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Hydraulic Aspects of the Design of a Passive Methane Oxidation Barrier (PMOB)

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Abstract
Passive methane oxidation barriers (PMOB) have been proposed in recent years as a component of cover systems. The aim is to favour growth of methanotrophic bacteria, which oxidizes fugitive CH_4 into CO_2. Several types of materials have been employed as "home" to methanotrophic bacteria, including mixtures of sand and compost. This paper describes the main preoccupations relating to the hydraulic aspects of the design of one of the three PMOBs constructed on the existing final cover of the St-Nicéphore municipal landfill facility, Quebec, Canada. The choice of mineral soils was partly dictated by their hydraulic/geotechnical parameters. The main hydraulic parameters of concern are the water retention curves of the different materials used and their hydraulic conductivity functions. The geotechnical parameters of concern were the initial density and gravimetric water content. Compaction was performed to attain an initial degree of saturation in the vicinity of 80%. Based on the geotechnical and hydraulic parameters, a model was created and numerical analyses were undertaken to forecast the hydraulic behaviour of the PMOBs. One particular type of problem that might arise is the accumulation of water at the interface between two types of materials with different hydraulic properties. Such accumulation is the result of a capillary break. The efficiency of the cover to oxidize methane depends on the extent of this accumulation, which in turn depends on the nature of the capillary break.

1 Introduction
In 2004, the GHG emissions from the Waste Sector in Canada contributed 29 Mt to the national inventory as compared with 25 Mt for 1990, representing an increase of 16%. The emissions from this sector represented 3.8% of the overall Canadian GHG emissions in 2004. The chief net contributor remains the CH_4 released from MSW landfills, which amounted to 25 Mt of CO_2-eq in 2004. In 2004, only 21% of the CH_4 generated by MSW landfills in Canada was captured and combusted (Government of Canada, 2004).

Although modern landfills are able to collect the majority of the biogas pro-

duced, no system is 100% efficient; therefore part of the biogas produced migrates though the cover system and ends up in the atmosphere, as fugitive emissions. Indeed, in the majority of the cases the biogas collection efficiency tops 75% (USEPA, 2002), but would not go beyond 40 to 60% (Humer and Lechner 1999; Morcet et al., 2003). Recent research efforts have been directed towards the development of a mitigation strategy whereby an engineered cover would promote growth of methane oxidizing bacteria in landfill covers (Huber-Humer, 2004), while performing its other purposes, such as infiltration control. A passive methane oxidation barrier (PMOB) has to be a "comfortable home" for methanotrophic bacteria, which oxidizes CH_4 into CO_2, in the presence of O_2. Several recent studies have shown that a PMOB can greatly reduce the CH_4 load associated with fugitive emissions (Huber-Humer and Lechner, 2002; Gebert and Gröngröft, 2006).

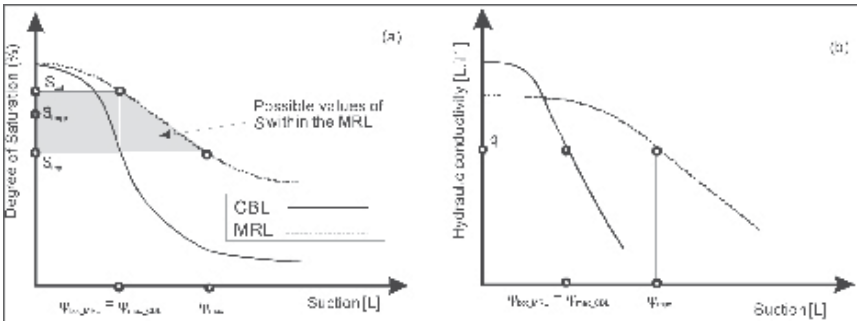
Many PMOBs reported in the literature (e.g. Huber-Humer and Lechner, 2002; Wawra and Holfelder 2003) include a gas distribution layer (made of very coarse material), a transition layer (such as sand) and an organic-rich layer (often compost mixed with a coarser material). This stacking of materials with different hydraulic properties forms a capillary break, which may result in accumulation of water at the interface, thus an increase in the degree of water saturation, S. Depending on the extent of this phenomenon gas flow may become more difficult, which increases the chances of preferential flow of CH_4 and of formation of extracellular polymeric substances – EPS (Hilger et al., 1999) that clogs the cover, thereby reducing the oxidation efficiency of the system.

The goal of this paper is to describe one aspect of a general procedure for the design of an efficient PMOB: the hydraulic aspect. Normally, a complete design includes, among others, concerns about the geotechnical behaviour of the materials and about their physical and chemical composition, which ultimately affects gas flow, microbial growth and activity, thus methane oxidation. The main control parameter is S. As mentioned above, if it is too high, there is risk of preferential flow, while if too low, the residence time for methane oxidation may be too short. Ideally, one seeks to maintain a value of S across the profile of the oxidation layer that is as close as possible to the target value ($S_{target} \approx 80\%$). The design procedure is based on the theory on unsaturated flow and was applied to the design of three instrumented PMOBs installed at the St-Nicéphore landfill.

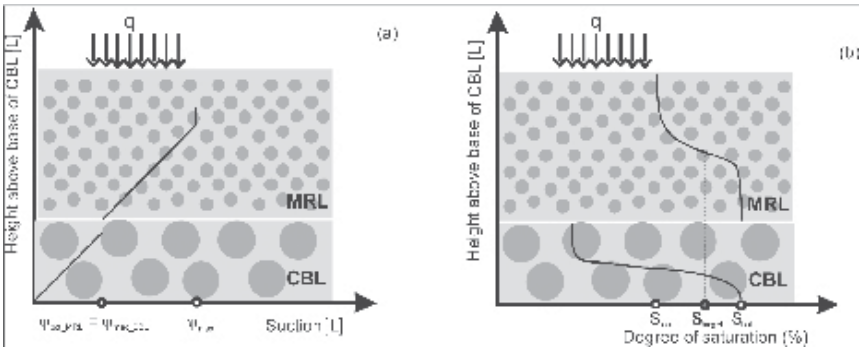
2 Theoretical background

The basic PMOB is composed of a coarse gas distribution layer and a substrate layer (often a mixture including materials such as compost), whose pore sizes are smaller. The superposition of the two materials forms a capillary barrier in which the gas distribution layer is the capillary block layer (CBL) and the substrate is the moisture retaining layer (MRL). Their schematic water retention curves (WRC) are presented in Figure 1a, and the associated hydraulic conductivity functions (k-fct), in Figure 1b. It is always these curves that dictate the hydraulic behaviour of the PMOB. For a given infiltration rate, q (that best represents the reality of the

field or a precise scenario to be investigated), and using the data from the WRC and k-fct, it is possible to obtain the suction and degree of saturation profiles shown schematically in Figure 2. The worst (and unlikely) case scenario possible is that the suction at the base is zero, i.e. the leachate level would touch the base of the cover. It can be noted in the case illustrated in Figure 2 that *S* remains quite high above the interface; this is a situation one wants to avoid most of the time.
In order to obtain degrees of saturation within the MRL that are as close as possible to S_{target}, the materials forming the PMOB must be carefully chosen (Parent and Cabral, 2005). The WRC and k-fct, which ultimately dictate the hydraulic behaviour and the efficiency of PMOB, must first be obtained. A following step is



to create a model of the PMOB and then to run numerical analyses using a model capable of handling unsaturated flow. At a preliminary stage, it is not necessary to use a multi-phase (gas and water) model; but this may become important later



in the process.

Fig. 1: (a) Water retention curves and (b) hydraulic conductivity functions of two materials forming a PMOB (schematic)

Fig. 2 : (a) Suction and (b) degree of saturation profiles for a PMOB (schematic)

3 Materials and methods

The profile adopted for the experimental PMOB discussed in this paper is presented in Figure 3. This cell was lined with a geomembrane and is equipped with a gas distribution layer; the biogas comes from the landfill itself. In order to reduce the hydraulic contrast between the ¾'' (19 mm) coarse gravel and the sand-compost (S-C) layer – and to respect the basic Terzaghi filter criteria - a thin layer of ¼'' (6.3 mm) gravel and an intermediate layer of sand were placed. The WRC of the sand layer has to be such that the air entry value (AEV) is low enough so that the saturated thickness remains as low as possible; concomitantly, it has to have a capacity to transmit a high enough suction to the S-C layer above it, so that the S at the base of the latter remains as close as possible to S_{target}. The WRC of the materials are presented in Figure 4a (all WRCs are being re-obtained). The actual k-fct of the mixture is presently being re-evaluated based on field water content and suction data. The curves presented in Figure 4b were estimated.

For reasons relating to important goals of this research project, the thickness of both the sand-compost layer and the sand layer were set to 0.4 m. Considering

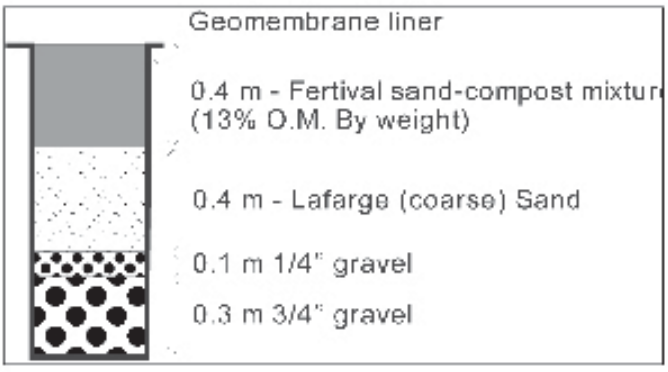


Fig. 3: Profile of the experimental PMOB -3 at the St-Nicéphore landfill, Quebec

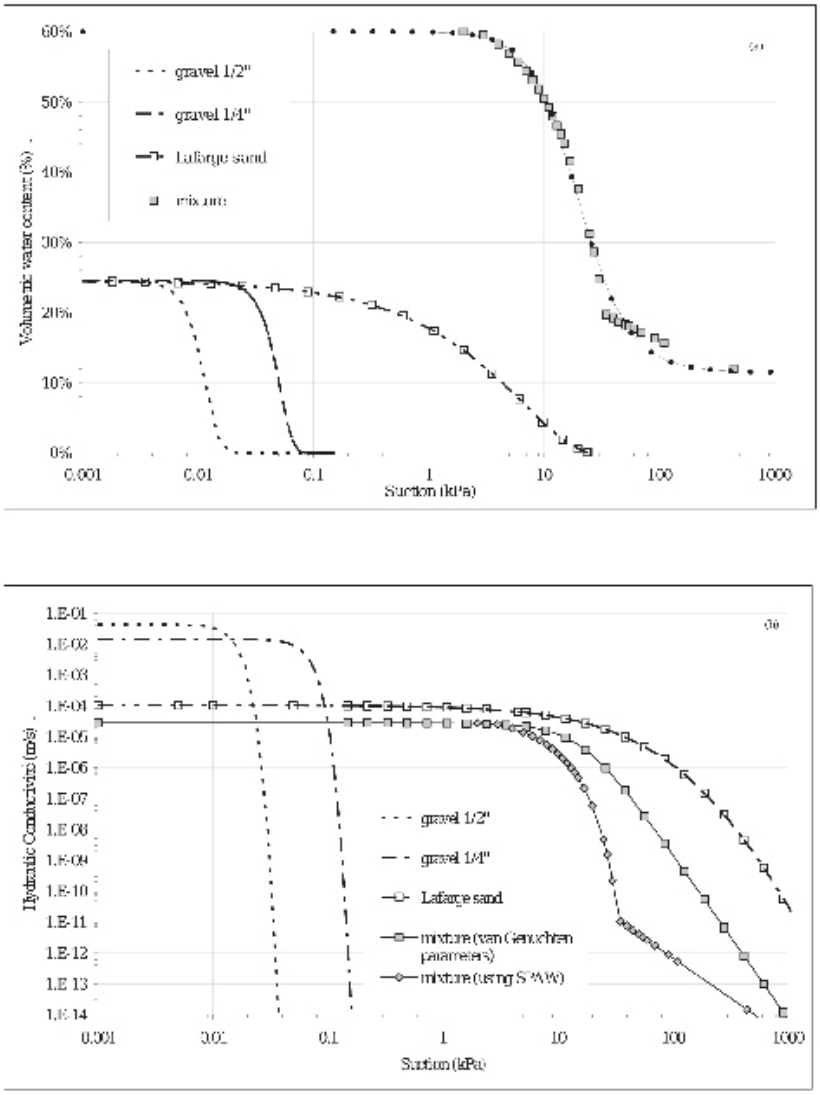


Fig. 4: (a) WRC and (b) k-fct of the materials employed to build PMOB-3 at St-Nicéphore

that the suction that can be transmitted from the gravel to the sand is negligible, the maximum suction that can develop within the sand layer – thus be transmitted to the S-C layer is 0.4 m (4 kPa). This value dictates part of the characteristics to be sought for when selecting materials for the sand-compost layer. For example, it dictates the maximum amount of compost that can be mixed, the granulometry of the sand, etc.

4 Numerical Analyses of the Hydraulic Behaviour of the St-Nicéphore PMOBs

Numerical simulations were performed using SEEP/W in order to obtain the suction and degree of saturation profiles of PMOB-3. The model was tested at steady state, for a constant infiltration rate, $q = 10^{-8}$ m/s (equivalent to 300 mm of infiltration per year), whereas the boundary condition at the base was set to pressure (or suction) equal to zero. This value of q is equivalent to approximately 1/3 of the total annual precipitation in Quebec. For a non revegetated surface, this appears to be the very maximum value possible.

The profiles obtained are presented in Figure 5. Irrespective of the applied q (the model was tested for other values of q), the gravel (be it the ¾'' or the ¼'') is not capable of transmitting much suction to the sand layer. The base of the sand becomes rather desaturated (S≈45%) and more so at the base of the interface with the S-C mixture. However, the target degree of saturation (S≈80%) could not be achieved within the S-C layer. At the base of this layer, S may be as high as 95%, which can affect the upward flow of CH_4. Near the surface, the value of S is still rather high and could affect the downward migration of O_2.

5 Conclusions

Consideration of hydraulic aspects, more particularly the degree of saturation, S, is fundamental in the design of passive methane oxidation barriers (PMOB). In order to ensure that the oxidation layer performs well, the designer needs to select materials whose hydraulic response to infiltration permit to attain the target S (= 80% in the case of the present project) across the profile of this layer, most of the time. A great concern is the creation of a hydraulic break at the interface between materials having different hydraulic properties.

This paper described the general steps of a procedure followed to specify the materials for an experimental PMOB installed at the St-Nicéphore landfill. Part of the procedure involves numerical modelling of unsaturated flow of water.

For the materials, thicknesses and profile (stacking of materials) chosen, the results show that for a constant infiltration rate equal to 10^{-8} m/s, there is risk of creation of a capillary break and the occurrence of degrees of saturation greater than S_{target}. Indeed, for the very high q applied, S remains rather high both at the base and at the top of the oxidation layer.

Despite these results – and for other reasons not discussed in this paper – this profile and the materials were retained for the field tests at the St-Nicéphore landfill. Field data collected since the end of July 2006, along with further testing and

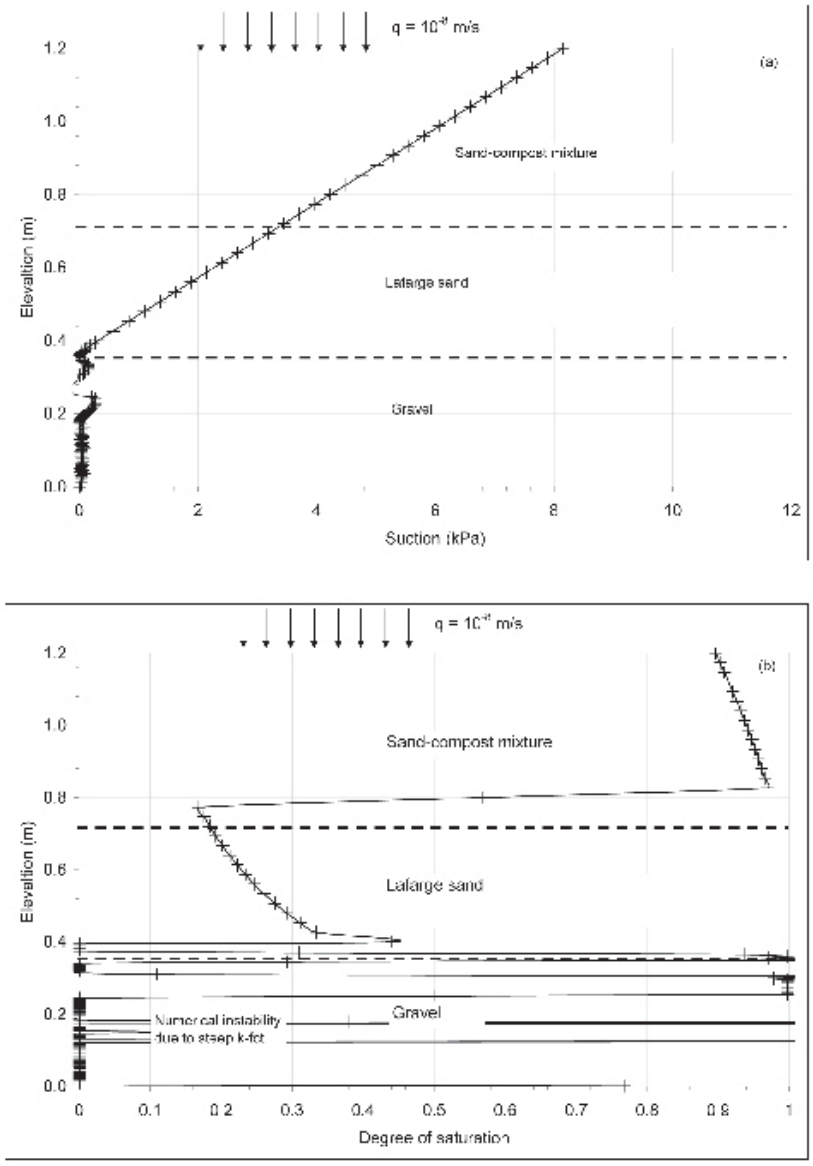


Fig. 5: Profiles obtained from numerical simulation: (a) suction; (b) degree of saturation

characterization of the materials involved, as well as modelling, are presently being undertaken and should confirm within the next years how effective the design of PMOB-3 is in terms of CH_4 oxidation under Nordic conditions. It is known however, that the degrees of saturation are never as high as the values obtained from the numerical modelling simulations.

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