A multi-scale study of water transfer through clayey geomaterials in landfill cap covers

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Abstract – **The cap cover of a municipal solid waste landfill, must ensure the containment of the wastes, control rainwater infiltrations and limit biogas leakage to the atmosphere. The specific characteristics of the cap cover are necessary to be maintained during all the lifespan of the landfill, despite the loadings to which it is subjected to: mechanical stresses, hydraulic load changes, physico-chemical variations and changes of climatic conditions. The water transfer through the clayey geomaterials, geosynthetic clay liners (GCL) installed as capping in landfill, is studied at three different scales. In-situ large scale experiments, laboratory experiments and intermediate scale experiments were conducted. Barriers remained effective after two years following installation. Percolation rates were less than 1% of the rainfall and the ion exchange in the GCL was 180 times lower than the initial. However, hydraulic conductivity increased slightly due to desiccation.**

I. INTRODUCTION

Geosynthetic clay liners (GCLs) are increasingly used as an alternative to compacted clay liners in the cell covers of municipal solid waste landfills. In landfill, the cover of a cell assumes several functions as hydraulic barrier. French regulation prescribes a final cover but does not completely specify the materials to be used in landfill capping system. GCLs composed by a thin layer of sodium or calcium bentonite bonded to layers of geosynthetics (geotextiles or geomembranes) have a very low hydraulic conductivity (k < 10^{-10} m/s) and a high self-healing capacity. Their popularity as a component of barriers in landfill is also due to their relatively low cost and their easy installation in situ ([1], [2]).

Different solicitations taking place in a landfill may alter the properties of GCL in the short or medium term [3]: (i) climatic variations (freeze/thaw cycles, wet/dry cycles), (ii) hydraulic load variations (during rainy events or dry periods) and (iii) especially physico-chemical conditions (ions exchange in the complex of cover).

The hydraulic conductivity and the swelling of GCLs in contact with inorganic permeant solutions have been measured in the laboratory in order to:
- characterize the initial conditions of GCLs: the type of bentonite, the confining stress and the prehydration conditions ([4], [5], [6], [7], [8, [9].)
- study the influence of in situ parameters on GCL durability, including the wet/dry cycles [10], [11], [12] and the influence of the cations.
The cation exchange depends on the type (monovalent, divalent or trivalent), the size and the concentration of cation in the permeant solution [13], [14], [15], [16], [17], [18], [19].

However, laboratory studies are often conducted under conditions that do not represent the actual conditions observed in situ [3]. Several GCL studies have been carried out at the site scale, where verification of the water balance of the landfill cover was carried out by pan lysimeters installed in the capping system. [20], [21], [22], [23], [24] have instrumented and compared different capping systems in landfills in France and Germany, over several years. However, such large-scale on-site tests were time consuming and comparisons between the results obtained from different sites were very often impossible. A coupling between laboratory studies and in situ tests for these sealing materials was critical to gaining a better understanding of their material behaviour (which can allow improvement in their in situ performance over time). This kind of study was not common ([25]; [26]) as it has involved excavation of the liner for sample retrieval and this might necessitate repair of the liner at each sampling location ([27], [28]).
The study presented here was a study of the water transfer through the clayey geomaterials installed as capping system with GCL in landfill, at three different scales:
- On site, two-year follow-up large-scale experiments were installed to monitor the infiltration of rainwater in different cap cover designs providing by complexes of geosynthetic clay liners (GCL), and measure cation exchange that takes place within them, in real time. The installation of the in situ devices and the data

recorded allowed a comparison of the hydrous behaviour of several configurations of the capping system with GCLs.

- In laboratory, tests with the oedopermeameter allowed to characterize the initial state of the GCLs and to evaluate possible variation in performances due to ageing or alteration. The laboratory characterization of the initial state of the cover materials was conducted under the same conditions as those in situ; this avoided excavation of samples which can cause damage to the cap cover. Also, a non-destructive analysis of the ion exchange in GCLs over time was conducted in the laboratory using unexcavated samples.
- In addition, for studies in intermediate scale, the landfill cell cap covers were faithfully reproduced in six pilot cells to get data difficult to achieve on site without exhumation of the cover materials.

This case study indicates that the barrier containing a GCL remains effective after two years of exploitation: the GCLs are correctly protected from freezing in winter by the cover soil, the percolations through the barrier are lower than one percent of the rainfall quantity, and the ion exchange in the GCL preserves its swelling ability.

Thus, the results of experiments in three scales, in situ, laboratory and pilot, were used to study the hydro-chemo-mechanical couplings on cap cover geomaterials under complex loadings.

The originality of the study was that it used different experimental techniques (lysimeter, oedopermeameter, rigid wall permeameter, volumetric water content probe) at different scales (in situ, laboratory and pilot scales) to gain a better understanding of the chemo-hydraulic behaviour depending on the nature of the materials (powdered or granular bentonite), the initial hydraulic conditions (pre-hydrated or without pre-hydration) and the type of capping (simple or overlap). The hydraulic and chemical results, from in situ, laboratory experiments and from pilots, were compared to obtain a better understanding of the behaviour of the whole cap cover system comprising GCLs.

II. DESCRIPTION OF THE EXPERIMENTS

A. Large scale - field intrumentation

The cover profile of the experimental cell, located approximately 120 km south of Lyon (France), consists of a 30 cm thick vegetated surface layer, a 40 cm thick layer of cover soil (gravel), a layer of geocomposite drainage, the GCL, another layer of drainage and a 40 cm thick protective layer (gravel) with a final slope of about 5%. Two different GCLs were installed in the test field, both of which were needle-punched; one contained powdered bentonite and the other granular bentonite. They are referred to throughout the paper as Po GCL and Gr GCL and they contain a minimum of 5.3 kg/m^2 and

4.9 kg/m^2 of bentonite, respectively.

Six pan lysimeters (17m x 2m) were installed beneath the cover, to measure the quantity of water crossing the GCLs. The lysimeters are composed by a geocomposite drainage layer placed on top of a PVC geomembrane in order to rapidly transmit seepage flow through the GCL to the measurement system. The lysimeters were placed under the Po GCL or Gr GCL, which were either pre-hydrated or not, and under a single layer of GCL and a GCL overlap. For these different six cover configurations, at the edge of the cell, the percolated water was collected in tanks to measure its volume. Thermocouples were installed in various layers of the cover to record the temperature changes in the GCLs. In addition, data on precipitation, air temperature and evapotranspiration were provided from a local meteorological station.

B. Small scale - laboratory characterisation of the capcover materials

The initial geotechnical characteristics of the cover soil and the GCLs were determined. The swell index, measured by the standard test ASTM D 5890, is over 24 mL/2g for both bentonites. Table 1 summarizes the exchangeable cations measured in the percolates of the cover soil by ICP-AES, after elution test on saturated specimens. Table 1 also presents the hydraulic conductivities measured by rigid wall permeameter, using a few centimeters hydraulic head, on compacted specimens composed by the vegetated surface layer and the gravel layer, with the same conditions as those in situ. The gravel layer contains 25% CaCO$_3$ and percolation from the overlying soils is a source of Ca ions. In fact, Ca appears as the dominant cation in the cover complex (vegetated surface and gravel layers), and its concentration reaches 74.2 mg/L in the pore volume.

Table 1. Exchangeable cations from column elution tests and saturated hydraulic conductivities of the cover layers

Permea-meter	Soil Type	Cations concentration (mg/L)				Hydraulic conductivity (m/s)
		Ca	Na	Mg	K	
1	Vegetated surface layer	147.0	3.5	2.6	0.8	6.3×10^{-5}
2	Gravel layer	31.8	1.1	0.4	0.6	1.4×10^{-4}
3	Vegetated surface layer and gravel layer	74.2	5.4	1.0	1.9	9.0×10^{-5}

The cation contents in both bentonites are given in Table 2: both bentonites contain the typical cation content generally observed in virgin sodium bentonite ([18], [26] and [19]). CEC was determined by means of cobalt

hexamine trichloride. Chemical analysis of of the extracts was conducted using spectrocolorimetry. The swell index, measured by the standard test ASTM D 5890, is over 24 mL/2g. Table 2 also gives the hydraulic conductivity of GCLs measured in an oedopermeameter (standard test: AFNOR XP 84-705; diameter: 25 cm; normal stress: 12 kPa). The results show a good agreement with Na-GCLs characteristics used in other studies.

Table 2. Cation exchange complex of Geosynthetic Clay Liners and saturated hydraulic conductivities from oedopermeameter tests.

GCL sample	Cation content (cmol/kg)				Hydraulic conductivity (m/s)
	Na	Ca	Mg	K	
Po bentonite	74.0	5.8	2.4	1.1	1.5×10^{-11}
Gr bentonite	54.8	11.4	1.4	1.5	3.2×10^{-11}

C. Intermediate scale - pilot experiments

An experimental device was designed to be complementary to the study conducted in situ on the site of Chatuzange-le-Goubet. It allows having access to data difficult to achieve in large scale experiments of this typology.

For four pilots, the reconstituted cap cover system is identical to the final cover of the in situ installation. This cover included: a GCL with 5 kg/m2 bentonite containing natural sodium bentonite, between two geodrains, a layer of 40 cm run material and in surface a topsoil of 30 cm. For this design, the different materials from the site were used. Within these four pilots, two geosynthetic clay liners are tested (powdered bentonite and granular bentonite) for two different initial hydration (water content coming from the water content of the GCL and hydrated GCL). Finally, the last two pilots reconstituted a cap cover containing calcareous materials. Again, the two types of geosynthetic clay liners are tested. The six configurations reconstituting a household waste storage facility cap cover system are located on the EEDEMS platform at INSA Lyon. They are reconstituted in a PEHD rectangular tank of following dimensions 1.2m x 0.8m x 1m high. They are laterally protected by an insulating and sealing between the tanks, provided by a PVC membrane.

The different materials were placed carefully in the pilot and the obtained wet densities were between 1.5 and 1.6, as the density in the cap cover in situ which was around 1.5.

On each pilot, can be controlled rainwater infiltration at all levels of the cap cover. Indeed, a water recovery system has been installed at three different levels (Fig. 2):
- at the geodrain located under the GCL

- at the geodrain on GCL
- on the surface, through a gutter which collects the water dripping.

Water content measurements at different depths in the cap cover system were conducted along a vertical profile, using a profile probe PR2 (Delta T).

The control of water infiltration allows the study of several phenomena:
- firstly this experiment allows a mass balance calculation of the cap cover. By measuring the volume of water collected at different levels and comparing them to the rainfall, the effective rainfall infiltrated in the cover and the amount of infiltrated water through the sealing system, can be evaluate.
- this device also offers the possibility of accelerating the aging process of cap cover by increasing hydraulic gradients applying to the GCL through a system of valves, allowing to assess the sustainability performance of the all cover design.

III. RESULTS AND DISCUSSION

A. Study of water transport

Figure 1 shows the quantity of water collected in the various lysimeters over 23 months. The GCLs were very effective in reducing the rainwater entry into the solid mass of waste: the quantity of water passing through the GCL varied between 0.2% and 0.9% of the rain water (Table 3). The percolated volumes are comparable to the volumes measured by [20], [26] and [22] for landfill cells with low slopes (3 in 8%). Moreover, both lysimeters located under the pre-hydrated GCLs received lower volumes than those located under the dry GCL. These in situ results confirm those obtained in the laboratory by [29], [8], [30] and [31] that lead to the recommendation that GCLs must be pre-hydrated during their installation. In the same way, the lysimeters located under GCL overlaps, collected lower (Gr GCL) or equal (Po GCL) volumes of water because of the increased bentonite quantity in GCL overlaps.

As observed by [22] and [25], a noticeable change in the water volumes collected occurred during the second year (Table 3). For the first year of measurements and for almost all the GCL configurations a calculation of the hydraulic conductivity k from the slope of the cumulative percolation curves during the rainy months, assuming unit gradient flow, gives 1.4×10^{-11} m/s $< k < 2.4 \times 10^{-10}$ m/s. During the second year, a slight increase of this coefficient was observed (5.0×10^{-10} m/s), corresponding to a peak in the quantity of water collected through the GCLs during the spring period.
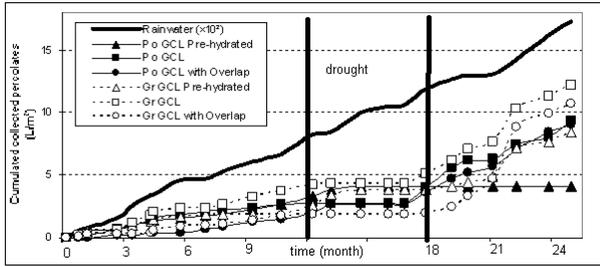
Fig. 1. Cumulated collected water in the lysimeters (L/m^2) and cumulated rainwater ($x100\ L/m^2$)

This change in the rate of percolated water through clayey barrier during the second year can generally be explained by the ion exchange in the cover materials ([22] and [25]) and the dehydration of the soils, with a corresponding desiccation of the GCL, which created cracks in the barrier, resulting in preferential flow paths and an increase of the hydraulic conductivity ([32] and [33]).

Table 3. Summary of the quantity of water collected through the GCLs in different configurations during the first two years after the installation of the cap cover.

GCL configuration	Water collected			
	mm	mm	% rainfall	% rainfall
	1[rst] year	2[d] year	1[rst] year	2[d] year
Po	2.65	4.86	0.4	0.6
Po Pre-hydrated	2.60	1.42	0.4	0.2
Po with overlap	1.47	5.65	0.2	0.7
Gr	3.77	6.52	0.6	0.9
Gr Pre-hydrated	1.86	5.28	0.3	0.7
Gr with overlap	1.74	7.09	0.3	0.9

By observing the measures in Fig. 2, several comments can be issued. The initial values of water content, which are between 1 and 7% in terms of pilot 1, 2 and 3 (and between 2 and 10% for the pilots 4, 5 and 6) corresponded to the initial water content of materials.
The higher initial values (17 to 32%) do not match the water content values of the materials placed in pilots, but can be explained by a capillary action, since these are the layers of materials in direct contact (located in high depth) with pre-hydrated GCL. The variation in time may separate into two trends:
- at the upper material, the very low increase in the humidity, suggest that rainwater seeps through the layer;
- to the lower material, in contact with the GCL, the humidity level is already significant in the case of pre-hydrated GCL. In the absence of pre-hydration was noted that the same level of moisture over time were achieved (rainfall water storage in this layer),
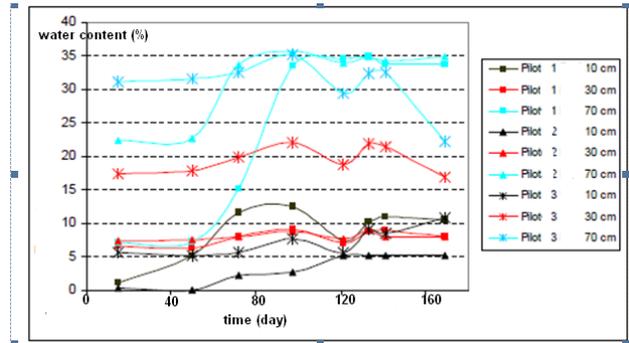

Fig. 2. Volumetric water content of soils for 3 different depths and 3 different pilots. Dark color corresponds to a shallow depth of 10 cm from the surface (in the topsoil), the intermediate color to a depth of 30 cm from the surface (top soil interface and limestone or run material, as the case) and the light color corresponds to a depth of 70 cm (either limestone or run material in contact with the GSB).

- the final water content after several rain events is around 35% for all the cap cover, for these materials in contact with the GCL, hydrated initially or not.
   During the early summer it was found that the moisture in the topsoil remained constant or presented a very slight decrease. However, the water content of the limestone decreases sharply (from 35% to 20%).

B. Study of cations exchange

Chemical analyses of the rainwater and the water samples collected in the lysimeters were carried out every month, to understand the origin of the permeability increase. This non-destructive analysis allows continuous monitoring of the ion exchange within GCLs during several years. Fig. 3 shows the time variation of the Na and the Ca concentrations for the Po GCL and the Gr GCL. In Fig. 3 the variations observed in the Na concentration curves are steady even if a plateau was observed. This indicates a small decrease in the Na ion substitution in the GCLs during this period. On the contrary, Fig. 3 showed an increase in the Ca ions collected in the GCLs. According to the results presented in Fig. 3, the maximum quantity of Na washed is about 0.45 g of Na/m^2, which is largely lower (more than 180 times) than the existing quantity of Na in both studied GCLs. Therefore, considering the very small quantities of Na washed, compared to the much bigger quantities of Na contained in the GCLs, it is clear that the ion exchange in the GCL is not significant. The desiccation of the barrier, could occur during a period of drought, where the GCL temperatures remained above 20°C, and the cumulative rainwater was very low (less than 20 mm in three months) Indeed, during the rainy events in winter, following this dry period, the rain water leached the cover soils through the cracks and carried away the ions that are naturally present in the soils.
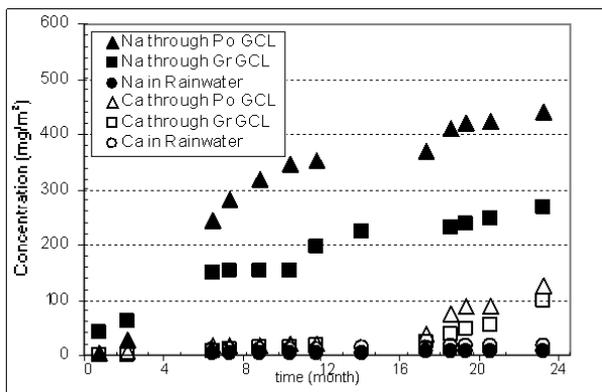
Fig. 3. Cumulated Na and Ca concentrations, in rainwater and in percolates, passing through the powder (Po GCL) and granular (Gr GCL) GCLs.

IV. CONCLUSIONS

A multiscale study, coupling on-site test, in laboratory tests and tests in intermediate scale were presented. The instrumentation installed in the cover of a landfill cell allowed to quantify water infiltrations in the waste, depending on various configurations of the cover including GCLs. It made also possible to follow the time depending ion exchanges in the GCLs.

This on-site study is coupled with a laboratory study which allowed the initial characteristics of the materials constituting the cap cover (soils and GCLs) to be determined.

The results obtained showed that the GCLs are correctly protected from freezing in mild winter by the 0.7 meters thickness of cover soil. After two years, the percolations through the barrier were very small for all the configurations (0.2 % to 0.9 % of the rain are passed through the GCLs), corresponding to a water quantity having crossed the GCLs which was less than the GCL pore volume. Nevertheless, after the second autumn, the GCL permeabilities increased beyond 4.0×10^{-10} m/s. The ion exchange was partially occurred. The ions concentration in percolated water represent only the 1/56 of total Na contained in the GCLs and only the 1/18 of Na washed in the leaching test. The desiccation of the cover materials during the second summer and during the second autumn which were particularly dry and hot (GCL temperature remained between 20 and 30°C during all this period), seems to be the cause of the increase of the quantity of percolated water during the second winter.

The findings from this case study indicated that the barrier containing a GCL remained quite effective after two years of exploitation. However, due to the increase of the permeability, a follow-up in the long term can be necessary to confirm that the barrier can preserve its sealing properties satisfactorily during the useful life of the landfill.

The reconstitution of the different designs of landfill cap cover, at a metric scale pilot, allowed understanding the influence of different factors studied.

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