State of the art and durability insights regarding the use of geosynthetics for lining in hydraulic and environmental applications

Touze-Foltz, N.
Cemagref, HBAN Unit, BP 44, 92163 Antony Cedex, France

Keywords: Geomembrane, GCL, lining, durability, performance, chemical compatibility

ABSTRACT: Geosynthetics have been widely used in the past thirty years in a number of hydraulic and environmental applications. The aim of this paper is first of all to illustrate the use of geosynthetics in some hydraulic and environmental applications, i.e. canals and dikes, ponds, covers for potable water impoundments, mountain reservoirs and ponds for environmental protection. A brief insight where documents exist on regulations or guides of recommendations for the use of geosynthetics in such applications is given. Then a discussion of the evaluation of the performance of liner systems at field scale is presented, with a brief overview of electrical leak detection systems and optic fiber measurement. The durability of bituminous, polyvinyl chloride and polypropylene geomembranes in hydraulic applications is then discussed based on field experience and some laboratory quantification of the flow of water through geomembranes. Field data related to the performance of geosynthetic clay liners (GCLs) in hydraulic applications are also presented based on a literature review. The factors impacting the performance of GCLs are discussed. An insight is also given in the factors impacting the performance of GCLs in landfill covers and a synthesis of common features and recommendations for those various applications is given. Finally, a discussion on the methodologies that can be used to evaluate the adequation of the bentonite in a GCL for a given application in order to ensure the best possible performance of the GCL is presented, together with preliminary recommendations.

1 INTRODUCTION

Geosynthetics have been widely used in the past thirty years in a number of hydraulic and environmental applications. A number of examples of use of those materials have been reported. Some lessons have been learned from experience on the different types of structures concerned at the successive stages in projects: design, testing, construction, inspection (Heibaum et al. 2006).

The main purpose of this paper is to deal with some performance issues regarding the use of geosynthetics for lining in hydraulic and environmental applications in order to introduce the debate in the discussion session dedicated to the performance of geosynthetics in environmental and hydraulic applications of the Ninth International Conference on geosynthetics.

As stated by Heibaum et al. (2006) hydraulic applications cover maybe the most widespread range of using geosynthetics. In this field, the scope of this paper will be limited to the performance of geosynthetics in the lining of canals and dikes, ponds, covers for potable water impoundments and mountain reservoirs. The application of geosynthetics for the lining of dams will not be discussed herein. Indeed, a Keynote Lecture will be given on this topic by Cazzuffi et al. (2010) in this conference.

Geoenvironmental applications range from the traditional use of geosynthetics in landfill base liners or drainage layers, landfill capping systems, liquid waste ponds, containment of past spills of hydrocarbons, secondary containment around fuel tanks, containment for fluid or gas in mining applications, for example (Rowe 2007). The case of the performance of geosynthetics in bottom liner systems will not be addressed in this paper. Indeed, it will be the scope of the paper presented by Pr. Kerry Rowe in the same discussion session (Rowe 2010). Furthermore, mining applications will be discussed in this conference by Fourie et al. (2010) so that topics related with this particular application of geosynthetics will not be repeated here. Then the geoenvironmental applications discussed in this paper will be restricted to landfill covers, focusing on the performance of geosynthetic clay liners (GCLs) and ponds for environmental protection like reed bed filters and runoff water ponds.

The purpose of Section 2 is to discuss the use of geosynthetics for lining in canals, ponds and covers for reservoirs. The focus of each subsection is to give a brief insight where documents exist on regulations or guides of recommendations for the use of geosynthetics in such applications, giving the state-of-practice. Those guides usually based on experience aim at ensuring that the best possible durability of the engineered structure is obtained.

Section 3 of this paper is dedicated to the discussion of the evaluation of the performance of liner systems at field scale. A brief overview of electrical leak detection systems for the check of the integrity of liner systems will be given. Optic fiber measurement which seems to be a promising technique for leak detection will also be addressed.

Section 4 of this paper aims at giving an insight in the durability of bituminous, polyvinyl chloride (PVC) and polypropylene (PP) geomembranes based on the results of recent studies for hydraulic applications. A methodology that was recently used in a canal in France to evaluate the stability of the cover layer on top of a geomembrane will also be presented.

The evolution of the hydraulic performance of GCLs, connected to durability issues on those materials will subsequently be addressed in Section 5 in parallel to the discussion of durability issues for geomembranes. Applications under consideration will be hydraulic (tunnels, canals, ponds) and environmental applications (landfill covers). A number of common parameters important to take into account to ensure the best possible performance of GCLs will be put into light.

Finally, the methodologies that can be used to check the adequation of the bentonite contained in the GCL to the environment in which the GCL will be installed will be discussed in Section 6 of this paper, enlarging the discussions to landfilling and other environmental applications, as this question has not been widely discussed up to now and is fundamental as regards the durability of GCLs.

2 STATE OF THE ART REGARDING THE USE OF GEOSYNTHETICS FOR HYDRAULIC APPLICATIONS

The purpose of this section is to give a brief overview of the use of geosynthetics for lining in canals and dikes, ponds, mountain reservoirs, reed bed filters and reservoir covers. The objective is not to focus on the kind of geosynthetics used but much more on the existing recommendations given for those particular applications. A brief insight in the related regulations, mainly based on the European experience will also be given. The presentation of those recommendations is essential as they aim at ensuring the best possible performance of geosynthetics in the aforementioned hydraulic applications.

2.1 *Liner systems in canals and dikes*

Heibaum et al. (2006) mention an increase use of geomembranes for the lining of canals, whether for the transport of water (for irrigation, drinking water or electricity production) or for navigation. Flaquet-Lacoux et al. (2004) mention the rehabilitation of 14 canals and a number of dykes using geomembranes in France. An example of a canal lined thanks to a geomembrane in presented on Figure 1.

Heibaum et al. (2006) also mention three applications of geosynthetic clay liners (GCLs) under water in canals. This use seems to become more widespread with the recent example of two dikes in Poland (Pers. Comm. Rémy Tourment) even if only a limited number of feedbacks exist on this type of application.

The relevant characteristics of geomembranes and GCLs for canals to be specified are given in EN 13361 (AFNOR 2005).

Additional documents regarding specifications and recommendations of use can be found. Fleischer and Heibaum (2008) mention in particular an issue on the Water, Waste Water and Waste Association dedicated to lining for dikes published in April 2005.

Similarly, the French chapter of the International Navigation Association (PIANC) is currently finalizing a guide making a synthesis of the use of geosynthetics for dikes (Galiana 2009).

Figure 1. Geomembrane installation in a canal (courtesy K. von Maubeuge)

2.2 *Liner systems in ponds*

The objective of this section is to describe the use of geosynthetics for the lining of ponds. Various types of ponds will be discussed, depending on their use either for water storage (water impoundments, mountain reservoirs) or for the containment of polluted liquids, either in waste water treatment plants or along roads. A focus will be made in each case on the durability issues.

The relevant characteristics of geomembranes and GCLs for liner systems in reservoirs are specified in EN 13361 (AFNOR 2005). The features required for geomembranes and GCLs used in the construction of liquid waste disposal sites, transfer stations or secondary containment is addressed in EN 13492 (AFNOR 2005).

A number of geomembranes and/or GCLs may be used in ponds. An example of a pond lined thanks to a geomembrane is shown on Figure 2. It is also possible to install double liner systems using two geomembranes with a drainage layer in-between them. This solution is still rare in liquid containment applications and is only applied where the risk must be reduced considerably. Only two references to double liner systems were found by the author in the literature for the applications under consideration in this paper: (1) a containment pond (Girollet 1983); and (b) a water reservoir in a mountainous area (Delorme et al. 2009).

Figure 2. The Barlovento water pond in the Canary Islands (courtesy H. Girard)

Touze-Foltz et al. (2008) presented an overview of references related to the use of geosynthetics in containment ponds based on the work performed by Duquennoi (2002) and Duquennoi & Coquant (2003). This synthesis tended to show that the majority of geomembrane liner systems were left uncovered in containment ponds presented in the litterature. Where a cover was applied, it generally consisted of granular layers, in-situ pour concrete covers, shortcrete cover and precast block cover. The above mentioned information has to be considered with caution since they may be influenced by the effect of publication – most pond work do not lead to publication and only reference to exceptional cases or failures are published in the literature (Duquennoi 2002). Whether or not it should be recommended to leave geomembrane liner systems uncovered is another question, since accelerated degradation of unprotected geomembranes attributed to excessive exposition has also been observed (Lambert et al. 1999). Garcin et al. (2002) mention that ponds are more and more designed with green aspect solutions in order to take care of the integration in the surrounding landscape. This recommendation will depend on the type of structure and will be subsequently discussed in the following sections.

2.2.1 *Specificities for mountain reservoirs*

In winter sports resorts, the construction of dams to provide water storage for the snowmaking have significantly increased over the last decade. There are about 105 of them in France (see Figure 3 for an example). Despite their small volumes (5,000 to 400,000m^3) and dam heights of between 5 and 20m, these structures do induce potentially high risks, due to their location in mountain at altitudes between 1,200 and 2,700m (Girard et al. 2010). These reservoirs are very often made watertight artificially by a geomembrane (85% of cases). If uncovered, the geomembrane is directly exposed to multiple attacks: freeze-thaw cycles, UV radiation, impacts and tensile stresses due to the floating ice, stone falls, slope sliding, etc. (Mériaux et al. 2006).

Figure 3. Example of an altitude dam under high paravalenge protection (from Mériaux et al. 2006).

Figure 4. Illustration of the effect of ice on the geomembrane (from Mériaux et al. 2006)

A survey conducted on about 70 of these reservoirs provided considerable information on their pathologies, incidents and even accidents and served as a basis for writing a set of guidelines for studying, designing, constructing, monitoring and rehabilitating. A synthesis of the guidelines provided in this guide is given in Girard et al. (2010) in this conference and will not thus be repeated here in detail. A focus is made on the need to protect the geomembrane, especially as regards the effect of snow (see Figure 4) and on the care in the support and underneath drainage layer preparation.

2.2.2 *Use of geomembranes for lining of reed bed filters*

Reed bed filters are increasingly gaining importance in wastewater treatment procedures adapted to small towns (Savoye et al. 2006). The surface sealing of filters is justified in terms of increasing functional reliability, improving sludge production and storing procedures and assessing the impact of waste on the outlet. Savoye et al. (2006) mention the use of ethylene propylene diene monomer (EPDM) geomembranes in such applications. They insist on the possibility that rhizomes from reeds may damage the geomembrane (see Figure 5). An adapted protection of the geomembrane must thus be designed.

Figure 5. Perforation of the EPDM geomembrane by a rhizome (from Savoye et al. 2006)

Global recommendations regarding the use of geomembranes for reed bed filters or wastewater lagoons were also presented by Fayoux et al. (2009) based on the experience of those authors. An emphasis was made in the paper on the need to properly design the gas drainage layer underneath the geomembrane especially as those installations may be set close to the outlet, i.e. in zones where the groundwater level is close to the surface.

Figure 6. Gas formation underneath the geomembrane of a wastewater treatment lagoon in a wetland results in the formation of bubbles in the geomembrane (From Fayoux et al. 2009)

The drainage level may thus be flooded resulting in the formation of bubbles in the geomembrane as shown on Figure 6. Design and construction measures must thus be taken to ensure that this drainage layer remains free of water.

2.2.3 *Use of geomembranes for runoff water ponds*

SETRA & LCPC (2000) produced a guide of recommendations regarding the design of runoff water ponds along roads using geomembranes. As no other document exists in France regarding the use of geosynthetics for ponds, except the case of mountain reservoirs, this guide is used in the design of a number of ponds. A number of recommendations are given to ensure the best possible performance of the liner system. The actual trend is to recommend a cover on the whole surface of the geomembrane. This is required by the need to get the bottom of the pond accessible for potential cleaning and for durability purposes. Figure 7 gives examples of liner systems for road runoff ponds based on SETRA & LCPC (2000) showing the use of geotextiles under and over the geomembrane in a variety of cases.

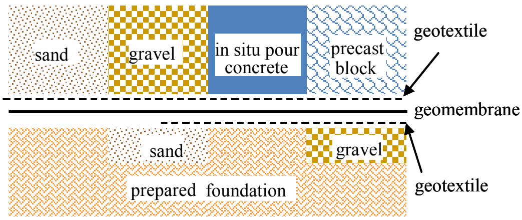

Figure 7. Example of liner systems for road runoff ponds (Adapted from SETRA & LCPC 2000)

2.3 *Geosynthetic covers for reservoirs*

A small number of studies mention the use of floating covers for potable water reservoirs.

Benedetti et al. (2009) give the example of the construction of two floating covers for potable water reservoirs in Corsica (see Figure 8). A reinforced PVC geomembrane was used for this application. The expected duration of the geomembrane under those climatic conditions is 20 years based on the samplings performed on one of those covers. Durability issues for PVC geomembranes will be further discussed in Section 4.2 of this paper. The face of the geomembrane contacting water is suitable for potability. The face of the geomembrane exposed to climatic conditions has a reinforced protection against UV. Water can be stored during a few months without an alteration of water quality and taste. The design has been adapted to the strong winds that can be encountered in Corsica.

Other studies refer to the use of TPO (Sadler & Taylor 2002) or polypropylene geomembranes for the construction of the floating covers for potable water storage (Peggs 2008). In the later case a number of failures were observed that will be discussed in Section 4.3 of this paper.

Figure 8. Ersa (Corsica, France) reservoir full (from Benedetti et al. 2009)

In a different field of application, Nortjé & Meyer (2006) presented the case of a floating cover for a molasses reservoir made of a 1.4mm thick reinforced PP geomembrane. The design had to take account of possible gas generation from the stored molasses as well as water removal from the cover. A system of floats and weights was designed for gas and water removal.

3 PERFORMANCE EVALUATION AT FIELD SCALE: LEAK DETECTION

The objective of this section is to give an update on the existing methods to evaluate the performance of geosynthetics, geomembranes and GCLs, at field scale, describing methods that have been widely used in the past 15 years but also giving an insight in methods that have been less widely used like fiber optic measurement, which seem to be promising.

3.1 *Leak detection for geomembranes*

Leak detection testing is the final stage of CQA programs for a lined facility with a geomembrane (seams, panels, penetrations, etc.) (Koerner & Koerner (2003), Koerner (1996), Peggs (1996), Phaneuf & Peggs (2001) and Thiel et al. (2003)). Testing of the entire system provides an opportunity to check for defects or damages that may have occurred during installation. Methods of CQA leak detection for landfills and other lined facilities lined thanks to a geomembrane generally rely on electrical methods (ASTM 2002, Berube et al. 2007, Darilek 1989, Hix 1998, Hruby & Barrie 2007, Koerner & Koerner 2003, Nosko et al. 1995, Peggs 1999, Phaneuf & Peggs 2001, Thiel et al. 2003). Those methods can also be used later on during the life of the facility especially as regards structures where an access to the geomembrane remains possible on the long term. In this perspect, the primary methods of leak detection is electrical leak location surveys (see Figure 9), and permanent in situ systems (see Figure 10). An alternative method, based on temperature measurement thanks to optic fibers that has been successfully used for canals and dikes will also be briefly presented in this section (see Figure 11). Finally, leak detection through GCLs will be addressed.

3.1.1 *Electrical leak location surveys*

Electrical leak location surveys consist of applying a voltage across the liner system, then systematically measuring the electrical resistance within the lined area (ASTM 2002, Colucci et al. 1996, Rollin et al. 2002). Areas with high resistance indicate the liner system is intact, while areas with low resistance are indicative of holes or tears in the liner.

The advantages of electrical resistivity surveys are that they are relatively easy to conduct and can provide real-time results during construction.

The disadvantages of electrical surveys are that they can only be effective prior to placing material other than a drainage granular layer onto the liner system as after materials are placed on the liner, it can be difficult to locate and repair leaks. The surveys are affected by the conductance of the material overlying and underlying the liner system and contact of the liner to the ground (Peggs & Wallace 2008). Finally, the efficacy of a resistivity survey is subject to human error (adequate coverage and/or operation of equipment). They thus require an experienced operator (Hruby & Barrie 2007). Peggs (2009) presented a synthesis of the factors affecting the results of leak detection surveys and of the precautions that must be taken in order to ensure that reliable results be obtained.

In the case of a permanent in situ leak detection system the method consists of burying a grid of electrodes within the foundation of the facility, prior to the installation of the liner system (see Figure 10). Similar to electrical resistance surveys, the electrical resistance is measured between each "node" of the electrode grid (White & Barker 1997). Areas with high resistance are indicative of "dry" conditions, while areas with low resistance indicate "moist" conditions, which may signify leakage through the liner.

The advantages of the electrode grid method are that:

- The method can be used during any time of the facility operation;
- The method provides uniform coverage of the facility; and
- The method is more automated so it reduces the potential for human error.

(a)

(b)

Figure 9. Electrical leak location survey: (a) on exposed geomembrane; and (b) on a covered geomembrane (courtesy of Solmers).

The disadvantages of the electrode grid method are that:

- In order to test for leaks a liquid must be placed over the lined surface;
- The grid is installed beneath the liner so it cannot be accessed if there is an electrical problem in the grid;
- The presence of moisture inferred by the resistance readings may not be indicative of a leak, but may reflect an increase in soil moisture due to a rising water table or local infiltration at the edge of the facility; and
- The difficulty to repair leaks is even larger in this case than for electrical surveys (Hruby & Barrie 2007).

Figure 10. Installation of cables prior to geomembrane installation for a permanent in situ leak detection system (Courtesy of Sensor).

3.1.2 *Leak detection thanks to optic fibers*

The distributed fiber optic measurement is an innovative measuring system for leakage detection. A description of its application for geosynthetic liner systems was first done by Stroebl et al. (2002) in the case of canals. A simple optic fiber cable was used in this case. The distributed fiber optic temperature measurement is based on the optical properties of the fiber. The system can measure temperatures along optical fibers, which can have a length of up to several kilometers. The cable can be heated up (active method) by applying an electrical voltage at the copper wires integrated in the cable. Those authors indicated that using the active method any seepage water flow under the geomembrane can be monitored and allows the exact locating of even small holes in the geomembrane.

Figure 11. View of the geotextile installation containing optic fibers in the testing pond (courtesy P. Royet)

A more recent application has been performed by Guidoux et al. (2007) in the pond presented on Figure 11 constructed in Cemagref Aix-en-Provence, with the objective to adapt the technique to leak detection in dry dikes. Indeed if the feasibility of the use of this method is proven for dams, it is not for dry dikes. In this case, the optic fibers are incorporated in a geotextile. Preliminary results obtained by these authors tended to demonstrate that leaks are detectable without heat up and without high contrast between air and water temperatures.

3.2 *Leak detection for GCLs*

Peggs (2002) reports on a leak location survey performed on a GCL in a decorative pond. The survey utilized the long-line natural potential (NP) method in which differences of potential are measured between a base electrode planted in soil and a roving electrode sampling along lines at regular intervals or at intermediate points. The NP technique, measuring the small currents generated by water flowing through soils, offers the possibility for application to all GCL-only liners placed on top of soil and that are actively leaking (Peggs 2002).

4 EVALUATION OF DURABILITY OF GEOMEMBRANES IN HYDRAULIC APPLICATIONS

Heibaum et al. (2006) indicated that based on a wide literature review the durability of the geomembranes in hydraulic applications reaches 20 to 30 years or more for exposed geomembranes, as long as their formulation is adequate and the liner system as a whole (including the sub-base, drainage and anchorage) has been well designed, built and monitored. The expected lifetime of covered geomembranes protected from climate and mechanical aggression is significantly much longer. A distinction was made however depending on the nature of the facilities, linked with their size. Indeed it seems that more pathologies appear in ponds and canals of modest dimensions than in dams. One of the explanations is that larger facilities involve significant safety issues while for modest structures it is the financial factor, unfortunately, that often becomes dominating.

Another difference between small and large works is that often less experienced people are concerned by small projects even though technical questions are similar.

The objective of this section is to discuss the durability of oxidized bituminous geomembranes, PVC geomembranes and PP geomembranes based on recent findings presented in the literature. The stability of the protection of geosynthetics in canals will also be discussed based on the results of an in situ experiment.

4.1 *Durability of oxidized bituminous geomembranes*

Touze-Foltz et al. (2010) reported on the hydraulic testing according to EN 14150 (AFNOR 2006) and an adaptation of EN14150 of oxidized bituminous geomembranes coming from six ponds and dams. The oldest geomembrane was 30 years old at the time of excavation. Among the geomembranes tested, four were exposed, one was not covered but located under water in a dam devoted to aquatic leisure (site 5), thus operated at constant full water level except for decennial inspections and one was covered and located under water (site 6).

All uncovered geomembranes exhibited cracks at their surface (see Figure 12). The surface of the covered bituminous geomembrane did not exhibit any crack even 30 years after installation (see Figure 13).

Those cracks could be, but not necessarily, an indication of an ageing of the geomembrane. Those authors thus recommend that a hydraulic test be performed on the geomembrane to evaluate the change in watertightness rather than to base the analysis only on the presence of cracks.

Figure 12. Aspect of the geomembrane surface from site 5 at the time of sampling (uncovered, under water)

Figure 13. Aspect of the underlying face of the geomembrane from site 6 during sampling (covered, under water)

All exposed geomembranes exhibited an increase in the flow rate though the materials compared to a virgin geomembrane of the same nature. This increase could be as large as 3500 times the limit of measurement of the flow rate in EN 14150 (equal to

$10^{-6}m^3/m^2/d$). In case the geomembrane was exposed but located under water the increase in the flow rate was much more limited, around one order of magnitude. In case the geomembrane was protected the level of watertightness was comparable to the one that can be obtained with a virgin oxidized bituminous geomembrane even after 30 years in service.

Based on those results it is recommended that oxidized bituminous geomembranes do not remain exposed if one aims at ensuring that they maintain their hydraulic performance on the long term. This conclusion must not be extended to elastomeric bituminous geomembranes for which there is a lack of feedback at the moment.

4.2 *Durability of PVC-P geomembranes*

The long-term performance of a PVC geomembrane is primarily governed by the retention property of the plasticizers which is greatly influenced by the molecular weight and molecular structure of the plasticizers (Hsuan et al. 2008).

The loss in plasticizer induces an increase in rigidity. Low temperature brittleness also increases. Simultaneously, an isotropic shrinkage is observed due to the loss of volume (Carreira & Tanghe 2008).

In a given situation the degradation of the geomembrane will be faster if the chemical composition of the product is not optimal (Girard et al. 2002). According to the formula, durability may vary between 1 to 2 years for poorly formulated geomembranes to over 20 years (Carreira & Tanghe 2008). This was perfectly illustrated by Savoye et al. (2009) who reported on the failure of a PVC geomembrane after 7 years in a sewage lagoon in a mountainous area. Among the criteria of failure those authors mention the formulation of the geomembrane which was not adequate. Indeed this geomembrane contained a significant amount of chalk. This component is added into the formulation to reduce the geomembrane cost, but it induces an additional porosity and sensitivity to acids, and makes the geomembrane less resistant and flexible.

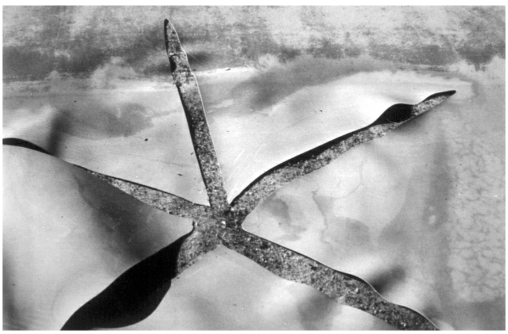

Figure 14. Examples of star-shaped tears (from Girard et al. 2002)

In the case of exposed geomembranes, weathering always results in the geomembrane becoming more rigid, shrinking and tearing (Girard et al. 2002). The time taken by this phenomenon will depend on the quality of the geomembrane and its exposure to UV radiations. Cold was also found to have a detrimental effect on the geomembrane by Savoye et al. (2009).

Tears that can then appear are either star-shaped tears (see Figure 14) or linear tears (see Figure 15).

Figure 15. Linear tear in PVC-P geomembrane (from Savoye et al. 2009)

The durability of a PVC geomembrane, like any other, also greatly depends on the design of the waterproofing system. Indeed, as shown by Savoye et al. (2009) an improper installation led to a tensioning in the PVC geomembrane which resulted, due to the loss of plasticizers, in mechanical ruptures of the geomembrane (see Figure 15). The thickness of the geomembrane, which was also too small as compared to the designed thickness, may also contribute to failure in this case.

In the case of covered geomembranes, an increase in durability was noticed by Girard et al. (2002). The use of reinforced geomembranes or composed ones (with an associated geotextile) to reduce shrinkage induced by manufacturing process and ageing can also be a solution to reinforce durability on major structures such as the Barlovento dam (Fayoux & Potié 2006) (see Figure 2). In parallel, a number of good behaviour of PVC geomembranes even exposed was observed and reported by Carreira & Tanghe (2008) for a number of dams, ponds and canals. Newman et al. (2002) also reported on the good behaviour after 30 years of PVC geomembranes used in twenty aquaculture ponds despite the presence of overgrown vegetation and microorganisms at a high concentration.

4.3 *Durability of polypropylene geomembranes*

Peggs (2008) presented a synthesis regarding the use of PP geomembranes for a number of hydraulic applications: potable water reservoirs and ponds for various applications and floating covers on potable water reservoirs. A number of failures occurred in the case of potable water reservoirs and covers, typically after three to ten years of service (see Figure 16). According to Peggs (2008) accelerated oxidation could be the result of synergies between: (1) UV exposure, (2) thermal exposure, (3) the presence of chlorine, (4) stress, and (54) stabilizer package. Investigations of the stabilizer package of several samples showed that the distribution was far from homogeneous for a geomembrane that undertook a failure, so that the protection was not homogeneous.

However excellent performance characteristics of PP geomembranes were observed in other weather-exposed applications and for some manufacturers in the case of potable water reservoir covers. Indeed, Wallace (2008) reports satisfactory performance of floating covers on potable water reservoirs for five years. Furthermore different PP resins also become available opening the door to potentially more efficient geomembranes.

Figure 16. Cracking in tensioned reinforced flexible polypropylene geomembrane (from Peggs 2008).

4.4 *Evaluation of the stability of geosynthetics in canals*

Flaquet-Lacoux et al. (2004) reported on an experiment they performed on Canal du Nord in France.

The study performed by those authors aimed at evaluating the stability of various protections on the bituminous geomembrane of a canal, under various conditions: filling, emptying, and the effect of waves. As the canal could not be emptied at the time of the installation of the experiment, only three types of protections were tested: gabions, concrete blocks anchored on a reinforcement geotextile and concrete blocks connected to metallic cables (see Figure 17).

Figure 17. Installation of concrete elements on the canal Nord experiment (from Flaquet-Lacoux et al. 2004).

The pressure of water under and above the protections (see Figure 18) and the strength in the anchorage were measured. No pressure under the protection was measured when waves were occurring. No displacement nor damage to the protection were observed during the five months the experiment lasted. An inspection performed in 2009 showed that the cover and lining system are still performing in a satisfactory way (Pers. Comm. H. Girard).

Figure 18: Pressure transducer installation in concrete blocks (Courtesy S. Fischer)

5 EVOLUTION OF HYDRAULIC PROPERTIES OF GCLs FOR VARIOUS HYDRAULIC APPLICATIONS

The objective of this section is to give an insight in the evolution of the hydraulic parameters of GCLs in hydraulic applications, and to discuss the various factors influencing those hydraulic parameters. It is important to discuss those performance and durability issues for GCLs in parallel to the discussion of durability issues for geomembranes presented in the previous section.

First the impact of the hydration without load as compared to the hydration under load is discussed, as regards its impact on the thickness and the hydraulic conductivity of GCLs.

Then the performance of GCLs in ponds and canals and dikes is discussed based on field experience. A number of parameters of influence on the hydraulic conductivity of the GCLs could be identified through those studies. Those parameters can be related to the parameters of influence of the performance of GCLs used in landfill covers as the sole liner as will be shown in Section 5.4.

Finally, a number of recommendations based on the results from those various studies are given, in order to try and ensure the best possible performance of GCLs in hydraulic applications and landfill covers.

5.1 *Impact of the hydration without load of GCLs*

In order to properly function GCLs have to be confined and hydrated. It is usually recommended that load be applied on top of the GCL immediately after installation. Nevertheless, there are a number of situations in which such a practise is not possible and GCLs may be left exposed to wetting without being confined. This can also arise when it is thought that a sufficient amount of water will not be supplied from the underlying soil to the GCL to ensure hydration.

The question that arises is related with the potential impact of the hydration without load on the final hydraulic performance of the GCL as compared to a situation where it would have been hydrated under load.

Petrov & Rowe (1997) studied for one needle punched GCL containing sodium bentonite with a dry mass per unit area of bentonite equal to 3.5 kg/m² the impact of the confining stress during hydration on the bulk void ratio of this GCL. The bulk GCL void ratio is defined as the ratio of the volume of voids to the volume of solids in the GCL (see Petrov & Rowe (1997) for related equations). The configurations studied were either a prehydration under a 6kPa confining stress until a constant thickness was reached prior to increase in the normal stress, or an hydration under the final confining stress. For a range of stresses from 6 to 800 kPa, the final void ratio at a given stress was highly dependant on the degree of bentonite hydration prior to confinement. At a 25kPa confining stress, corresponding to the point where the difference between the bulk void ratio obtained for both configurations of hydration reaches a maximum, the difference in void ratio obtained would result in projected hydraulic conductivities for this product from about 3×10^{-11} to 3×10^{-10}m/s. This illustrates that a significant swell prior to confinement can have a significant impact on void ratio and thus on hydraulic conductivity.

Petrov et al. (1997) carried additional tests on the same GCL, in one case with fibers (needle punched) and in the other case fiber free. They studied the impact of the confining stress on the bulk GCL void ratio during hydration for confining stresses in the range 3 to 400 kPa. They showed the beneficial impact of needle punching. Indeed, no impact of the confining stress value in the range 3 to 6 kPa was noticed for the needle punched GCL. Furthermore low confining stresses in the range 3 to 6 kPa were essentially equivalent to an additional 10 to 15 kPa of overburden in terms of GCL swell. Conversely, significant effect of the magnitude of swelling was observed for the fiber free GCL for 3 and 6 kPa suggesting the need to investigate the potential benefits of a thin overlying saturated soil layer during hydration for the fiber-free product.

Lake & Rowe (2000) studied the impact of bentonite impregnation in the cover geotextile of GCLs and thermally treating GCLs fibers on swelling properties. Thermally treated GCLs refer to fibers that are heated on the bottom geotextile after needle punching. Constant stress swell tests were performed for confining stresses in the range 6 to 400 kPa with distilled water as the hydration fluid. Specified volume swell tests were also performed. The method of manufacturing was found to have an impact for the lowest stresses. In the case of the GCL with bentonite impregnated in the cover geotextile, there will be a high contrast between the void ratio of the surface bentonite and the one which is in the core of the GCL at low stresses. Furthermore the thermally treated needle punched fibers appear to be as or more effective at restricting the GCL swelling.

Touze-Foltz et al. (2009) investigated the impact of various hydration modes on five different GCLs. Contrarily to what was performed in the previous constant stress swell tests, the swell equilibrium was not necessarily reached. The aim of those tests was to evaluate the impact of a five days hydration without load, under various configurations, on the flow rate through the GCL. Three different hydration conditions were tested.

The first one aims at reproducing a variety of applications including landfills and ponds for environmental protection where the GCL can be immersed in water prior to confining stress application. Immersion was performed during five days in oedopermeameters according to NF P 84-705 (AFNOR 2008) previously used by Norotte et al. (2004), Guyonnet et al. (2005) and Guyonnet et al. (2009) for quantification of leachate flow through GCLs (see Figure 19).

The second hydration protocol aimed at simulating heavy rainfalls for GCLs installed horizontally on tunnel extrados. A 0.8mx0.8m piece of GCL was located on a rigid plate nearly horizontal (slight slope). Rainfall events were simulated six hours a day during five days. A sample was removed from the piece of GCL at its centre at the end of the hydration period in order to quantify the hydraulic parameters thanks to oedopermeater tests.

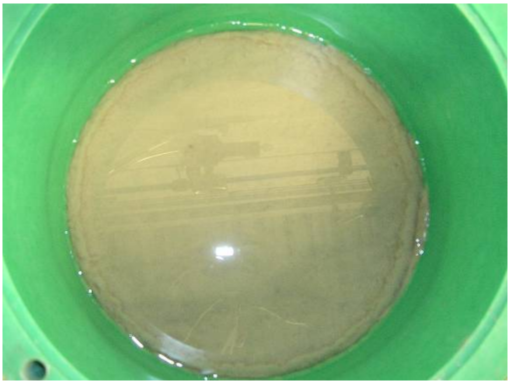

Figure 19. Immersion in oedopermeameter cell

Heavy rainfalls for GCLs installed vertically on tunnel intrados were simulated and evaluated in the same way as for heavy rainfalls for GCLs installed horizontally except that the GCL was installed vertically (See figure 20).

Figure 20. Heavy rainfalls for GCLs installed vertically (courtesy V. Norotte)

Flow rates measurements were performed for virgin GCL samples saturated under a 20kPa load and GCL samples hydrated following the different modes previously presented according to NF P 84-705 (see Figure 21).

Figures 22 and 23 illustrate the evolution of flow rates measured for a needle punched sample and a stitch bonded sample. In the case of the needle punched GCL the hydraulic performance is only slightly affected by hydration without load for the various experimental conditions tested. Indeed a factor two was obtained between the flow rates measured for prehydration under load and the immersion case which is the most detrimental case of all.

Figure 21. Ongoing test in oedopermeameter cell test under 20°kPa

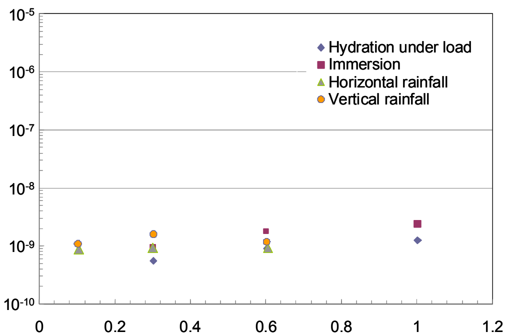

Figure 22. Typical flow rates obtained for needle punched GCLs depending on the hydration mode

Results obtained for the two stitch bonded GCLs are significantly different for the two products. Indeed, in one case the immersion of the GCL was really detrimental to the GCL and no flow rate could be measured for hydraulic heads larger than 0.3m as they became too large. In this case this GCL does no longer perform its lining function. Results obtained with the second stitch bonded GCL, are significantly different. Indeed, even if an increase in the flow rate is observed between the situation where the GCL is hydrated under load and the case where it is immersed for the hydration without load, the increase of flow is only by a factor 5 (see Figure 23).

It is thus consequently recommended that stitch bonded GCLs be covered immediately after installation, what would not necessarily be required for needle punched GCLs. However the susceptibility to puncturing for those hydrated products without load has not been taken into account in the conclusions and is a point that would deserve additional research.

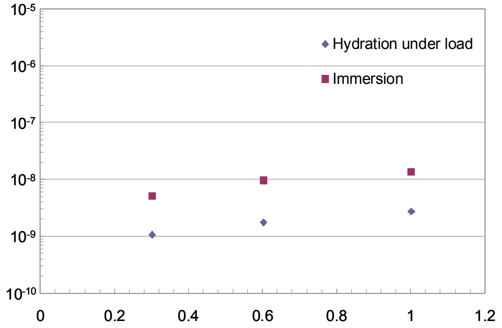

Figure 23. Flow rates obtained for GCL3 depending on the hydration mode

5.2 *Performance of GCLs in hydraulic applications*

5.2.1 *Performance of GCLs in ponds*

Peggs & Olsta (1999) report on the use of a single GCL liner for the containment of 3.4m of liquid in three wastewater treatment lagoons using soils containing stones up to 150mm diameter as subgrade and confining materials. The soil cover on top of the GCL liner was 0.45m thick. The GCL failed to ensure watertightness in the three ponds: hydraulic heads larger than 2.1m above the GCLs could not be reached. An investigation was performed in order to determine the reasons of failure of this GCL. Among the reasons was the granulometry of the subgrade (see Figure 24) which was not uniformly supporting the GCL and may have been responsible for internal erosion of the bentonite. Internal erosion in GCLs was studied by Rowe & Orsini (2003). They demonstrated that for GCLs with a conventional woven or nonwoven carrier geotextile, resting on a gravel or geonet, high hydraulic gradients could cause internal erosion within the GCL that could result in an increase in hydraulic conductivity of at least one order of magnitude. The method of construction of the GCL was shown to be important. The tests on GCLs with a scrimreinforced geotextile carrier layer indicated that hydraulic gradients of up to 7000 (equivalent to about 70m of water head) could be sustained without measurable internal erosion for the cases examined. When the GCLs were resting on a sand subgrade, no evidence of internal erosion was noticed with applied water heads of up to about 70m.

The presence of large stones also led to other detrimental effects. Indeed, as the GCL was not uniformly supported, a uniform confining pressure necessary to ensure a maximum impermeability could not be generated. Furthermore, the large stones caused the formation of holes in the GCL (see Figure 25) (Peggs & Olsta 1999).

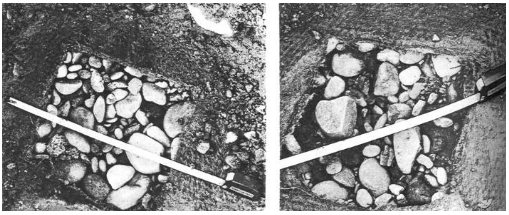

Figure 24. Views of the subgrade under the GCL (from Peggs & Olsta 1999)

Finally those authors state that for a good containment, the maximum depth of water for a single GCL liner would be about 1.5m even if depths of 3m or more have been contained. As depth increases, the granulometry of the finer soil particles in the subgrade and confining soil has to be decreased.

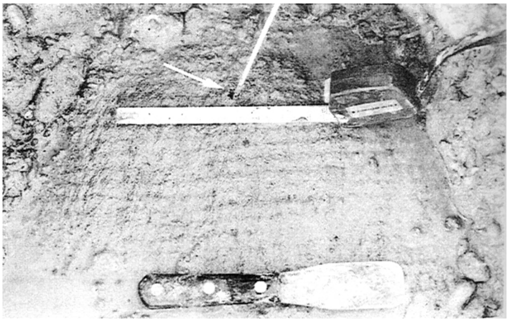

Figure 25. View of a hole in the GCL (from Peggs & Olsta 1999)

Regarding the nature of the liquid that can be contained by GCLs, Egloffstein et al. (2002) suggested that GCLs should not be used for lining of ponds containing concentrated solutions in non-polar organic liquids with a low dielectric constant like petrol, chlorinated hydrocarbons, xylol, and ethanol for example. Exceptions would only be possible when the GCL is saturated with water and when the contact remains short. No applications for permanent sealing purposes against acid with pH values lower than 3 and alkaline solutions with pH values greater than 13 are recommended. According to these authors preliminary tests should be performed for hard groundwaters (Ca^{2+}, Mg^{2+}), waters containing iron and leachate with high electrolytic concentrations. For highly concentrated pure solutions containing K^+ and NH^{4+} the application should be limited due to the specific interaction between those ions and montmorillonite. For heavy metals of high concentrations, the use of GCLs must also be evaluated by preliminary testing, like for hydrous solutions with polar organic liquids or leachate with high concentrations of organic cations. Those authors also recommend for the use of GCLs with leachate and chemical solutions that the pre-swelling of the GCL be performed with water with low electrolyte content. The GCL should also be covered with at least 1m of soil. This is consistent with elements given by Renken et al. (2007) who indicate that a GCL may fail when it is needed to contain highly acidic solutions with a pH lower than 2 and that ion exchange may also be an issue for acid rock drainage as it contains high concentrations of divalent cations like Cu^{2+}, Zn^{2+} and Pb^{2+}.

Failures can occur if those conditions are not respected. For example, Touze-Foltz & Hatton (2006) reported on the case of the use of a GCL as the single liner in ponds dedicated to the collection of wastewater. Cation exchange occurred between the GCL containing natural sodium bentonite and the subgrade and conducted to a change in hydraulic conductivity from 4×10^{-11}m/s to 10^{-9}m/s after 3 months of exposure. This resulted in a failure of the GCL liner. In this case the GCL was not prehydrated with a solution having a low electrolytic content, and the confining soil thickness was very low (0.3m of calcareous soil).

5.2.2 *Performance of GCLs in canals and dikes*

The use of GCLs for lining applications in navigation canals and dikes is rather new. Heibaum et al. (2006) reported on three cases of GCL installations in canals under water. The excavation of some of those GCLs performed by Fleischer & Heibaum (2008) has provided some information after a few years (between three and five) in service of those products. The GCLs were covered by a sandmat and armourstones.

Some indentations in the GCLs could be noticed as shown on Figure 26 that occurred during installation of the riprap. The conversion of sodium initially present in the bentonite to calcium had been completed in around five years probably in relation with the large content in ions in the canal water. Out of the specimens taken from the GCLs, some had a hydraulic conductivity value, k, that increased by more than a factor 10. This limit in increase of the k value is given in the supplementary technical contract conditions for hydraulic engineering (ZTV 2006). For the specimens for which the hydraulic conductivity value was below this limit, the increase in hydraulic conductivity was attributed to ion exchange and frost.

In case the increase in hydraulic conductivity was larger, the local compression of the bentonite (see figure 27) was the explanation.

Fleischer & Heibaum (2008) also report on the excavation of a GCL on a dyke after six years in service. The GCL was located under 0.8m of a protective covering layer comprising sand and gravel. The grass covered dyke foreland was usually dry but was flooded several times during the service period. The excavated GCL was in excellent conditions and did not exhibit any depressions. The hydraulic conductivity had only increased slightly even if the sodium had been nearly totally exchanged by calcium. This emphasizes that a proper design of the GCL protective cover with a sufficient thickness protecting against thinning, freeze/thaw cycles, and desiccation is required.

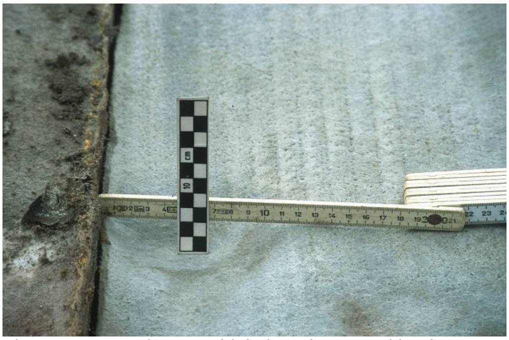

Figure 26. Bentonite mat with indentation caused by riprap (From Fleischer and Heibaum 2008)

Figure 27. Section through an excavated bentonite mat showing a considerable local reduction in thickness (Courtesy M. Heibaum)

This is consistent with findings regarding the use of GCLs for landfill covers, as will be described in the following section of this paper.

5.3 *Performance of GCLs in landfill covers*

The long-term performance of GCLs in landfill cover systems depends on a number of factors among which: (1) the surcharge from the soil cover; (2) the water reservoir of the restoration layer; (3) the drainage layer; (4) roots in the soil; (5) the properties of the adjoining layers; (6) the climatic conditions; and (7) the GCL itself (Zanzinger & Touze-Foltz 2009). The real performance has been studied by continuous measurements on site over reasonable periods of time and/or by excavations of GCLs after certain durations in service. A number of conclusions were obtained from tests field studies and excavations that were performed in the past to evaluate the performance of GCLs in landfill covers, regarding the influence of roots, cation exchange and desiccation, composition of capping system and thickness, climatic conditions and GCLs features that will be subsequently discussed.

5.3.1 *Influence of roots*

Roots can have two effects on the performance of a GCL in a cover. First, roots may have an effect on the dehydration of mineral liners in landfill cover systems. Roots which reach the GCL will take the moisture directly from the bentonite whatever the depth of the liner. This may enforce the dehydration process of a GCL in addition to thermal gradients in a landfill capping system. Second, roots can have an influence of the hydraulic conductivity of a GCL. Indeed if a root penetrates a liner and as long as a vital root is still alive the permeability of the liner might not change or even be improved. In a later stage if the roots die there will be a leakage by the root itself and the percolation will increase locally (Zanzinger & Touze-Foltz 2009).

5.3.2 *Cation exchange and desiccation*

The use of GCLs in capping systems is problematic if they are not adequately protected (Melchior 2002, Benson et al. 2007). It has to be expected that when desiccation and ion exchange take place after a short period of time irreversible damages to the GCL will occur. According to values from 12 excavations mainly of landfill caps reported by Egloffstein (2001) the ion exchange usually takes approximately 1 to 2 years when the GCL is used in unsaturated conditions. Further, it has been established that due to cation exchange, the hydraulic conductivity of the GCL is about one order of magnitude larger than that of the original Na bentonite as long as there are no desiccation cracks (Sporer & Gartung 2002). When desiccation cracks occur, the cation exchange in the interlayers prevents the desired self-healing of the fissures. The ensuing leakage cannot be avoided. This emphasizes the need to prevent desiccation of the bentonite. Investigating more deeply this phenomenon, Benson & Meer (2009) showed that the RMD, corresponding to the ratio of the total molarity of monovalent cations to the square root of the molarity of divalent cations, controls the final swell index of the bentonite and the final hydraulic conductivity of bentonite exposed to wet-dry cycles. Ionic strength was found to affect the number of wet-dry cycles required for a change in hydraulic conductivity to occur and the rate of change in swell index.

5.3.3 *Thickness of capping system*

From various experiences in Germany reported by Zanzinger (2008), it appears that a 1 m thick restoration layer is sufficient in protecting GCLs from desiccation (see Figure 28).

Cover soil thicknesses slightly smaller (0.8 to 0.9 m) in Northern America could not guarantee a good behavior of GCLs in covers (Meer & Benson 2007, Mackey & Olsta 2003). This emphasizes the need for a better knowledge of a number of parameters to better understand the behavior of GCLs in covers for a number of conditions.

Figure 28. Soil cover on top of a GCL at the time of excavation (from Zanzinger and Touze-Foltz 2009).

Ramke (2003) summarizes the German practise, to protect mineral liners in landfill caps from desiccation. He recommends that a restoration layer must have a minimum thickness of 1.5 m. Under dry climatic conditions (average annual precipitation of less than 800 mm/a) a thickness of 1.8 to 2m of the restoration layer with water storage function seem to be suitable.

5.3.4 *GCL features*

As poor and bad performance was found for GCLs with very low mass per unit area (<4 kg/m²) sometimes combined with low soil cover thickness (<0.5 m) the minimum dry mass of bentonite per unit area is seen as the basic differentiation feature for GCLs. As a recommendation Zanzinger & Touze-Foltz (2009) give a minimum dry mass of bentonite per unit area equal to 4.5 kg/m² for sodium bentonite in a GCL. This is consistent with recommendations from the French Chapter of IGS (CFG 2010).

Even though the effect of granulometry (granular versus powder) has not been clearly investigated up to date as regards the field performance of GCLs, this factor could have an impact on the behavior of the GCL that remains to be addressed.

5.4 *Conclusions regarding the use of GCLs for hydraulic applications*

From the above studies, some important conclusions regarding the use of single GCL liners in hydraulic applications and landfill covers can be given:

- Cation exchange will occur in any case, unless the GCL is installed in an environment containing mainly sodium ions which is not a usual situation;
- Consequently, a GCL requires adequate uniform confining pressure to provide adequate barrier performance characteristics (Peggs & Olsta 1999); the GCL should be covered with at least 1m of soil ; this should ensure that freeze/thaw cycles and hydration/desiccation cycles do not take place in the GCL; and
- Soils with a large granulometry (stones larger than 25 mm and up to 150mm) and a low percentage of fines can result in the generation of holes in the GCL and migration of the bentonite.

6 NATURE OF BENTONITE FOR GCLS

The question of the adequation of the nature of the geomembrane for hydraulic and environmental applications is often raised, but the question of the adaptation of the nature of the bentonite in a GCL is far less often discussed. If this may not be a crucial issue in Northern America where mostly natural sodium bentonite from Wyoming is available, it can be an issue in other parts of the world like Southern America, Europe, Africa, Asia or Australia where various types of natural sodium bentonite, sodium activated calcium bentonites and natural calcium bentonites can be encountered (Chung 2004).

According to Gates et al. (2009) the consensus now is that to simply specify the clay component with a generic term like "sodium bentonite" is insufficient as it ignores subtle differences like impurities and particle size. Small changes within bentonite mineralogy, clay chemicals and particle size can both have a significant effect on the short and long term performance of GCLs. Indeed the nature of bentonite contained in GCLs can have an impact on the flow rate through the GCL as will be shown in the following section.

6.1 *Insights regarding the impact of the nature of the bentonite on transfers through GCLs*

Research presented by Benson et al. (2008) showed that permeation with leachate from an alumina refinery after 8 pore volumes of flow led to a significant impact on the hydraulic conductivity, with differences observed based on the nature of the bentonite contained in the GCL. Prehydration also had a significant effect on the hydraulic conductivity. It was found that the hydraulic conductivity of the GCL containing an Australian bentonite was 60 to 800 times larger to leachate than to tap water. For a calcium activated Chinese bentonite, the ratio of hydraulic conductivities ranged between 120 and 390.

Recommendations expressed in the Guide of recommendations, for third party experts, relative to the assessment of equivalence in France (MEDD 2002) stated that natural sodium bentonite GCLs are to be preferred to sodium activated calcium bentonite GCLs for bottom liner systems in landfills. This principle was reinforced by Guyonnet et al. (2005) who showed that a GCL containing natural sodium bentonite performed systematically better, in identical experimental conditions, than a GCL containing sodium activated calcium bentonite. It is believed that the main reason for this was the higher calcium carbonate content of the activated bentonite GCL (10 % in weight) in relation with the activation process (mixture with $NaHCO_3$ volcanic ash). Calcium carbonate, associated with the bentonite clay, provides a pool of divalent cations that are ready to exchange with the clay upon dissolution. Such results have prompted landfill operators in France to prefer natural Na-bentonite GCLs rather than Na-activated Ca-bentonite GCLs in agreement with recommendations expressed in the Guide of recommendations, for third party experts, relative to the assessment of equivalence (MEDD 2002). However, the distinction between natural and activated bentonite is only part of the issue and other criteria are needed in order to check whether a given product is suitable for a given application (Guyonnet et al. 2008). This statement is reinforced by data presented by Lee & Shackelford (2005) who investigated the behaviour of two needle punched GCLs containing different sodium bentonites, one having a higher montmorillonite content, plasticity index and cation exchange capacity (CEC) than the other. While permeated with $CaCl_2$ solutions the hydraulic conductivity of both GCLs increased with increasing concentration and the hydraulic conductivity of the bentonite having the higher montmorillonite content was the largest. Thus the GCL with the higher bentonite quality was the more subject to chemical attack upon permeation by the $CaCl_2$ solution. Consequently additional criteria are required to evaluate the adequation of a bentonite to a given environment. A possible way to perform this evaluation will be presented in the following section.

6.2 *Evaluation of the chemical compatibility between bentonite and various solutions through filter press tests*

Filter press tests were investigated as a possible way to quickly evaluate the potential interaction between a bentonite and a leachate. The filter press test is very similar to the fluid loss test (ASTM D 5891) except that the effluent is collected all along the test in order to obtain a filtration curve which allows calculating the permittivity of the bentonite cake formed during testing (Pantet & Monnet 2007; Paumier et al. 2009). 40g of bentonite extracted from the GCL is dispersed in 400g of fluid. The filtration cell containing 300ml of the bentonite dispersion is submitted to a constant pressure of 700kPa during one hour. The filter press test is performed after 24 hours of ageing of the dispersion. The filter press test gives a single point corresponding to the chemical equilibrium of the dispersion which may not be representative of the chemical equilibrium that could be reached on site. However it provides useful information regarding the behavior of bentonite in contact with various solutions as will be shown later in this section.

Three sodium activated calcium bentonites (B1, B3 and B4) and one natural sodium bentonite (B2) presented in Table 1 were studied.

Table 1. Initial characterization of the bentonite

	Calcite	Smectite	CEC	Exchangeable cations (% exchange sites)			
	wt%	wt%	Meq /100g	Ca	K	Mg	Na
B1	2.1	76	88	8	1	8	84
B2	1.5	69	77	27	1	6	65
B3	2.7	71	87	11	1	10	79
B4	2.8	75	83	13	1	5	81

Note: CEC = cation exchange capacity

The various bentonites were dispersed in five solutions: (1) a synthetic leachate (SL) formulated by Guyonnet et al. (2009) with the aim to reproduce an "aggressive" acidogenic leachate; (2) an acidogenic leachate (AL); (3) a leachate from a green waste repository (GL); (4) a sewage sludge (SS); and (5) a methanogenic leachate (ML). The cationic composition of those various fluids is given in Table 2. The SL solution was tested either as is or diluted at various ratios in osmosed water to produce a range of fluids $F1_{BX}$ to $F3_{BX}$, BX designing the bentonite (B1, B2, B3 or B4). Those fluids are easily reproducible, with a potential contrasted impact on the bentonite. The SL dilution was adapted for each bentonite according to its swell index so that the swelling of the bentonite dispersed in $F1_{BX}$ reached 25% of the maximal swelling obtained with the osmosed water for the bentonite BX. For $F2_{BX}$ and $F3_{BX}$ fluids, the swelling reached respectively 50% and 75% of the maximum swelling as indicated in Table 3.

Table 2. Cationic composition of the five fluids tested.

	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}
SL	714	810	537	379	1072	3803	417
AL	877	1220	1016	162	46	1363	194
GL	55	7	562	33	111	282	<d
SS	84	1095	81	32	35	170	<d
ML	5683	2856	4132	<d	24	5397	21

Note: <d: under detection limit

Table 3. Composition of the F1 to F3 fluids in percent of SL in water, according to the bentonite.

	B1	B2	B3	B4
$F1_{BX}$	10	11	11	13
$F2_{BX}$	21	23	21	26
$F3_{BX}$	51	57	47	61

The permittivity of the cake was calculated for each test and reported as a function of the electrical conductivity of the dispersion in Figure 29.

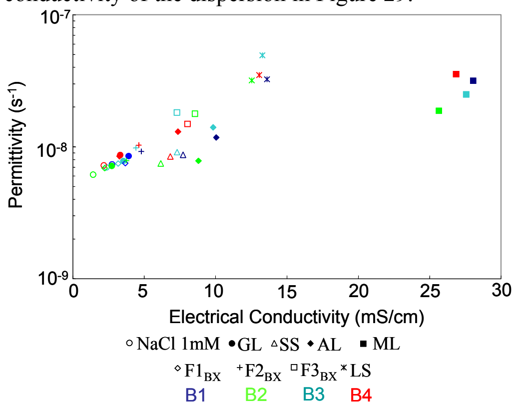

Figure 29. Permittivity determined by filter press tests for each fluid.

The bentonite dispersions have contrasted electrical conductivities even if the same fluid is used. The differences are due to the dissolution of soluble salts contained in the bentonite. This cationic and anionic contribution modifies the initial chemical composition of the fluid. The nature of the bentonite can also affect the permittivity of the dispersion. For dispersions made with the same fluid, for example, and various bentonites, the permittivities were contrasted. GL, SS, F1 and F2 did not significantly impact the value of permittivity, whatever the bentonite, as compared to a dilute NaCl solution.

For the SL dispersions and SL, the evolution was exponential. B3 appeared to be the most sensitive to SL. The permittivities of B1, B3 and B4 dispersed in AL were close to values obtained with F2. ML dispersions had the largest permittivities of all with contrasted values for the different bentonites.

For each bentonite, the permittivity of the dispersion increased with the electrical conductivity of the dispersion. For calcium fluids like SL dispersions, the permittivities of the fluids increased faster than for soda fluids like ML.

From those results it appears that filter press tests may provide a tool for the choice of the most adapted bentonite for the containment of a given fluid.

6.3 *Recommendations regarding the choice of bentonite for landfill applications*

Table 4 issued from Guyonnet et al. (2009) gives the main features that have to be fulfilled by the bentonite contained in GCLs used for bottom liners, based on a research program they performed. In this research program eight different GCLs containing either natural sodium bentonite, calcium activated bentonite or natural calcium bentonite were characterized and permeated with three different fluids: a low ionic concentration sodium chloride solution, a real leachate and a synthetic leachate.

Table 4. Indicators allowing to control the sodium GCLs used in bottom liner systems (from Guyonnet et al. 2009)

Indicator	Value
Mass per unit area (kg/m^2)[1] NF EN 14196	5
Swell index[2] XP P 84-703	≥ 24 $cm^3/2g$
Cation exchange capacity (CEC) [3] NF X 31.130	≥ 70 meq/100 g
$CaCO_3$ content [4] NF P 94-048	≤ 5% of the dry mass of bentonite
Carbone et Oxygen isotopes [5]	

[1]Dry mass of bentonite (0% water content)

[2]Value usually given in technical data sheets

[3]Correlated to smectite content

[4]This proportion of $CaCO_3$ could, after dissolution saturate a CEC of 75 meq/100 g with Ca^{2+} ions

[5]In case one wants to check the origin of the bentonite

An emphasis is made through this study on the calcium carbonate content. Indeed calcium carbonate, associated with the bentonite clay, provides a pool of divalent cations that are ready to exchange with the clay upon dissolution.

Based on those recommendations, the Guide of recommendations, for third party experts, relative to the assessment of equivalence from MEDD (2002) has recently been revised (MEEDAT 2009) and no distinction is made any longer between calcium activated bentonites and natural sodium bentonites.

Additional investigations are required on this topic as regards the impact of granulometry of the bentonite, nature of the bentonite, activation and assembly mode to guarantee the adequation of a given GCL for a given application.

7 CONCLUSIONS

The objective of this paper was, based on a number of experiences reported in the literature, to give an insight in the state of practice and durability regarding the use of geosynthetics for lining in geoenvironmental and hydraulic applications. Mining applications, dams and bottom landfill liners were not taken into account except for the question of the adequation of the bentonite in a GCL to its environment as those topics were addressed in detail by different authors in the same conference. First the use of geosynthetics for lining in canals, ponds and reservoir covers was discussed. A brief insight in regulations or guides of recommendations for the use of geosynthetics in such applications was given when available. The evaluation of the performance of liner systems at field scale was further discussed. A brief overview of electrical leak detection systems for the check of the integrity of liner systems was given and optic fiber measurement was also presented. An insight was also given regarding the methods to evaluate the performance of GCL liners on site, a question often raised.

Based on a literature review elements regarding the durability of bituminous, polyvinyl chloride and polypropylene geomembranes was presented.

Another important point discussed was the evolution of the hydraulic performance of GCLs for hydraulic (tunnels, canals, ponds) and environmental applications (landfill covers) in relation with hydration conditions, cation exchange and design parameters like the soil cover thickness on top of the GCL.

Finally, the methodologies that can be used to check the adequation of the bentonite contained in the GCL to the environment in which the GCL will be installed were discussed. Recommendations from the literature were presented regarding the choice of a bentonite for bottom landfill liners. This review allowed to notice that if the geomembrane formulation, or the nature of the bentonite and the mode of fabric of the GCL can affect its performance, design, construction and use of the facility will also have an effect. It seems that oxidized bituminous and PVC geomembranes perform better when covered. A minimum soil cover thickness on top of GCLs seems to be the minimum requirement for middle European climates. In any case for those products, the cover must allow to prevent form freeze/thaw and desiccation/hydration cycles in the bentonite. A methodology was proposed to evaluate the adequation of the bentonite for a given environment. It should be one of the primary goals, for geomembranes and GCLs to adapt the nature of the product to the environment in which it has to perform as a watertight material.

ACNOWLEDGEMENTS

The writers sincerely appreciate the opportunity given by the organizers of this conference to present this work. Many people offered information and assistance in the preparation of this Keynote Lecture. The following people are thanked for providing data used in the preparation of some figures: D. Fayoux, S. Fischer, H. Girard, M. Heibaum, T. Jacquelin, V. Norotte, P. Royet, I. Peggs, L. Peggs, D. Savoye, K. von Maubeuge and H. Zanzinger.

The careful review of the written text by H. Girard is very much appreciated. Finally, the contribution from S. Paumier who assisted the author in the preparation of the section dedicated to the nature of bentonite in GCLs is also acknowledged.

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