Hydraulic barrier and its impact on the performance of cover with double capillary barrier effect

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ABSTRACT
An experimental cell was constructed at the Saint-Tite-des-Caps municipal landfill, Quebec, Canada, to evaluate the hydraulic behaviour of a double capillary barrier (DCB). This alternative cover system includes a 0.60 m layer of deinking by-products (DBP) that acts as hydraulic barrier. The DBP layer superimposes a capillary barrier (CB) built with coarse materials: a 0.4-m thick sand layer as moisture retaining layer and a 0.2-m capillary break layer constructed using gravel. In order to monitor the performance of the DCB, several monitoring instruments such as lysimeters, tensiometers and settlement plates, were installed. The post-construction saturated hydraulic conductivity (K_{sat}) of the DBP was 10^{-8} m/s. Analysis of settlement data layer and of density determinations on the DBP layer made during the construction phase made it possible to estimate the change in void ratio after 2 years and, consequently to determine the new K_{sat} value of the DBP. The latter was cross checked by means of field permeability tests using infiltrometers and by analyses of infiltration data from lysimeters. The reduction in hydraulic conductivity of the DBP layer results in a reduction of the infiltration rate arriving at the CB made of sand and gravel, which in turn increases the diversion length (DL). This results in lower infiltrations rates into the gravel, and consequently into the wastes.

RÉSUMÉ
Une parcelle expérimentale construite sur le site d'enfouissement de Saint-Tite-des-Caps, Québec, Canada a pour but d'évaluer l'efficacité d'une couverture avec effet de double barrière capillaire (CEDBC). Ce recouvrement alternatif inclut une couche de 0,60 m de sous-produit de désencrage (SPD), qui agit comme barrière hydraulique. Une barrière capillaire (BC), installée en dessous de la couche de SPD, est construite avec des matériaux grossiers : 0,4 m de sable comme couche de rétention capillaire et 0,2 m de gravier comme couche de bris capillaire. Pour faire le suivi de cette CEDBC, plusieurs instruments ont été installés, tel : lysimètres, tensiomètre et plaque de tassement. La conductivité hydraulique saturée (K_{sat}) du SPD après la construction était de 10^{-8} m/s. Les analyses des plaques de tassement et des densités de la couche de SPD déterminée lors de la construction permettent d'estimer l'indice des vides après 2 ans et, ainsi, de déterminer la variation du K_{sat}. Ces valeurs ont pu être vérifiées en analysant la moyenne des essais de perméabilité in situ utilisant un infiltromètre et par l'analyse des données d'infiltration des lysimètres. La réduction de la conductivité hydraulique du SPD entraîne la réduction du taux d'infiltration arrivant à la BC composé de sable et de gravier, entraînant de ce fait l'augmentation de la longueur de transfert (LT). Les infiltrations dans le gravier, et ainsi dans les déchets, sont ainsi diminuées.

1 INTRODUCTION

Land filled wastes are a source of two types of problems: (i) contamination of soil and groundwater caused by the production of leachate and (ii) the contribution to climate change (global warming) caused by the microbial decomposition of organic wastes that generate methane (CH_4) and carbon dioxide (CO_2). Therefore, the need of appropriate cover design becomes paramount. Several types of covers exist; the materials composing them depend on regulatory constraints, on the nature of the wastes and on climatic conditions. Covers with capillary barrier effect (CCBE) have been used in the last decade as an alternative cover design to reduce water infiltration into landfills (e.g. Kämpf et al. 1999, Parent and Cabral 2006(a)) or to prevent the migration of oxygen to acid producing mine tailings (e.g. Bussière et al. 2003, Cabral et al. 2004). The capillary barrier (CB) concept is still far from receiving widespread acceptance in the case of landfills; yet reports from many projects in Europe (e.g. Kämpf and Montenegro 1997) and North America (e.g. Khire et al. 2000) are helping to promote its use. The simplest CCBE design consists of a homogeneous layer of fine soil (moisture retaining layer, MRL) placed over a coarser soil layer (capillary break layer, CBL). When designing inclined CCBEs, the MRL has to divert water laterally (Stormont 1996, Parent and Cabral 2006(a)). Several authors (Hakonson, T., and al. 1994, Morris and Stormont 1998) pretend that simple CCBEs divert water laterally over distances shorter than 10 m. Such short diversion lengths (DL) are possibly due to the relatively low hydraulic conductivity (k) of the fine soil that does not drain laterally very well; over a short distance, the degree of saturation of the material becomes high enough causing the loss of the CB effect, i.e. water infiltrates downwards. An MRL with a higher k-value can divert water over greater distances, but will allow greater infiltration rates during periods of high surge. Again, this situation leads to loss of the CB effect. Parent and Cabral (2006(a)) suggested an alternative design of CCBE that includes a hydraulic barrier to control the rate of infiltration reaching an MRL constituted of sand. In this case, deinking by-products (DBP) were employed as hydraulic barrier, resulting in a double capillary barrier (DCB).

DBP is a highly compressible material (Parent et al. 2004), i.e. it undergoes significant settlement. Such condition has to be considered during the design of CCBEs. This paper elaborates on the findings of an analysis of settlement data obtained from monitoring an experimental DCB built at the Saint-Tite-des-Caps municipal waste landfill, Quebec, Canada. Furthermore, the performance of the DCB in terms of infiltration control and diversion capacity is analysed.

2 BACKGRAOUND

2.1 Deinking By-Products (DBP)

DBP are produced at the early stages of the paper recycling process. They consist of a spongy grey mass made of clay and fibres. They were traditionally considered as a waste material, but have recently been used as alternative geotechnical cover material for landfills (Kraus et al. 1997, Cabral et al. 1999(b), Burnotte et al. 2000, Kamon et al. 2002, Parent and Cabral 2006(a)), and mine waste top covers (Cabral et al. 1999(a)).

2.2 Basic Principles of Capillary Barriers (CB)

The basic physical principles of capillary barriers are well understood albeit not entirely intuitive: when infiltration through a layer of a relatively finer material (moisture retaining layer, MRL) reaches a layer of coarser material, if the suction at the interface is not low enough, water is held by capillarity within the finer-textured layer and is either evaporated out or flows downstream. In fact, this “natural” hydraulic break is due to the water retention properties of the materials and their associated hydraulic conductivity functions (*k-fct*). Beyond a certain level of suction, the *k*-value of the coarser material becomes lower than that of the finer material, thereby creating a “blockage” to downward flow; thus the term capillary break layer (CBL) for the coarse material layer. As more water gathers at the interface between the two layers, suction decreases and the capillary break may eventually be overcome at a certain distance from the top of the slope; the diversion length (DL).

The CBL of an ideal inclined capillary barrier should include a material within which capillarity forces are as weak as possible for the infiltration rate considered, whereas the MRL must be capable of developing the strongest capillarity forces possible, for the same infiltration rate. In addition, the MRL must be as permeable as possible, so that water is efficiently drained downslope and eventually collected.

Of the many design variables that can influence the overall performance of CCBEs, the unsaturated *k* and infiltration rate (that is dictated by climatic variables) are the most important. These two factors directly influence the choice of materials, the thickness of the layers, the maximum flow that can be transported through the finer-textured layer (diversion capacity) and the DL (Parent and Cabral 2006(a)).

One area that still deserves attention is the development of effective means to monitor the actual infiltration through capillary barriers. Many techniques and types of equipment are used, such as lysimeters (Parent and Cabral., 2006(b)), tensiometers, water content probes (Benson et al. 2001), etc. Large scale – field or laboratory - experiments have been attempting to use some of these means to evaluate the performance of capillary barriers; however, there still remains much work to be done to convince landfill designers and – mostly – regulators that CCBEs constitute a valid option.

2.3 Alternative Cover Including the Hydraulic Barrier

If materials such as sand and gravel are used as MRL and CBL, lateral drainage can be very efficient, but the capillary break becomes quite susceptible to high precipitation, i.e. the diversion capacity may be overcome quickly if it strong or continuous rainfall events occur. Thus the need to couple this system with an infiltration control layer (or hydraulic barrier), whose maximum infiltration rate is its saturated hydraulic conductivity, k_{sat}.

Since good hydraulic barriers are made of fine-textured materials, a capillary break is formed at the interface between the hydraulic barrier and the MRL (sand in the example above). However, the drainage capacity of the fine-textured material forming the hydraulic barrier may be limited, leading to a short DL.. Finally, in a DCB, one counts on the low k_{sat} of the hydraulic barrier, the lateral drainage capacity of the MRL and on the hydraulic break between the MRL and the CBL.

2.4 Settlement and hydraulic conductivity of deinking by-products

DBP is a soil-like material in which a fraction of the solid phase is prone to biodegradation and loss of solids due to physiochemical processes. From the mechanical point of view, the behaviour of DBP is somehow similar to that of organic soils; in particular, this material is submitted to important settlement and this for a long period of time (creep). In general the settlement is given by eq. 1:

$$s=H_0\,(\Delta e/1+e_0) \qquad [1]$$

where s represents settlement, H_0 is the initial layer thickness, e_0 is the initial void ratio and Δe is the change in voids ratio.

Settlement is directly related to hydraulic conductivity. The more a material settles, the lower its void ratio; accordingly, the lower is its *k*. For clay, a linear relationship can be set between void ratio and the logarithm of *k*. The relationship between *k* and void ratio is indicated by the C_k factor (Terzaghi et al. 1967) and can be given by eq 2. Robart (1998) reports a value of C_k between 0,43 and 0,97, for DBP

$$C_k=\Delta e/\Delta \log k \qquad [2]$$

In the design of capillary barriers, the k_{sat} of DBP is considered as the maximum infiltration rate that can enter the MRL. Thus, the evolution of the K_{sat} of DBP due to the settlement becomes an important parameter, as far as design is concerned. This also has implications in terms of layer thickness optimisation (Parent and Cabral 2006(a)), as well as in the design of infiltration control instrumentation, such as lysimeters (Parent and Cabral. 2006(b)).

According to Maltby and Eppstein (1994) study, during a six year period, a membrane of DBP exhibited 33% settlement compared to its initial thickness. In the laboratory, a consolidation of 18% was observed after two years by Quiroz et al. (2000). The results of a laboratory study using large samples, for which a load of 10kPa was applied, showed that DPB underwent 23 to 26% settlement after 56 months (Bédard 2005).

3 EXPERIMENTAL INCLINED DCB

3.1 Cover Configuration

The dimensions of the current experimental cover, built at Saint-Tite-des-Caps municipal landfill; Quebec; Canada; are 30 m (length) by 10 m (width). The cell was built in the late summer of 2005 but its performance has only been monitored since May 2006. Instrumentation includes 6 zero-tension lysimeters (Parent and Cabral. 2006(b)) for measuring flow rates, EC5-ECH$_2$O water content probes (connected to data loggers), 3 settlement plates, and 16 conventional tensiometers (10 UMS Model T4 and 6 Model LT from Irrometer Company) connected to dataloggers (DL6, from Delta-T Devices; and irrometer RSU for the Irrometers). The tensiometers were installed within the DBP layer and along the DBP/Sand and Sand/Gravel interfaces. Three of them were installed to verify the reliability of the lysimeters (see explanation hereafter).

As indicated in Figure 1, 3 lysimeters were installed in the gravel layer, whereas 3 others were placed in the sand layer. Water collected in the latter permit evaluating the infiltration rate from the DBP layer, whereas the lysimeters in the gravel layer permits evaluating the net infiltration into the waste mass. A weather station completes the instrumentation; Figure 1 shows some of the instruments installed at St-Tite cell.

3.2 Hydraulic properties of the materials used in the DCB

A capillary barrier is designed based on the following parameters: (1) the dip and length of the slope; (2) the *k-functions* of the materials constituting it (which includes the k_{sat}); and (3) the maximum acceptable infiltration rate. To obtain the design water diversion capacity, given an realistic percolation rate, the materials and/or layer thicknesses have to be chosen accordingly. The relevant parameters must be determined are: the saturated and residual water contents, the air-entry-value (AEV), and the desaturation slope. Figure 2(a) presents the Water retention curves (WRC) of the selected gravel, sands and DBP tested (Lacroix Vachon et al. 2007). This study is based of the drying curve data. However, Morris and Stormont (1998) argue that the simulations using the wetting curve data provide a better representation of the reality in the field.

The k_{sat} was obtained initially in the laboratory (10^{-8} m/s), but later this value was confirmed by in-situ tests using a mini-disk infltrometer (Decagon Devices Inc.). The unsaturated hydraulic conductivities as a function of suction head of the materials used in the alternative cover are given in Figure 2(b).

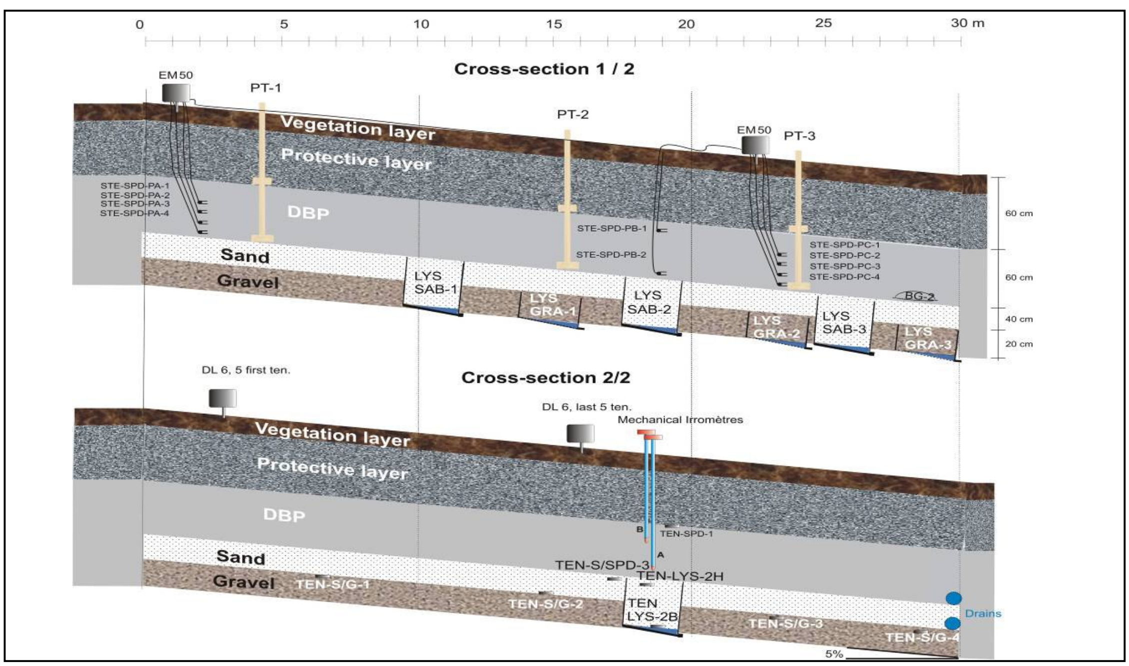

Figure 1. Profile of the double capillary barrier at the experimental site and some of the instruments installed

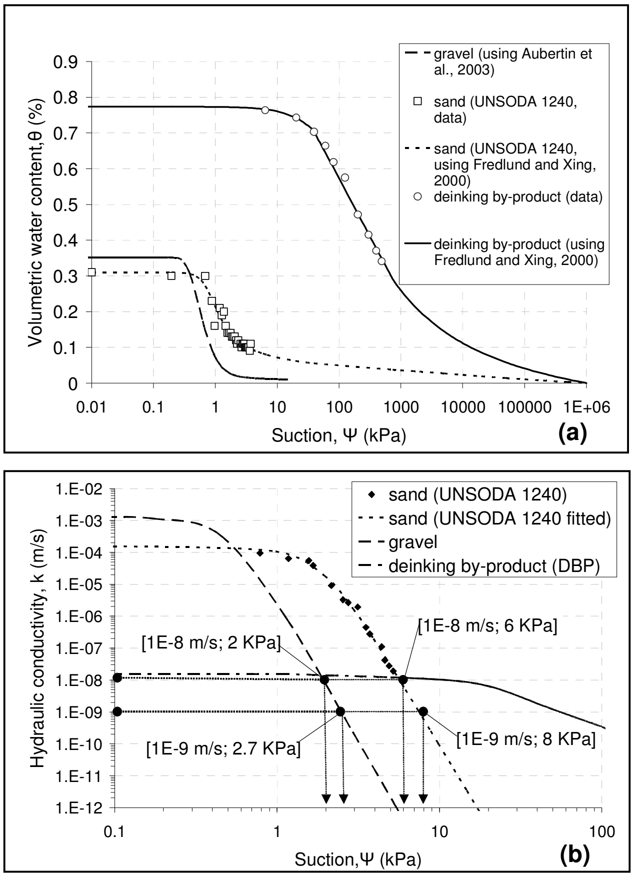

Figure 2. (a) Water retention curve (WRC) of the materials tested for the DCB; (b) *k*-fct for the same materials.

4 RESULTS AND DISCUSSION

Materials, layer thicknesses, and all other design parameters were selected in such a way that the DL would be attained right before 30 meters, i.e. the length of the DCB. .Several alternative covers were tested by means of numerical simulation using *SEEP/W* (Parent and Cabral 2006(b)). The 5% slope value was selected as a representative of the natural slope of the actual cover at the St-Tite experimental plot. The other design starting point was the k_{sat} of the DBP (10^{-8} m/s) that is equal to the design-acceptable infiltration rate entering MRL. It is evident that infiltration rates are directly affected by changes of k_{sat}. Herein, this phenomenon is analysed and its impacts on the DL is discussed.

4.1 Variation of the Hydraulics Properties of the DBP

4.1.1 Decrease in *k* estimated from settlement plate data

Based on monitoring data from the 3 settlement plates (SP) and using equations 1 and 2, the change in k_{sat}, during two years, was calculated. The results of sand cone tests performed during the construction phase make it possible to calculate the initial void ratio of the DBP, at the proximity of each plate (Table 1). The load due to the protective layer was estimated to be about 12 KPa. According the undergone research related to the consolidation properties of DBP (consolidometer tests under different loading levels), the C_k value would be closer to 0.7.

Table 1. Characteristics of DBPs that corresponds each settlement plate

	Initial dry density ρ_s (kg/m^3)	Initial void ratio e_0	C_k
Settlement plate # 1(PT1)	598	2.34	0.7
Settlement plate # 2 (PT2)	598	2.34	0.7
Settlement plate # 3 (PT3)	633	2.16	0.7

Figure 3 illustrates the relationship between hydraulic conductivity and void ratio for DBP. In 2005, the K_{sat} obtained in the laboratory was 10^{-8} m/s. In 2007, this factor decreased by one order of magnitude to reach 10^{-9} m/s. The change in k_{sat}, caused by physical compression and creep, was confirmed by water content probes, infiltration data from lysimeters installed in the sand layer and from direct infiltrometer tests. This paper does not address all other potential reasons for the decrease in k_{sat} than settlement of DBP. The results for SP-3 differ form the other two, because the region around had to be re-excavated; recompaction of a small region led to a different initial density, thus a different initial void ratio.

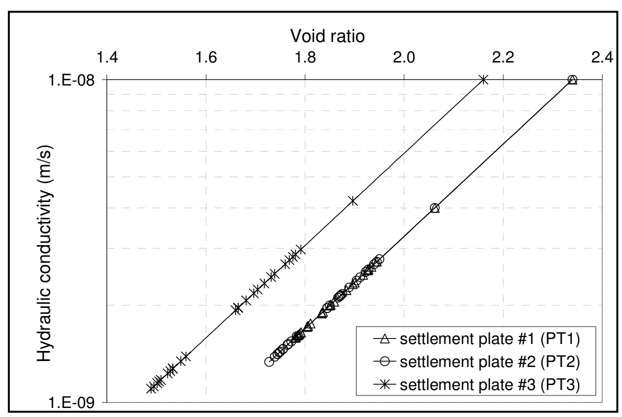

Figure 3. Relationship between hydraulic conductivity of and void ratio of DBP (data from the last two years)

4.1.2 Water Retention Curve (WRC)

Due to its high fibre content, DBP possess a reasonable water holding capacity. Indeed, monitoring data confirms that the DBP layer remained at a very high degree of saturation since the beginning of the monitoring period.

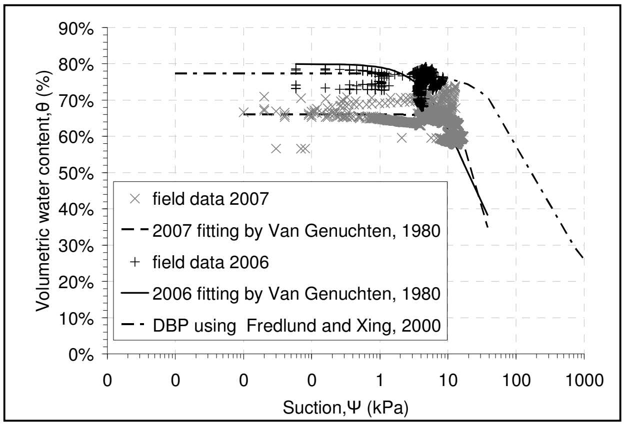

Figure 4. Comparison between the available water content measurements for 2006 and 2007 and the WRC determined using different models.

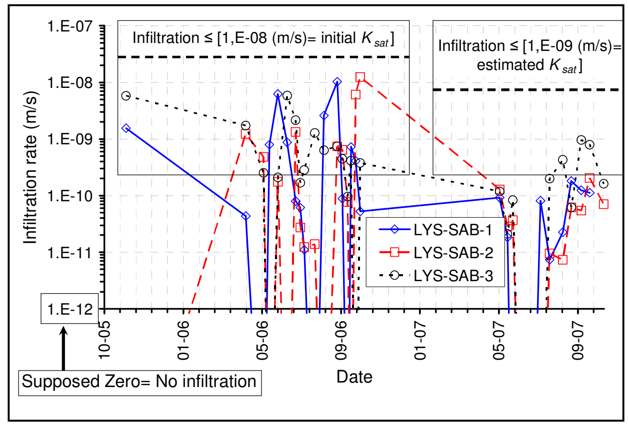

Figure 5. Evolution of Infiltration rates by lysimeters installed in the sand layer, during two years

Figure 4 shows the WRC of DBP obtained using different models. Field data (water content and suction) was plotted on the same graphic and show that a clear shift of the WRC, i.e. as settlement progresses, lower values of θ are obtained for a same value of ψ.. For illustrative purposes, Table 2 shows the fitting parameters used for the Van Genuchten model (van Genuchten 1980). The downward shift of the WRC leads to a similar downward shift of the k-fct of the material; i.e. for similar suction values, low k-values are obtained.

Table 2. Fitting parameters of Van Genuchten model

Date	α	M	n	θ_s
2006	0.1133	0.346	1.529	0.80
2007	0.03541	0.618	2.617	0.661

4.1.3 Infiltration rates using lysimeters and water content probes

The zero-tension lysimeter used in this study is a container placed at the desired depth within the cover system that captures infiltrating water. The bottom of the container is connected to a pipe that diverts water to a collection device at atmospheric pressure. Design and installation of this type of lysimeter is elaborately described by Parent and Cabral (2006(b)).

As mentioned earlier, the admissible infiltration rate, i.e. the rate that the MRL (sand layer) can evacuate laterally without letting water infiltrate into the CBL (gravel layer), is controlled by he K_{sat} of the DBP. Weather station data showed that the total precipitations in 2006 and 2007 are by all practical means equal (532 mm for 2006& 581 mm for 2007).

Figure 5 presents infiltration rate data obtained from the 3 lysimeters installed in the sand layer. Throughout 2006, the maximum infiltration rate did not exceed 10^{-8} m/s whereas in 2007, the maximum attained was 10^{-9} m/s. This observation tends to confirm the impact of settlement on k_{sat}, thus on infiltration rates.

In order to verify the reliability of the lysimeters, the evolution of suction values in TEN-LYS-2H and TEN-S/SPD-3 were compared. As indicated in Figure 1, these two tensiometers are at the same level, one being at the center of the lysimètre, whereas the other is just outside of its rim. Figure 6 shows that, in 2006, suction values in the two tensiometers are practically most of the time, the same, indicating that the lysimeter design is appropriate; i.e. infiltrating water is not by-passing the lysimeter. During certain periods (e.g. early July 2006), differences in suction readings were mainly due to desaturation of the tensiometers. Suction values registered by the tensiometer placed at the bottom of the lysimètre (TEN-LYS-2B; Figure 1) are approximately zero most of the time, indicating that ponding occurred only for very short periods of time.

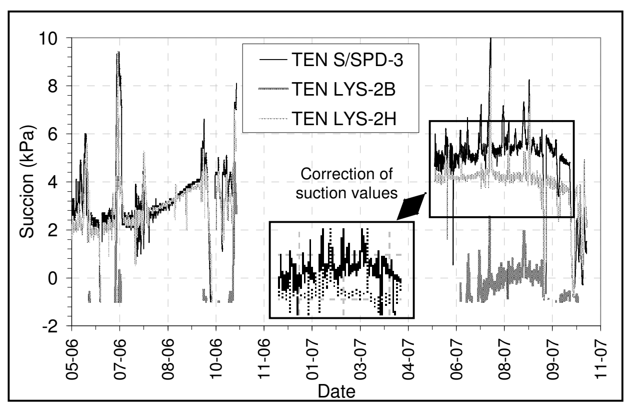

Figure 6. Evolution of suction in tensiometers TEN-S/SPD-3, TEN-LYS-2H and TEN-LYS-2B (Figure 1)

During periods in 2007, considerable divergence in suction readings between TEN-LYS-2H and TEN-S/SPD 3 is observed. There are two scenarios for explaining this difference: In the first, the lysimeter did not function as anticipated due to the change in the *k* of DBP that lead to lower infiltration rates. With lower infiltration rates, suctions at the top of the lysimeter are lower than those outside of it (for the same elevation); as a consequence, water deviates (avoids) the lysimeter. In order to collect as much infiltration as outside, the lysimeter walls would have to be higher.

The difference can also be explained by a certain level of clogging at the exit of the lysimeter. Indeed, positive pore pressures were registered more often in 2007 than in 2006. When this occurs, suctions at the top are lower than outside, such as in scenario 1. In fact, it is highly probable that a combination of the two has caused the difference in readings obtained (Figure 6).

As indicated in the insert in Figure 6, a correction was made to the readings for lysimeter TEN-LYS-2H; in this case, the suction was increased by a value equivalent to the positive water pressure registered at the base (TEN-LYS-2B). This is equivalent to increasing the wall height. Despite this correction, a difference remains for certain periods, which can be explained by the decrease in infiltration rates during these periods. Further investigation is presently under way about this issue. One preliminary conclusion, however, is that a factor of safety related to consolidation of the DBP would have to be considered in the initial design of the lysimeters.

4.1.4 In-situ permeability tests

Several in-situ permeability tests were performed in the DBP layer using a handheld Mini-disk Infiltrometer (Decagon). The tests were performed in the vicinity of the experimental plot, where DBP were used as final cover for a 3-hectare cell at the St-Tite-des-Caps landfill. Table 3 shows that the k-value of DBP decreased by nearly one order of magnitude from 2006 to 2007, confirming the calculations made.

Table 3. Results of Mini-Disk infiltrometer tests realized of the DBP outside of experimental cell

Test number	Measured *K (m/s)* in 2006	Measured *K (m/s)* in 2007
1	3.76E-08	2.29E-08
2	1.88E-08	7.73E-08
3	2.82E-08	3.43E-09
4	6.59E-07	1.87E-09
5	3.20E-07	2.29E-08
6	1.87E-08	7.35E-09
Average value of *K (m/s)*	1.56E-07	2.26E-08

4.2 Performance of the DCB

Analysis of the amounts of water collected in the lysimeters installed in the gravel layer permits to verify whether or not the DCB performs as designed, i.e. if the equivalent *k* of the system (equal to the rate of infiltration into the waste mass) is lower than what is usually required by regulation. It also permits to verify if the method adopted to estimate the DL is precise enough and how the DL is affected by the observed decrease in K_{sat} of the DBP, due to consolidation/creep.

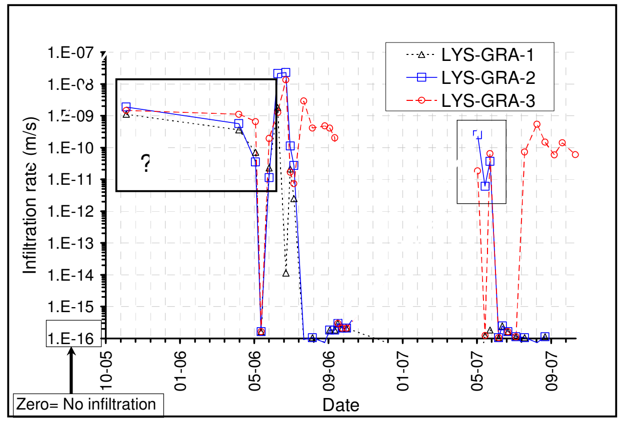

Figure 7. Evolution of infiltration rates by lysimeters installed in the sand layer, during two years

Figure 7 presents the measured infiltration rates in the 3 lysimeters installed in the gravel layer. LYS-GRA-2 and LYS-GRA-3 were respectively installed at 24 and 30 meters from the top of the slope (Figure 1). For most of 2006, the infiltrations collected by these two lysimeters are quite similar. Consequently, the DL must to be shorter than 24 m. However at 2007, apart from the month the LYS-GRA-2 remained dry. This means that the DL increased as a result of a decrease in the *k*-value of DBP. For 2007, the minimum DL value is 24 m.

In order to more precisely determine the DL, data from the four tensiometers placed along the sand/gravel interface were analyzed for different periods of intermittent to intense precipitation.

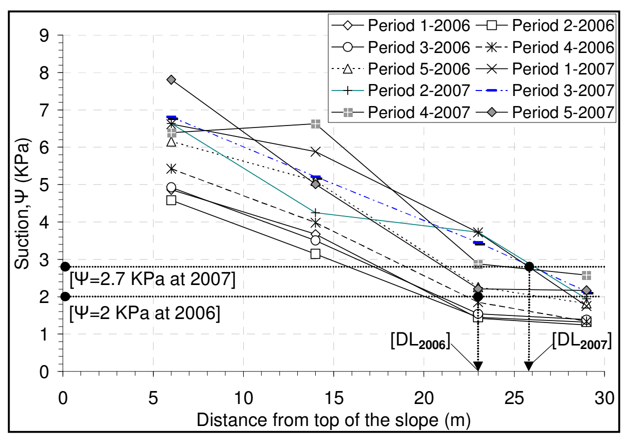

Figure 8. Evolution of suction along the sand/gravel interface for several periods of 2006 and 2007

The results, presented in Figure 8, show that suction values decrease towards the toe of the slope and, in 2006, start to stabilize at approximately the 24-meter mark for all the periods. This indicates that the DL has been attained (Lacroix Vachon et al. 2007). This means that, when the suction value in the sand/gravel interface reaches 2KPa, the sand layer is no longer capable of transferring laterally. In Thus, in 2006, the DL reaches close to 24-meter and after this distance, the suction value start to stabilize.

In 2007, following the decrease in k_{sat} of the hydraulic barrier, the infiltration rate changes, causing an increase of the DL. Higher suctions are now found in the sand layer both at upstream part (6 to 8 kPa) and downstream part (~2.7 kPa) of the DCB. Theoretically the DL must increase as the infiltration rate decreases. It can be observed in Figure 8 that, apart period 4 in 2007, the suction value in the sand/gravel interface, shows no sign of stabilization at 24-meter mark.

5 CONCLUSION

An experimental landfill cover including a hydraulic barrier constituted of deinking by-products (DBP) and a capillary barrier constituted of a layer of sand superimposed on a layer of gravel was constructed at the Saint-Tite-des-Caps municipal landfill. This study analyzed some aspects of the performance of this alternative landfill cover design. The main performance criteria analyzed were the maximum rate of infiltration into the waste mass and the transfer length.

The instrumentation used in the field included tensiometers, lysimeters, settlement plates, and a weather station. Tensiometers placed outside and inside the lysimeters permitted to confirm that the latter are working properly, i.e. that there is no horizontal hydraulic gradient between the interior and the exterior of the lysimeter.

Analysis of settlement plate data shows that during the two years of monitoring, the k_{sat} of the DBP decreased by approximately one order of magnitude, from 10^{-8} m/s to 10^{-9} m/s. This decrease in k_{sat} can be validated using the amounts of water collected in the lysimeters installed in the sand layer. The reduction of K_{sat} causes a reduction in the infiltration rate into the sand layer, which leads to an increase in the diversion length, which, according to this study was slightly lower than 24 m in 2006 and became greater than 24 m in 2007. In other words, the alternative cover becomes even more performing with time, being able to prevent water from reaching the waste mass at greater distances.

The settlement of the hydraulic barrier and the consequent decrease in k is an important parameter to take into account, as far as design is concerned. k is also the design infiltration rate reaching the capillary barrier, over which a hydraulic barrier is superimposed. A decrease in k affects the magnitude of the DL, but also affects the required thickness of MRL and CBL, and affects the performance of lysimeters. In the case of the latter, higher walls become necessary if one uses them as means to monitor performance.

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REFERENCES

Bédard, D. 2005. Effet du fluage à long terme des sous-produits de désencrage dû à la perte de masse et son effet sur la compression et la conductivité hydraulique (effect of creep of DBP due to mass loss and impact on the compressibility and hydraulic conductivity). M.Sc.A, Université de Sherbrooke, Sherbrooke.

Benson, C., Abichou, T., Albright, W., and Gee, G. and Roesler, A. 2001. Field evaluation of alternative earthen final covers, International Journal of Phytoremediation, 3: 105-127.

Bussière, B., Aubertin, M., and Chapuis, R.P. 2003. The behaviour of inclined covers used as oxygen barriers, Canadian Geotechnical Journal, 40: 512-535.

Burnotte, F., Lefebvre, G., Cabral, A., Audet, C., and Veilleux, A. 2000. Use of deinking residues for the final cover of a MSW landfill. *In* 53rd Canadian Geotechnical Conference, Montreal, Vol. 1, pp. 585-591.

Bussière, B., Aubertin, M., and Chapuis, R.P. 2003. The behaviour of inclined covers used as oxygen barriers, Canadian Geotechnical Journal, 40: 512-535.

Cabral, A.R., Lefebvre, G., and Burnotte, F. 1999(a). Caractérisation de la membrane de recouvrement de résidus de désencrage du site minier clinton - analyse finale de données recueillies jusqu'en décembre 1998. Université de Sherbrooke, Sherbrooke.

Cabral, A.R., Lefebvre, G., Burnotte, F., Panarotto, C.T., and Pastore, E. 1999(b). Use of pulp and paper residues as an alternative cover material to landfill and to acid generating tailings. *In* 2º Seminario de Meio Ambiente em Industrias de Processo, Sao Paulo, Brazil, pp. 56-70.

Cabral, A.R., Planchet, L., F.A., M., and Lefebvre, G. 2004. Determination of the soil water characteristic curve of highly compressible materials: Case study of pulp and paper by-product, Geotechnical Testing Journal, 27: 154-162.

Hakonson, T., and al. 1994. Hydrologic evaluation of four landfill cover designs at hill airforce base, utah. *rep. no. LAUR-93-4469*. Livermore, Calif.

Kamon, M., Inazumi, S., Rajasekaran, G., and Katsumi, T. 2002. Evaluation of waste sludge compatibility for landfill cover application, Soils & Foundations, 42: 13-27.

Kämpf, M. and Montenegro, H. 1997. On the performance of capillary barriers as landfill cover, Hydrology and Earth Systems Sciences, 4: 925-929.

Kämpf, M., Holfelder, T., and Montenegro, H. 1999. Designing capillary barriers. *In* 7th international waste management and landfill symposium, Sardina, pp. 381-388.

Khire, M.V., Benson, C.H., and Bosscher, P.J. 2000. Capillary barriers: Design variables and water balance, Journal of Geotechnical & Geoenvironmental Engineering, 126: 695-708.

Kraus, J.F., Benson, C.H., Van Maltby, C., and Wang, X. 1997. Laboratory and field hydraulic conductivity of three compacted paper mill sludges. Journal of Geotechnical and Geoenvironmental Engineering, 123: 654-662.

Lacroix Vachon, B., El-Ghabi, B., and and Cabral, A.R. 2007. Évaluation préliminaire de l'efficacité du recouvrement avec double effet de barrière capillaire installé au site de st-tite-des-caps, qc. *In* , Ottawa.

Maltby, V. and Eppstein, K. 1994. A field-scale of the use of paper industry sludges as hydraulic barriers in landfill cover systems. *In* Hydraulic Conductivity and Waste Contaminant Transport in Soil *Edited by* American Society of Civil Engineers. Philadelphia, pp. 546-558.

Morris, C. and Stormont, J. 1998. Evaluation of numerical simulations of capillary barriers, Geotechnical and Geoenvironmental Engineering, 16: 201-213.

Parent, S. and Cabral, A.R. 2006(a). Design of inclined covers with capillary barrier effect, Geotechnical and Geological Engineering Journal, 24: 689-710.

Parent and Cabral., 2006(b). Design and installation of zero-tension lysimeters in an inclined cover. *In Unsaturated Soil Conference*, Carefree, Arizona

Parent, S., Cabral, A.R., Dell'Avanzi, E., and Zornberg, J.G. 2004. Determination of the hydraulic conductivity function of a highly compressible material based on tests with saturated samples, Geotechnical Testing Journal, 27: 1-5.

Quiroz, J.D., Simpson, P.T., and Zimmie, T.F. 2000. Evaluation of paper sludge landfill cover settlement. *In* , Reston, Vol. 10, pp. 16-31.

Robart, G. 1998. Étude de la perméabilité de la compressibilité des résidus de désencrage (study of the permeability and compressibility of deinking residues). Master, Université de Sherbrooke, Sherbrooke.

Stormont, J.C. 1996. The effectiveness of two barriers on a 10% slope capillary, Geotechnical and Geological Engineering, 14: 243-267.

Terzaghi, K., Peck, R.B., and Mesri, G. 1967. Soil mechanics in engineering practice. New York.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Science Society of America Journal, 44: 892-898.