of construction simplicity, cost effectiveness, low maintenance and operating cost as reported by several other researchers. However, Bohn *et al.* (2011) stated that this technology is faced by the disadvantage of the permeable nature of the cover layer. Hence, in order to minimise the emission of landfill gas, a low permeability landfill cap layer must be constructed leading to the use of a capillary barrier layer in combination with the bio-cover to act as a gas distribution layer. Passive bioreactors have been investigated by several researchers. Barlaz *et al.* (2004) evaluated the effectiveness of removing methane emissions in bio-cover by using an intermittent soil cover and a biological cover made of yard waste compost. The bio-cover performed better than soil due to increased organic content and good moisture retention capacity thereby making it less vulnerable to cracks.

Huber-Humer *et al* (2008) reported a successful methane emission reduction in a landfill in Australia between 1999 and 2002 using an intermediate bio-cover of mature compost overlaying a gravel layer of 0.3-0.5m. Experimental reports from Liptay *et al.* (1998), Chanton and Liptay (2000) and Borjesson *et al* (2001) demonstrated that the oxidation rate of methane in a bio-cover during the winter did not decline in contrast to the decline recorded in an intermediate soil cover. Straka *et al.* (1999) came to the conclusion that the use of a passive venting system with bio-filtration is a much cheaper mitigation technique than the active venting system with advantages especially in small and old landfills. However, covering with a compost biofilter can prevent certain after-uses of such sites if they require the provision of hard standing. The aim of this work was to examine the possibility of installing a biofilter within paved areas, making use of modified pervious paving, both to allow the escape of ground gas and avoid contamination of groundwater.

1.1. Landfill methane treatment in combination with Sustainable Drainage

A previous study at Coventry University reported the suitability of application of municipal and agricultural based compost on Sustainable drainage (SuDS) devices such as Swales (Charlesworth *et al*. 2012). Pervious pavements systems (PPS) are an integral and widely implemented component of sustainable drainage system (EA. 2012) and descriptively equivalent to the term “best management practice” (BMP) used in North America (EPA. 1993). They are designed to deal with stormwater at source and, in keeping with the SuDS philosophy, provide stormwater treatment, volume control and amenity. The traditional design of PPS consists of the natural stone sub-base layer which acts as both load bearing structure and a water storage reservoir. This is covered by a gravel laying course, sometimes separated from the sub-base by geotextile material and a surface matrix of concrete blocks, with voids necessary for stormwater infiltration. PPS that use plastic void forming boxes, to provide some or all of the sub-surface storage volume, offer an alternative to PPS based on aggregate sub-bases (Newman *et al*. 2011). However, care must be taken to ensure that the boxes are not used inappropriate applications, as many are insufficiently strong to be used close to the surface as sub-base replacements, particularly in areas that will be subject to vehicular traffic. Plastic boxes within a PPS have also proved useful to allow incorporation of additional treatment options within the system. The extra void space of the plastic void forming units has been exploited to incorporate floating mats to absorb oil (Newman *et al.* 2004a; Puehmeier 2009) and specialised foams to provide long-term water storage as well as additional pollutant retaining capacity (Nnadi *et al.* 2014). The incorporation of additional treatment enhancement layers such as sorbents or biodegradation enhancements into traditional stone sub-based pervious pavements has also been proposed (Puehmeier and Newman 2008, Bentarzi et al 2010, 2013), but the problems of compaction under the load of upper layers of a system and or potential instability as the active medium layer disintegrates cannot be ignored. These active media have, to date been solely concerned with trapping and or degrading pollutants from percolating stormwater as they pass downwards through the pavement. This article proposes the incorporation of an active layer within a void forming box with a view to making a dual use of the pervious pavement providing both a drainage feature and a ground gas vent whilst providing an active layer for the oxidation of methane by bacterial action. This approach would be suitable where hard surfaces need to be incorporated into historic landfill sites. This could allow the implementation of suitably designed development options to take place. Such circumstances could include parking areas at visitor centres, where the landfill has been devoted to recreational use, or hard standing areas on industrial sites built on closed landfills.

Another approach that has been taken to address the problem of the control of ground gas emissions from older landfill sites is the system known as a “Virtual Curtain” in which gas collecting nodes are vibro-inserted into the ground, providing means for gas escape into a line of void forming plastic boxes (these are identical to the ones used in PPS applications) linked to wind driven passive extraction vents. Such systems can be installed to prevent the spread of ground gas away from the gas generating site, but they are also widely used to protect receptors by providing a barrier to gas transmission towards buildings. Whilst arrangements are usually made in this system to dilute the ground gas before release to atmosphere, there is currently no provision for reducing the mass of methane released and hence reducing the greenhouse gas contribution of the site. Furthermore, this article proposes to address this issue by means of the potential introduction of a biofilter system within the plastic void forming units, used as the means of transmitting the gas to the vents.

1.2. Non-constructed methane rich environments

Many non-constructed environments are known to have metabolically active populations of methanogens and methanotrophs and these include wetlands, lakes, rice paddies, peat soils (both temperate and tropical peat) and oceans (Hanson and Hanson. 1996). A brief survey of literature on selected methane rich systems is presented here to determine the biotic and abiotic conditions that give rise to methanogenesis or the conditions that favour the action of methanotrophs that may be relevant to the present study.

The oxygen profile of the methane rich environment, as well as the surrounding medium, is important in defining the area of methanogenesis and its uptake by methanotrophs. This is because methanogens are obligate anaerobes and methanotrophs are typically aerobic Zebulun *et al.* (2013). Environmental management of landfill gas often involves mitigating the impact of methanogens, but there are many situations where sensitive environments have been affected by land management (e.g. the drainage of waterlogged soil), and restoration involves an attempt to restore the methanogen communities and balance them with the adjoining methanotrophs, often by reinstating the waterlogged conditions of a methane rich soil. An example of this was the restoration methodologies used on Finnish boreal peatlands (Juottonen *et al*. 2012). In a long-term field study of boreal peat, a previously drained peat soil showed depressed numbers of methanogens and methanotrophs relative to undisturbed peat, 12 years after restoration. In tropical peat soils Arai *et al*. (2014) described low levels of methane flux irrespective of land use, whether the soils were undrained, drained or subjected to burning. Increases in the percentage of water in soil pores were correlated positively with the flux of methane, but the soil pore filling by water correlated negatively with the number of methanotrophs, determined by most probable number (MPN) estimates. Crucially for the study described in our paper, the work of Arai *et al* reported that as well as the percentage of water filled soil pores, the presence of labile plant litter material in flooded conditions (as distinct from recalcitrant, woody, less labile material) was thought to be the main material facilitating methane production. This finding is of relevance to the study presented in this paper, that used green waste compost, with a mix of particle sizes and component types.

The identification of characteristic bacteria in landfill using molecular biology techniques has partially overcome the problems of representative sampling from landfills and the problem of non-cultural strains. In a mini review, Zebulun *et al*. (2013), named *Methylobacter*, *Methylococcus, Nitrospira, Nitrosomonas, Methylosphaera, Methylomonas, Methylocystis, Methylofolis, Methanoculleus, Methylosinus, Methanosarcina, Methanospirillum, Methylomicrobium* and *Proteobacteria* as key genera in landfill, identified by polymerase chain reaction (PCR), fluorescent *in-situ* hybridisation (FISH) and phospholipid fatty acid analysis (PLFA), summarising 10 separate landfill studies between 2003-2013.

In the study of an anaerobic aquifer in the Netherlands, polluted by landfill leachate, Brad *et al.* (2008) examined the eukaryotic microorganisms sampled along a transect from closer to further distant from the polluted plume. This study included sampling for protists and fungi as well as groundwater mesofauna, which addressed a major deficiency in the understanding of the response of the microbial community to pollution from landfill, most previous studies having concentrated chiefly on prokaryotes. Fungal diversity was high in the leachate enriched aquifer and dominated by *Basidiomycota*. Protists were represented by green algae and the heterotrophic nanoflagellate *Heteromita globosa*; groundwater mesofauna were not detected. Brad *et al*. stated that the aquifer food chain was relatively short and composed of decomposers and protistan primary consumers. It should be noted that the eukaryotes were not sampled from the landfill itself and the understanding of in-landfill eukaryotic microbiology remains a significant gap in the literature.

The combination of hard engineered SuDS devices with compost as a methane treatment and management system builds on previous research to determine the rate and effectiveness of hydrocarbon retention and biodegradation in SuDS (Pratt *et al*. 1999), protection of groundwater (Newman *et al*. 2004b) and investigation of the eukaryotic communities of oil degrading drainage systems (Coupe *et al*. 2003). Research has shown that whilst methanotrophs are capable of degrading methane in landfill gas, environmental factors can determine the microbiological oxidation rate of methane (Dever *et al.* 2011, Rachor *et al.* 2011). One of these factors is the necessity to keep the pathways of gas migration open to as great a volume of support medium as possible. The incorporation of an active ingredient within a plastic load bearing structure would serve to prevent compaction of the medium. This could have advantages in both passive venting systems based on pervious pavements and on such active systems as the Virtual Curtain. This article is a preliminary report which outlines the results to date from studies aimed at providing both support to the proposed landfill treatment and justification for further work. Omar and Rohani (2015) provided a recent review of methane remediation methods which confirms the novelty of methane mitigation method proposed by authors. Hence, it was considered pertinent to provide detailed explanation of the experimental protocol showing why each stage of the experiment was conducted, the steps taken and the outcome of these steps. In the following sections, scientific explanations of the materials and methods, the experimental protocol as well as results is presented in such a way as to make these processes clearer to the reader and to enable repeatability. Similar approaches were adopted by Brandstätter *et al.* (2013).

2.0 Materials and Methods

2.1 Setting-up the Test Models and Establishing the Methanotrophic Organisms

The test models were constructed on the footprint of a Permavoid® void forming unit which in plan measures 71cm x 36cm. The models consisted of a welded polypropylene chamber sufficient to hold 3 layers of these units with a flange on the upper lip to allow a lid to be bolted down, forming a sealed system with a depth of 45.2 cm (Figure 1). A series of gas entry/exit ports were provided in both the base and sides of the model allowing sampling from either upper or lower sub-chambers.

A lower, empty, Permavoid® unit was used to support the active unit containing a loose fill of compost which was wrapped in geotextile to prevent loss into the lower box. Compost used in this study was 'green compost' from garden and farm waste (i.e. tree clippings, leaves, grass cuttings, weeds, parts of harvested plants, etc.). The physicochemical characteristics of compost are presented in Table 1 and the water holding capacity over a 20-day period is shown in Figure 2. Gas mixtures were introduced at this level. An empty volume equal in size to a Permavoid unit was provided above the active unit to provide a suitable chamber from which to extract samples of effluent gas. Before sealing the lid, sufficient distilled water was added to the top of the system to provide starting water content of 25% v/v in the compost since in actual use, this system would largely be hydrated by the infiltration of rainwater from above. The box was then sealed. Within the system used to supply flowing gases into the model, a humidification system was used to ensure that the gases passing into the boxes would be saturated with water vapour, thus preventing or reducing evaporation of water from the system and mimicking the humid nature of most ground gas. This consisted of a large glass demijohn with a dip tube reaching to the base of the container, filled with distilled water. Gases were forced down the dip tube, bubbled up through the water and exited through a short outlet tube fitted to the same rubber bung as the dip tube. This system was set up in duplicate with the intention that one box would never be supplied with methane and thus could be used as a control. Before this control box was established, an experiment was carried out to check for leakage methane degradation in a static/ compost free box. This was found to be negligible.

Initial dynamic "slug" experiments were carried out with the designated methane-exposed model. This used methane gas from the gas main supplied through an integrating gas meter. Gas was introduced simultaneously as air was passed into the box using a gap-meter type flow meter. There were two aims to these experiments. The first was to develop an understanding of the lag time between the introduction of a slug of pure methane (into the lower box with a flowing air stream) and its appearance in the upper box. The second was to allow the development of an appropriate mechanism for allowing the box to be kept in a static condition with an initial methane concentration just below the lower explosive limit (LEL). This was to allow the compost to be exposed to relatively high concentrations of methane, under aerobic conditions, so as to allow the development of methanotrophic bacteria. In a typical experiment, with the air flowing through the humidifier at 2 l/min, slugs of methane from 1 to 10 litres were introduced into the lower box and sampling ports in both the upper and lower void box sections were used to draw sample into a Gas Data GFM400 (manufactured by Gas Data Ltd, Coventry, UK) analyser for measurement of CH_4 and CO_2.This Gas analyser was used in previous studies, such as Orozco *et al.* (2013); Brandstätter *et al*. (2015); Mbanaso *et al*. (2013). The concentrations of CO_2 and CH_4 were measured by infra-red absorption and O_2 was measured electrochemically. Accuracies were

3% for CO_2, 3% for CH_4 and 0.5% for O_2 (relative %) at average duration of gas analysis of 40 seconds. Limits of detection were 0-100% for CO_2 and CH_4; 0-25% for O_2. Methane free air was continually pumped into the lower box until the level of methane in the upper box appeared to have exceeded its peak concentration and had started to decline. The concentrations experienced in both boxes commonly exceeded the LEL. Figure 3 illustrates a typical experimental run using a 5-litre slug.

As expected, the concentration of methane in the lower chamber, where the slug of methane was introduced, fell approximately exponentially, whilst the concentration in the upper chamber rose to a peak concentration after about 20 minutes, around the time when the concentrations in the two chambers were approximately equal.

2.2 Establishing the Methanotrophic Organisms

Previous studies have established that compost is suitable for establishment and growth of methane oxidizing microbes (Philopoulos *et al*. 2009; Del, 2010; Hettiarachchi *et al*. 2011; Huang *et al*. 2011; Meia *et al*. 2011; Abushammala *et al*. 2014; Mancebo and Hettiaratchi 2015; Muenmee *et al*. 2015). Detailed reviews of the relationship between methanotrophs and their environment was provided by Segers (1998). As the compost had not been exposed to methane for a significant length of time it was expected that suitable populations of methanotrophic organisms would take a while to establish. Using the knowledge obtained in the above experiments, the methane-exposed box was treated to encourage the further development of the methanotrophs. A slug of 5l of methane (from the gas main) was introduced into the box and methane free air was introduced into the box (exiting through a port in the upper chamber) until, based on the results of previous experiments, it was felt that whilst retaining a significant methane concentration in both upper and lower chambers, it was safe to leave the box in the laboratory overnight without having to leave the fume hood running. Before closing down the airflow the methane concentrations in both chambers were measured. Typically, the methane concentrations would be around 30% of the LEL (but no attempt was made to obtain consistent concentrations). Thus, the compost was exposed to relatively high concentrations of both methane and oxygen. These procedures were continued 3 times per week for a period of 3 weeks before commencement of the experiments. This procedure was also used regularly to maintain the organisms during any periods during which dynamic methane flows were not established. In this preliminary experiment, no attempt was made to determine the nature or population of the methanotrophs. The authors acknowledge that this would be essential if the system was to progress to field trials.

2.3 Initial Static Tests

These tests were carried out on 5 occasions with a range of starting methane concentrations. The system was pulsed with 5 to 10 litres of methane and airflow was applied until a methane concentration of between 30% and 60% of the lower explosive limit (LEL) was present in both upper and lower boxes. The model was then sealed and the internal atmosphere in both chambers was re-analysed after the exposure period. The first experiment was carried out over a weekend with all other experiments being carried out overnight. The resulting methane concentrations were, in all cases, less than the limit of detection of the analyser with carbon dioxide concentrations always higher than the typical resting concentrations for carbon dioxide in the control model which was run in parallel to the test model. This indicated that the methanotrophic bacteria had been established and were capable, with sufficient contact time, of degrading the introduced methane. The difference between methane levels in treatment and control rigs was considered a sufficient indication of the establishment of methanotrophs. Similar method was used by Visvanathan *et al*. (1999) and Crespo-Medina *et al*. (2014). The next stage was to investigate the effects of methane degradation on flowing gas streams.

2.4 Dynamic Experiments

This series of experiments was thus initiated starting with a blank run (on the methane exposed box) using methane free air. The airflow rate was 100ml/min. This box had been sealed for 4 days prior to the experiment and the initial concentration of carbon dioxide in the upper chamber was 8.7%. After 24 hours pre-equilibration, regular (half hourly) sampling was started. The results obtained are shown below. A subsequent repeat experiment using hourly sampling gave essentially similar results. Three experiments were then carried out, using a 2.5% methane (21% oxygen, balance Nitrogen) mixture (Air Products Ltd, UK) as the feed gas, supplied at a flow rate of 100ml/min. Finally, an experiment was carried out, using a feed gas flow rate to 200ml/min. In all cases the feed gas was applied for 24 hours before starting the analysis.

3.0 Results

Figure 4 shows graphically the variation with time of the first blank run on the methane adapted model. The mean carbon dioxide concentration for this run was 0.45% and for the subsequent run it was 0.42%

The summary results for the four runs with a feed gas containing 2.5% methane which were scheduled 1 week apart are shown in Table 1, with the full results obtained for runs 3 and 4 shown graphically in Figure 5.

It can be seen from Table 2 that the apparent effectiveness of methane oxidation at 100ml/min feed rate had improved dramatically from the first experiment with the drop in methane concentration being mirrored by an increase in carbon dioxide.

Figure 5(b) shows results shows the 200ml/minute experiment which indicate a performance significantly poorer than the second and third 100 ml/min experiments but still showing a useful reduction in methane concentration of around 40%.

4.0 Discussion

The results indicate that the passage of methane laden air at a concentration of 2.5% at 100ml/minute through a compost filled Permavoid box gives sufficient methane removal to offer the potential benefits in both proposed applications. Although the removal was not 100% we need to consider that these systems would be installed where there was no attempt to remove methane and thus any significant removal would provide a worthwhile environmental benefit. In the UK, there would be another less obvious advantage, in that obtaining central government grant aid to local authorities for the remediation of contaminated sites is a competitive process, in which a proposal incorporating greenhouse gas reduction is given priority. To date, the flow rate at which methane oxidation is effective is limited. A feed rate of 200ml/min represents a gas emission rate through a pervious pavement surface of 0.8 litres per min per m^2. However the effectiveness would be expected to increase with time and to date no real attempt has been made to optimise the process. The experiment was also limited to a single oxygen concentration of 21% in the feed gas. This is slightly higher than would be experienced when dealing with gas emissions from either older landfills or contaminated land with limited methane production, but in our previous experiments on oil biodegradation in pervious pavements, oxygen diffusion into the system was found to be sufficient to maintain the system in an aerobic state despite data showing active aerobic biodegradation (Pratt *et al*. 1999). In the case of the potential application to a virtual curtain or similar system, the technology already has facility for introducing dilution air at an appropriate level in the system and thus oxygen concentrations could be managed.

More knowledge of the microbial assemblages which are developed in the boxes would be of great interest, but the organisms which would have developed in this small-scale system may not have represented those developing in a field system, since recruitment of organisms from the outside environment was limited in this experiment and thus any organisms developing would be limited to those already present in the compost. This would be the same as in the initial life of any compost blanket, representing a minimum level of efficacy of the methanotrophic assemblage. The methane processing capability would be expected to improve with time in the field, as organisms more suited to the local conditions would be recruited from surrounding locations, be encouraged to attach to surfaces as biofilm, metabolise methane and generate new biomass. Evidence from natural environments has shown that methanotrophs exist in viable numbers in methane rich conditions and that these autochthonous organisms respond to the presence of CH_4 coming from the action of methanogens; also that the water budget is crucial to maintaining the environment that sustains this association (Juottonen *et al.* 2012; Arai *et al*, 2014). Novarino *et al*. (1997) and Brad *et al*. (2008) described the eukaryotic communities that grow in aquifers subject to organic contaminants, including landfill leachate pollution, suggesting that methanotrophs in methane degrading compost would be subjected to grazing and regulation by protists as they are in permeable pavements (Coupe *et al*. 2003, Mbanaso *et al*. 2013). It is unclear whether predatory behaviour on methanotrophs would affect the rate of methane treatment from landfill, nor is it clear what eukaryotic community structure would be produced from microorganisms feeding on methanogenic bacteria in compost, but Murase *et al*. (2006) found that protist grazing of bacteria in flooded rice fields increased overall bacterial diversity but reduced the total biomass of bacteria. Murase *et al.* also determined that predatory activity and the impacts of this behaviour, were most pronounced under partially anoxic conditions, but could be detected when the rice fields were anaerobic.

A degree of heterogeneity in the compost filled units in water availability, oxygen concentration and methane concentrations that could be found in scaled-up and field-based reactors for landfill gas would be likely to provide suitable conditions for methanotrophs and other heterotrophs, plus a further food web to develop.

5.0 Conclusions

The results of this preliminary study appears to be very promising as a flow of 2.5% methane gas at 100ml/min through compost filled box gives sufficient methane removal. Also, methane oxidation by methanotrophic organisms was effective and can be potentially optimised. The significant methane removal observed in this study is expected to offer a worthwhile environmental benefit, in reduction of emission of greenhouse gases and find application in waste management in landfills, especially in the management of methane emission from old landfills. Further work would confirm the performance of in an in-ground situation and help to optimise the process. The treatment rate of the compost in this pilot trial has been shown to be viable for the further development of this technology and further study of the compost medium, the optimisation of the material and in-depth investigations into the manipulation of the methane-utilising environment, with monitoring of the impact of these modifications on microbial processes are the key areas to establish the potential wide scale use of this treatment technology.

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