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Characterizing the ageing of a geosynthetic clay liner through electrical resistivity

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Abstract: In closed hazardous waste landfills, impermeable layered covers mainly composed of clays, geosynthetic clay liner (GCL) or geomembrane, etc. are used to seal in the waste to minimize water infiltration and accumulation of leachate inside the waste. An experimental site of landfill cap was realized with sodium-activated calcium bentonite GCL at a depth of 0.45 m covered by gravels and top soil. The monitoring of this site was performed during 32 months with measurements of weather conditions, and electrical resistivity tomography (ERT) and geotechnical measurements at the end of the monitoring. The two different methods underlined that the GCL's electrical resistivity decreased after 22 months subsequent to its installation; moreover, it was possible to detect the defects that had been made in the GCL prior to closure, to simulate factors affecting GCL performance. Thereby the analyses made on the GCL samples taken at two locations in the vicinity of the ERT profile highlighted changes in the intrinsic properties of the material. Changes in the proportion of sodium and calcium cations occurred and its hydraulic conductivity increased from 5×10^{-11} to 3×10^{-6} m/s. Thus, this study shows that electrical resistivity is suitable to characterize the ageing of a GCL.

Key words: geosynthetic clay liner (GCL), electrical resistivity tomography, landfill cover, hydraulic conductivity, cation exchange.

Résumé : Sur les installations de stockage de déchets dangereux, des couvertures imperméables composées d'argile parfois accompagnées de GSB (géocomposite synthétique benthonique contenant de la bentonite calcique activée au sodium) ou de géomembrane, sont mises en place pour isoler les déchets des infiltrations d'eau et diminuer la quantité de lixiviat. Un site expérimental contenant un GSB à 0.45 m de profondeur, surmonté par des graviers et de la terre végétale, a été mis en place. Ce site équipé d'une station météorologique et de mesure d'humidité a fait l'objet d'un suivi temporel de 32 mois, et d'une caractérisation par tomographie de résistivité électrique et géotechnique en fin de suivi. Les mesures géophysiques montrent que la résistivité électrique du GSB décroit fortement 22 mois après sa mise en place; de plus, des défauts mécaniques créés à travers le GSB au moment de la construction deviennent détectables. Les analyses réalisées sur deux échantillons de GSB prélevés à proximité du profil de mesure démontrent, quant à elles, un changement des propriétés du matériau. Ainsi les proportions de cations calciques et sodiques diffèrent de celles du GSB initial témoignant d'échanges cationiques et s'accompagnent d'une augmentation de la perméabilité hydraulique, passant de 5×10^{-11} à 3×10^{-6} m/s. Cette étude montre ainsi que la résistivité électrique permet de mettre en évidence le vieillissement du GSB.

Mots-clés : géocomposite synthétique benthonique (GSB), tomographie de résistivité électrique, couverture d'installations de stockage de déchets, conductivité hydraulique, échanges cationiques.

Introduction

In France, landfill sites are subject to very strict monitoring procedures according to well-established legislation. In the case of landfills that store dangerous waste (known in France as ISDDs, for example chemical, hospital, industrial waste), monitoring after their closure is obligatory, as laid out in the *Journal Officiel de la République Française* (La République Française 1993) of 18 December 1992. This consists in particular in collecting and treating biogas and leachate. As leachate treatment represents a significant cost for landfill managers, minimizing the quantity of leachate produced is essential. At this type of site, the production of leachate is limited essentially by the addition of an impermeable cap whose watertight properties are ensured by a layer of clay along with either a geosynthetic clay liner (GCL) (Bouazza 2002) or a geomembrane. Unusually large increases in the quantity of leachate produced by old landfill sites following rain events raise questions over the origin and the nature of factors affecting GCL performance since their closure. Melchior (1997), Cazzuffi et al. (2005), Zanzinger and Touze-Foltz (2009), Benson et al. (2010), and Camp et al. (2010) have shown that poor performance over the years could be due to mechanical, climatic, and hydraulic stresses or ageing . Given the need to perform some kind of remediation on these caps, it would seem of primary importance to be able to identify the consequence of ageing and the location of such damage.

So a research program was established to test various nondestructive geophysical methods capable of pinpointing the GCL performance. Three geophysical methods have been tested (electrical resistivity tomography (ERT), self-potential, and automatic resistivity profiling); it has been shown that the ERT method is currently the most promising (Genelle et al. 2014). To study ageing in the cap, an experimental site was constructed to replicate two impermeable covers (Genelle et al. 2012; Sirieix et al. 2013). In this article, the results of the research into the ageing and mechanical

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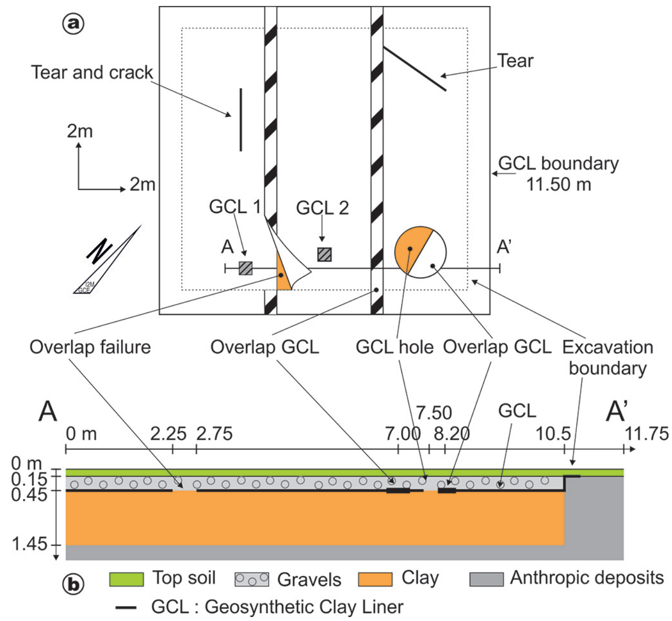
Fig. 1. Location of studied area.

Fig. 2. (*a*) Plan overview; (*b*) section of landfill experimental site.



defects of an experimental landfill cap fitted with a GCL are presented. ERT measurements were taken over less than a 3 year period and under various different climatic conditions. ERT is a geophysical technique for imaging subsurface structures. The measurements are taken at surface by electrodes. Current is injected in the soil between two electrodes and the potential is measured between two others electrodes. Taking into account the geometrical aspect, the apparent resistivity was calculated. With many points of measurement and different distances between electrodes, a two-dimensional (2D) image of apparent resistivity was obtained. Next, data must be inverted to obtain a tomography (2D) of the resistivity of the soil. Two methods of data inversion were employed to estimate the electrical resistivity of the GCL, namely RES2DINV and particle swarm optimization (PSO). The aim of this research was to highlight changes in the electrical resistivity of a GCL over time. Given the initially very high resistivity (Beck 2011) and low thickness of such materials, characterizing them is a challenge for geophysicists. Samples of the GCL exhumed from the site almost 3 years after its installation were characterized in a laboratory (hydraulic conductivity, cation exchange, thickness), and these results were compared to the electrical resistivity values.

Description of experimental site

An experimental site was constructed in September 2009 near Angoulême (France), in an urban environment and an oceanic climate (Fig. 1). A plot 11 m by 12 m was dug 0.85 m down into anthropogenic deposits and alluviums (Fig. 2). To represent an impermeable cover measuring 1.45 m thick, the constituent materials from top to bottom were as follows:

- 0.15 m of top soil
- a geotextile separating layer
- 0.30 m of gravel
- a 0.006 m thick GCL (as it was measured, see section titled "Electrical resisitivity tomography (ERT) measurements")
- 1.0 m of gravelly clay material

This gravelly clay material came from land 10 km from the site. These ancient alluviums were composed of silts, plastic clay, and gravel. The GCL (Bentomat AS3700) was made up of two layers of geotextile separated by sodium-activated calcium bentonite. The GCL is characterized by a level of permeability when new of less than 5×10^{-11} m/s according to the product specification sheet. The 5 m wide GCL was installed according to the recommendations of the Comité Français des Géosynthétiques (2011). The strips of GCL were made to overlap each other by about 0.5 m, and a 0.1 m wide band of bentonite powder was placed where they joined. Furthermore, the gravelly clay material was watered prior to the installation of the GCL to help with its hydration (Rayhani et al. 2011). Before covering it over with a layer of gravel, defects were made in the GCL (Fig. 3). Four defects were made – (*i*) a simple tear (length 3 m and width 0.05 m), (*ii*) a tear plus a crack in the gravelly clay material underneath (length 2.5 m, width 0.04 m), (*iii*) a hole in GCL (diameter 2 m), and (*iv*) failure of the GCLs to overlap (see Fig. 2*a*). Several geophysical methods were tested under different climatic conditions with the aim of studying their ability to detect these defects (Genelle 2012).

A weather station was also installed near the experimental site. Cumulative effective rainfall and average atmospheric temperatures are given over a 7 day period prior to each geophysical survey (Table 1). Effective rainfall was defined as precipitation minus evapotranspiration (Gilli et al. 2008), the latter being estimated using the Food and Agriculture Organization (FAO) Penman–Monteith equation (Allen et al. 1998).

Measurements taken at the experimental site

Of the eight geophysical measurements performed at the site between September 2009 and May 2012, the five viewed as most significant from the standpoint of the different weather conditions pertaining at the time will be presented. Additional measurements can be found in Sirieix et al. (2013) and Genelle (2012).

Weather conditions

The measurements presented herein were performed under a diverse set of weather conditions. The measurements from 4 February 2010 were taken against the background of effective rainfall of 6.4 mm and average temperature of 2.8 °C over the preceding 7 days (Table 1). The measurements from 28 September 2010 took place following a hot dry summer (with a –6.9 mm

Fig. 3. Some details of the site construction: (*a*) GCL installation; (*b*) GCL hole; (*c*) gravel installation.

Table 1. Meteorological conditions preceding each survey.

Date of the survey	Over the week preceding each survey: Effective rainfall (mm)	Over the week preceding each survey: Average atmospheric temperature (°C)
4 February 2010	6.4	2.8
28 September 2010	−6.9	15.4
22 July 2011	29.2	17.0
29 July 2011	−7.2	18.3
10 May 2012	−12.9	15.3

cumulative effective rainfall over the preceding 7 days). It is interesting to note that this survey was carried out under weather conditions that were quite similar to those of the 29 July 2011, albeit with a slightly lower average temperature (15.4 °C rather than 18.3 °C). In contrast, the survey dated 22 July 2011 differs from the others in that the effective rainfall was higher over the 7 days prior to the measurements being taken at 29.2 mm. Lastly, the survey from 10 May 2012 was performed under climatic conditions that were fairly comparable to those of 29 July 2011 and 28 September 2010.

Electrical resistivity tomography (ERT)

This geophysical method is used to characterize the electrical resistivity of subsoil and enables researchers to create a 2D map of the ground being studied for example to map landfill geometry (Reynolds and Taylor 1996; Bernstone et al. 2000) or to characterize contaminated plumes (Chambers et al. 2006; Gallas et al. 2011), to define the nature of materials and waste at a site (Guérin et al. 2004; Boudreault et al. 2010).

At the study site, the measurements were performed by installing 48 stainless electrodes (rods 0.3 m in length and 0.01 m in diameter) placed up to a depth of 0.10 m and reinstalled for each survey, with a 0.25 m electrode spacing. The ERT profile AA' (in Fig. 2*a*) was marked out using two stakes placed permanently at each end of the profile. The electrodes were then connected to a fast multichannel resistivity meter with a Syscal Pro (IRIS Instruments) using a dipole–dipole array.

Characterization of the geosynthetic clay liner (GCL)

On 11 May 2012, that is to say 32 months after its installation, samples of the GCL were exhumed with samples of the gravel (Fig. 4). The samples of the GCL were taken at a distance of 0.8 and 4 m, respectively, from point A, one directly on the profile AA' (labelled GCL_1 in Fig. 2*a*) and the other one in close proximity to it (labelled GCL_2 in Fig. 2*a*). From these samples 0.39 m by 0.54 m, measurements of saturated hydraulic conductivity, water content, swell index, and composition of the exchange complex were performed in the laboratory according to AFNOR standards (AFNOR (1999) NF X 31-130, AFNOR (2002) XP P84-703, and AFNOR (2008) NF P 84-705).

In addition, the same analysis was carried out on a virgin sample of the GCL (labelled GCL_0) that had been left outside under a tarpaulin during several months (close to the site).

Methods for estimating electrical resistivity of the GCL

Two methods of inversion were used to estimate the bulk resistivity of the GCL (Sirieix et al. 2013), something that is problematic due to it being so thin (6×10^{-3} m) and to its very high resistivity (higher than 10^5 ohm·m).

ERT surveys were first inverted using the commercial software RES2DINV (Loke and Barker 1995). The best results were obtained with forward modelling using the finite difference module with model refinement, and the inversion using the L1 norm smoothness-constrained optimization method (Loke et al. 2003).

In this case, the use of the principle of equivalence is necessary (Maillet 1947) to interpret the value of resistivity: when a layer is bound by two conductive layers, the product of its resistivity by its thickness is a constant. As the GCL is situated between two conductive layers and the true thickness of the GCL (6×10^{-3} m), its resistivity, and its thickness on the inverse model resistivity were known, it was possible to estimate the bulk resistivity of the GCL (Table 2).

Fig. 4. (*a*) Sampling of GCL; (*b*) view of gravelly clay material, GCL, and gravels after a GCL's sample.

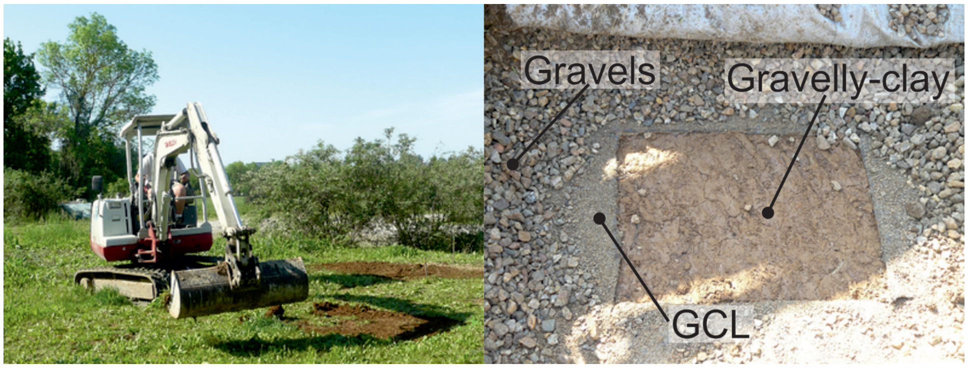


Table 2. Estimation of GCL resistivity from ERT dipole–dipole inversion and from PSO inversion at 4 m from the beginning of the ERT profile.

			GCL resistivity (ohm·m)	
Date of the survey	GCL inverted resistivity (ohm·m) ERT	Thickness inverted (m) at 4 m ERT	Estimated for a GCL thickness of 6 mm ERT	Inverted by PSO, at 4 m (median value)
4 February 2010	5500	0.5	$4.58{\times}10^5$	$3{\times}10^5$
28 September 2010	13 000	0.7	$15.2{\times}10^5$	$10{\times}10^5$
22 July 2011	2300	0.3	$1.15{\times}10^5$	$0.4{\times}10^5$
29 July 2011	1300	0.6	$1.30{\times}10^5$	$0.4{\times}10^5$
10 May 2012	2400	0.3	$1.20{\times}10^5$	$0.52{\times}10^5$

The second method used to perform the inversion was the PSO (Fernández Martínez and García Gonzalo 2009; Fernández Martínez et al. 2010). The software used was designed to invert the one-dimensional (1D) vertical electrical sounding (VES) in Schlumberger array. So the VES was extracted on an homogeneous place along the profile measured in dipole–dipole array (4 m from the beginning of the profile), previously transformed in Schlumberger array (Patella 1974 in Sirieix et al. 2013).

Results

Electrical resistivity tomography (ERT) measurements

The models of ERT along profile AA′ initially show a succession of three horizons (Fig. 5):

- A first conductive horizon that is not very thick and that corresponds in part to the top soil.
- A second horizon that is highly resistive and whose thickness changes over time. This is attributed in part to the layer of gravel overlying the GCL and the GCL (Sirieix et al 2013); no limit can be clearly identified between gravel and GCL. That can be explained by the so called the principle of suppression (Maillet 1947): a thin layer of small resistivity in contrast with respect to the background will be missed, the layer will then be averaged into on overlying or underlying layer in the interpretation. That is why, the gravel layer with intermediate resistivity between top soil and GCL cannot be distinguished on ERT images.
- A final conductive horizon that is not very wide on the first measurements (between 4 and 7 m on the profile in Figs. 5*a*, 5*b*) and that is associated with the gravelly clay material laid under the GCL.

Based on these ERT models, previous results (Genelle 2012) have shown that the GCL properties are estimated as a high resistivity and greatly overestimated thickness. These results have been corrected by applying Maillet's principle of equivalence to arrive at a more realistic estimate of the bulk resistivity of the GCL. Following the samples from May 2012, a thickness of 6 mm (taken from measurements of the GCL samples) was chosen for the calculations (Table 2).

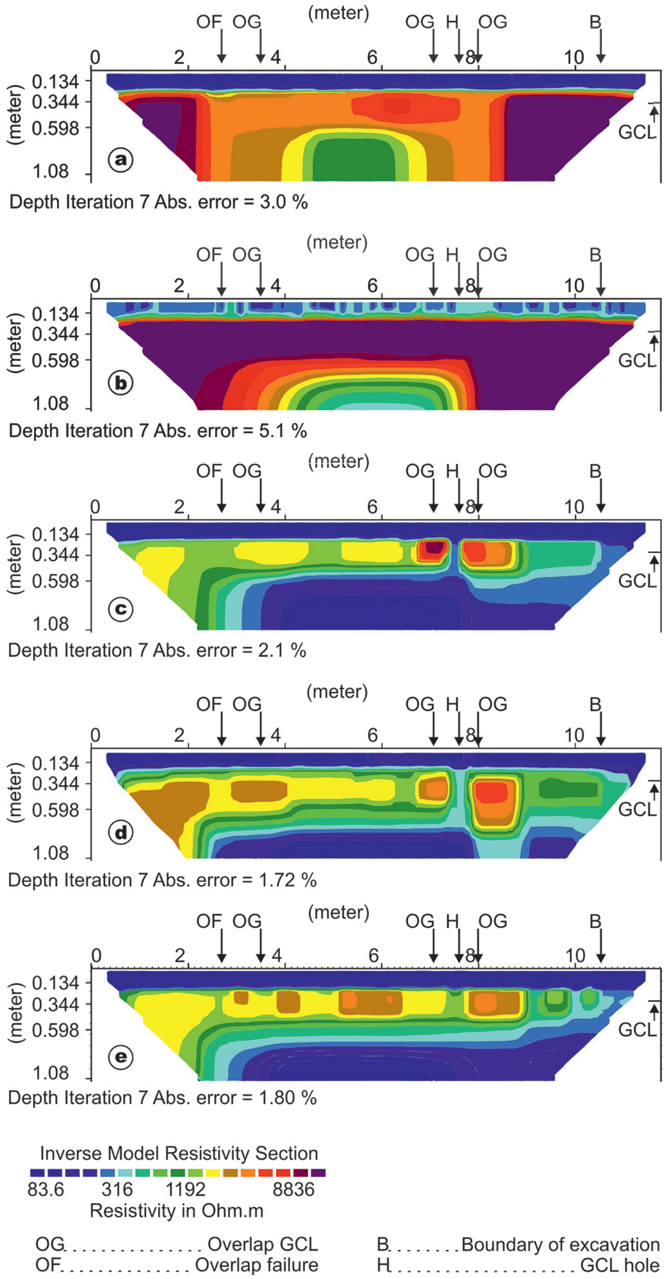
Secondly, the monitoring using ERT highlighted changes in the electrical resistivity of the GCL that occur over time. A significant diminution in electrical resistivity was observed between the measurements taken in February 2010 and those of July 2011 (Genelle 2012; Sirieix et al. 2013). Over the course of the first year, resistivity values varied between 5×10^5 and 15×10^5 ohm·m according to the prevailing climatic conditions (Table 2), with the highest value having been recorded after a hot dry summer (in September 2010; see Table 1). From the measurements of 22 July 2011 onwards, the resistivity of the GCL was in the order of 1×10^5 ohm·m, and it remained lower compared to earlier measurements.

Lastly, the electrical resistivity models performed since July 2011 reveal the existence of a contrast in electrical resistivity between 7.5 and 7.7 m from 0.2 m in depth (vertically down from point H in Figs. 5*c*, 5*d*, and 5*e*). This decrease in electrical resistivity is located in the area where the gravelly clay material is in direct contact with the gravel (Fig. 2*b*), meaning that it is indeed possible to detect the hole in the GCL. A lower decrease of resistivity appears also at 2.5 m (vertically down from point OF in Figs. 5*c*, 5*d*, and 5*e*) and corresponds to the overlap failure (Fig. 2) that is narrower than the GCL hole. The overlap of GCL seems pinpointed by the increase of resistivity seen on July 2011 surveys (vertically down from point OG in Figs. 5*c*, 5*d*). At the same time, the resistivity of the deeper layer decreases and this layer becomes wider and higher. This layer corresponds to the gravelly clay materials.

Estimating electrical resistivity of the GCL using particle swarm optimization (PSO)

To perform the inversion, PSO was used following the procedures presented by Fernández Martínez et al. (2010). In this case, the inversion problem is solved as a sampling problem using PSO. Particle swarm provides a proxy for the posterior distribution of the inverse model parameters if it is used in its explorative form.

Fig. 5. Inverse model resistivity section. (*a*) 4 February 2010; (*b*) 28 September 2010; (*c*) 22 July 2011; (*d*) 29 July 2011; (*e*) 10 May 2012.



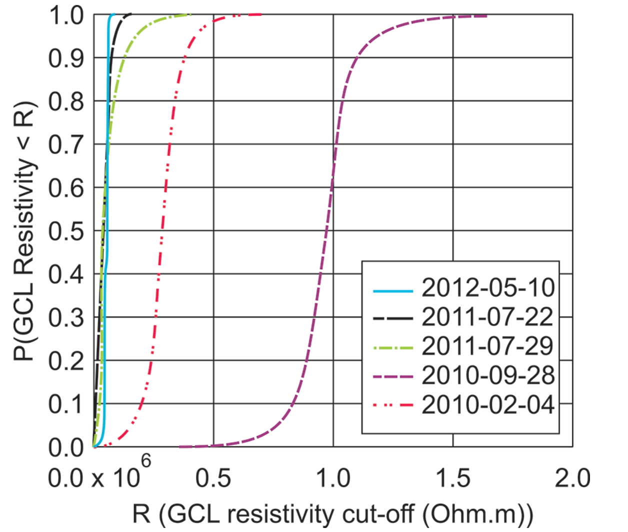
In this case, the posterior sampling under explorative conditions on the relative misfit is lower than 10%. The prior information that is used in the sampling procedure is the model search space. A four-layer model (top soil, gravel, GCL, and gravelly clay material) was adopted with the following lower and upper limits, both for the resistivity and thickness of the respective layers:

$$\text{Resistivity} = [20 - 100;\, 500 - 4500;\, 5000 - 10^{6};\, 10 - 100]\ \text{ohm}\cdot\text{m}$$

$$\text{Thickness} = [0.1 - 0.2;\, 0.23 - 0.35;\, 4\times10^{-3} - 7\times10^{-3}]\ \text{m}$$

Due to the very dry conditions observed for the survey conducted in September 2010, it was necessary to modify the resistivity search space (conserving the thickness) as follows:

Fig. 6. Temporal evolution of cumulative probability curve of GCL resistivity, deduced from posterior sampling of this parameter via PSO in the region of relative misfit lower than 10%.



$$\text{Resistivity} = [20 - 400;\, 500 - 500.10^{3};\, 5\times10^{3} - 2\times10^{6};\, 10 - 100]\ \text{ohm}\cdot\text{m}$$

To compare values of resistivity, the median value of the GCL (Table 2) was extracted and the cumulative probability curves of the GCL's resistivity for each survey were shown (Fig. 6). From the temporal evolution of this curve, it can be observed that these cumulative probability curves can be clustered into three groups:

- The first group is characterized by a low median resistive value (between 0.4×10^5 and 0.5×10^5 ohm·m) and corresponds to the surveys conducted from July 2011.
- The second group having a median resistivity of around 3×10^5 ohm·m corresponds to February 2010.
- The third group corresponding to September 2010 has a median of 10×10^5 ohm·m and corresponds to very dry conditions.

A drop in electrical resistivity of at least an order of magnitude can be clearly observed from July 2011 onwards. The values of resistivity with PSO are more contrasted than with RES2DINV and seem to be more precise because they take into account the true thickness of the GCL and the one of other materials. So the influence of ageing is more important with a group around 0.5×10^5 ohm·m after 2 years while the other groups are between 3×10^5 and 10×10^5 ohm·m.

Characterization of the GCL in position

To understand why the electrical resistivity of the GCL decreases with time, samples of the GCL were exhumed from the site in May 2012. It should be remembered that the GCL being used is a sodium-activated calcium bentonite GCL. As it is known that the clay layer of the GCL is the only component that serves as a hydraulic barrier, any change in the clay layer composition induces a modification of the permeability of the GCL: as a low permeability barrier, sodium-activated calcium bentonite has better characteristics than the calcium bentonite. As a consequence, analyses to check variations of physical properties of the CGL (saturated hydraulic conductivity, water content, swell index, and composition of the exchange complex) were performed and correlated to the electrical resistivity variations of the GCL.

The results of the analysis performed on three samples (two of which were exhumed from the site while the third one came from the virgin unused roll left outside under a tarpaulin during several months) are summarized in Table 3.

Table 3. Comparison of intrinsic properties of the two GCL samples from experimental site and another from the virgin unused roll of GCL.

	GCL_1	GCL_2	GCL_0
Na^+ (%)	4.2	5.3	78.7
Ca^{2+} (%)	81.5	81.1	13.7
Swell index (mL/2 g)	<10	<10	23
Average hydraulic conductivity (m/s)	$4.8{\times}10^{-6}$	$1.3{\times}10^{-6}$	$2.2{\times}10^{-10}$

The first observation is that there was a change in the proportion of sodium and calcium ions over time: Ca^{2+} has replaced Na^+. The proportion of sodium ions Na^+ went from 78.7% (for sample GCL_0) to 4.2% and 5.3%, respectively, for the samples GCL_1 and GCL_2. At the same time, an increase was also observed in the proportion of calcium ions Ca^{2+}, which reached values as high as 81% whereas the initial level was only 13.7% for sample GCL_0. These increases in divalent cations (Ca^{2+}) could be the result of either rain water percolating through the materials above the GCL (Melchior 2002) or through the material underneath (Meer and Benson 2007). In this particular case, the material in contact with the GCL contained approximately 67% Ca^{2+}. So it seems that this material is the source of Ca^{2+}.

Furthermore, the swell index decreases from 23 mL/2 g for GCL_0 to less than 10 mL/2 g for GCL_1 and GCL_2. This low value confirms the evolution of clay content of the bentonite.

The cationic exchange phenomenon as well as the effect of wetting–drying cycles inside the bentonite, made possible by the thinness of the confinement of the GCL, explains the significant drop in performance of the GCL (Bouazza et al. 2007). In fact, it is noted that the hydraulic conductivity is considerably greater for the samples in place than for the virgin one. Average values were 5×10^{-6} and 1.3×10^{-6} m/s, respectively, for samples GCL_1 and GCL_2 compared to 2.2×10^{-10} m/s for the unused sample GCL_0. The values for the different hydraulic head applied during the test are presented in Fig. 7. These values clearly show an increase in the hydraulic properties of the GCL relative to the hydraulic conductivity data supplied by the manufacturer (5×10^{-11} m/s). This loss of watertightness is consistent with analyses carried out on the GCL samples taken from different landfill sites in the United States after several years of service (Meer and Benson 2007; Benson and Meer 2009; Scalia and Benson 2011) and in France (Touze-Foltz et al. 2010; Barral et al. 2012).

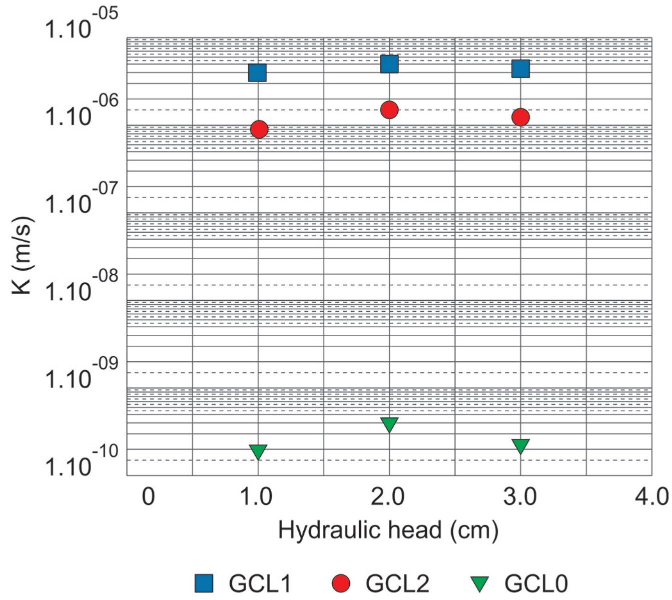
It should be noted, however, that because the GCL was installed below a thin layer of gravel (only 0.45 m), climatic conditions have had a strong influence on it and in a shorter timeframe than if it had been installed at a greater depth (French recommendation — Comité Français des Géosynthétiques 2011 — is more than 1 m) and had been protected by a layer of clay (Melchior 1997).

Discussion

This geophysical monitoring emphasizes the effect of time on the electrical resistivity of the GCL and also the effect of rainfall. Firstly, with a similar cumulative effective rainfall, respectively –6.9 and –7.2 mm for the 28 September 2010 and 29 July 2011, the electrical resistivity drops from 10×10^5 to 0.4×10^5 ohm·m with PSO and from 15.2×10^5 to 1.3×10^5 ohm·m with ERT (Table 2). In this case, the effect of time is emphasized.

Nevertheless, on the two first surveys the cumulative effective rainfall seems to make an impact on the electrical resistivity of the GCL, which increases from 3×10^5 to 10×10^5 ohm·m with a respective cumulative rainfall of 6.4 and –6.9 mm. On the contrary, it has not been the case since July 2011 where the electrical resistivity is around 0.4×10^5 ohm·m while the cumulative rainfall is quite different (29.2 and –12.9 mm).

Fig. 7. Hydraulic conductivity of the GCL samples for three hydraulic heads.



Thus ageing of the GCL correlated with the increase of its hydraulic conductivity seems to be the only cause of the decrease of electrical resistivity. So, the ERT method appears to be well fitted to detect the loss of watertightness of the GCL. On this experimental site, electrical resistivity values less than 0.6×10^5 ohm·m with PSO and 1.4×10^5 ohm·m with ERT can be linked with this ageing process.

Changes in hydraulic conductivity of the GCL can be due to the phenomenon of cation exchange between Na^+ and Ca^{2+} ions combined with hydration–desiccation cycles. As the electrical resistivity decreased from more than 3×10^5 ohm·m in September 2010 to less than 1.3×10^5 ohm·m in July 2011, it can be assumed that the increase of the GCL hydraulic conductivity occurred between these two dates. Moreover, another survey carried out in May 2011 (Sirieix et al. 2013) shows an electrical resistivity of 3×10^5 ohm·m for the GCL, similar to February 2010. So the high decrease of electrical resistivity appeared between May and July 2011, corresponding to 20 to 22 months after the GCL installation. This phenomenon of cation exchange combined with hydration–desiccation cycles also occurred at a landfill site in Germany with the same GCL cover thickness within the same timeframe (Melchior 2002) and led to an equivalent increase of the GCL hydraulic conductivity. Laboratory investigation of GCL samples after 24 months since its installation in a landfill cover in France (Touze-Foltz et al. 2010) also shows a poor hydraulic behaviour in relation with a low confining stress (0.5 m), cation exchange, and the presence of cracks in the bentonite.

In addition, it has been found that for the first two surveys, the GCL appears as very resistive on the inverse model resistivity, and particularly the 28 September 2010. It is clear that defects cannot be detected along the AA′ profile (Figs. 5*a* and 5*b*). Thus, the ERT method is not suitable for the detection of defects at least during the first year after the installation of the GCL. However, the three following surveys make the hole and the overlap failure in the GCL detectable, with a clear decrease of resistivity for the former one (Figs. 5*c*, 5*d*, and 5*e*).

Conclusion

Temporal monitoring of changes in the electrical resistivity of a GCL on an experimental landfill cap was carried out over

32 months. A decrease in the electrical resistivity of the GCL was observed 22 months subsequent to the installation of the site. Although it is difficult to estimate the GCL's electrical resistivity from the tomography (due to its true thickness being overestimated), a more precise estimation is possible using the PSO method. However in both cases, the reduction in electrical resistivity is significant, decreasing from one order of magnitude (from 10^5 to 10^4 ohm·m) according to PSO and at least a decreasing from 5×10^5 to 1.3×10^5 ohm·m with ERT. So because the decrease of the GCL's electrical resistivity, it is also possible to detect the hole in the GCL on the ERT images.

The decrease of the GCL's electrical resistivity could be explained by changes in the intrinsic properties of this material over time. Laboratory tests on samples of the GCL removed almost 3 years after its installation highlight a substantial increase in its permeability, rising from 10^{-11} to 10^{-6}m/s. These tests also show the action of the process of cation exchange, the sodium ion content falling from 79% to less than 6%, combined with hydration–desiccation cycles experienced by the GCL.

The electrical measurements used at the research site clearly demonstrate their capacity to detect changes in the intrinsic properties of the GCL (i.e., the ageing process), and the accompanying loss of impermeability that occurs over time. It could be a good method to survey the GCL if the electrical resistivity value of the GCL just after its installation is known or if this value is less than 10^4 ohm·m. Such information is of real importance to landfill site managers as it facilitates the choice of the most suitable method of remediation. However, it should be stressed that the ERT method cannot be used to characterize the condition of the cover just after its installation because its resistivity is very high. This technique could be employed on site, whatever the materials above the GCL or the surface topography of the landfill.

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