Geosynthetic drainage and lining systems in piggy-back landfills

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ABSTRACT: During the last decades, considerable efforts have been devoted to the reduction of ultimate municipal solid waste (MSW), but landfills are still a major step in the MSW treatment process since a great part of MSW are not recyclable with the current techniques. However, it is becoming fairly difficult to find new sites to build new landfills because of several reasons such as the limited available footprint and the opposition from nearby residents. To address that problem and to increase the waste storage capacity while using the existing operating infrastructures, an attractive alternative is to build new landfills over older ones. This new way of building what is called piggy-back landfills requires implementing an efficient drainage and lining system (DLS) between the old and new waste. By addressing a comprehensive review of landfills worldwide, this study aims to show the main components of the DLS necessary to guarantee its stability and integrity. This study also provides the regulatory framework and some state of the art and international standardization in the design of the DLS in the context of piggy-back landfills. The purpose is to provide some safe practices in the design of such DLS.

Keywords: geosynthetics, drainage and lining system, piggy-back landfills

1 INTRODUCTION

In 1987 in New-York state (USA), the Blydenburgh landfill (in operation since the 1950's) operators, were facing a challenge of limited available footprint. It was decided to increase the waste storage volume by building a new waste cell over the existing one. This was the first landfill expansion commonly termed as piggy-back landfill. This new way of building has gradually developed over years and across the world because it offers several advantages like the possibility of using the existing operating infrastructures with significant cost-benefits.

The piggy-back landfill requires the implementation of a new piggy-back landfill lining systems (PBLS) to avoid the leachate percolation in old waste and then in groundwater. For an efficient performance, this PBLS should be designed based on some key considerations such as differential settlements, the chemical environment, the interface stability and the drainage of potential gas and leachate from the old waste. However, major differences can be found between the designs of PBLSs from one site to another. This is mainly due to the fact that, during a long time, there was a lack of regulations or guidelines specific to the design of

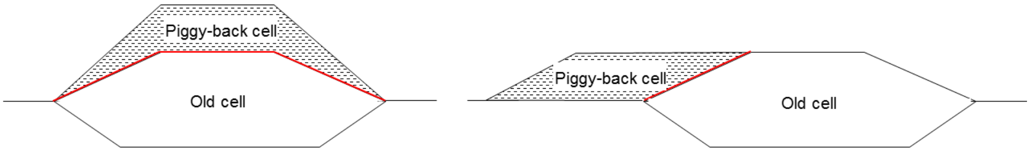
PBLS. It is hence important to draw up a state of start of the current practices for the design of PBLS and to provide minimum technical requirements. In this study, the general and regulatory frameworks of piggy-back landfills are firstly presented before the comprehensive review of 22 PBLS structures around 6 countries. Some general guidelines for the selection of the various geosynthetics within a typical PBLS, are provided for a safe design.

2 GENERAL FRAMEWORK

Due to the scarcity of suitable ground (low permeability, etc.), limited available footprint, social pressure (nearby residents), as well as the long permitting and approval process of new landfill construction, landfill operators often choose to maximize the existing landfill airspace by the construction of new waste cells over older ones. This specific mode of storage commonly known as piggy-back landfill is an interesting way to continue storing the waste with significant cost-benefits. The three common configurations of piggy-back landfill are:

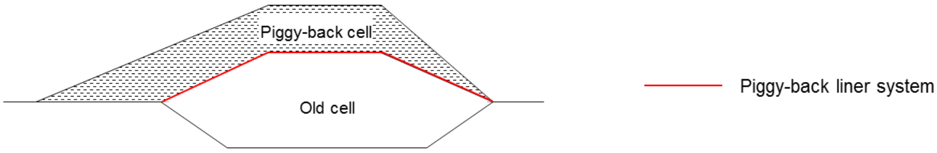
- Vertical expansion (V): the new waste cell is built exclusively over the top surface of the old (existing) cell. (Figure 1a),
- Lateral expansion (L): the existing landfill is extended laterally with the construction of the new cell supported as part over the side slopes of the existing landfill (Figure 1b), and
- Mixed expansion (M): this is the case where the two previous configurations are combined (Figure 1c).

The three above configurations are often associated with additional infrastructures like perimeter berms on the toe of the slopes and can have some particularities depending on the site conditions.



a) Vertical

b) Lateral



c) Mixed

Figure 1: simplified geometric configurations of piggy-back landfills (Tano et al., 2015)

3 REGULATORY FRAMEWORK SPECIFIC TO PIGGY-BACK LANDFILLS

In order to prevent leachate percolation into groundwater and to keep a safe sanitary environment, modern landfills commonly use mineral materials and geosynthetics (GSY) as a lining and drainage system. This system is designed based on regulations and standards. In France, landfills were designed according to the European Union Council Directive n° 1999/31/CE (26/04/1999) and to the modified ministerial order (1997, 2001, 2006, 2007, 2011 and 2012) specific to landfills. More recently, a new version of the ministerial order has entered in force by the beginning of 2016.

In Table 1, the current section of the drainage and lining system for a standard landfill which are required by the applicable law are presented. This typical section includes from bottom to top, a passive barrier and an active barrier. The passive barrier is made of a 5 m thick geological barrier at a permeability $k \leq 10^{-6}$ m/s and a 1 m thick clay layer at a permeability $k \leq 10^{-9}$

m/s. The active barrier is made of a sealing material typically a geomembrane (GMB) and a 0.5m thick drainage material (gravel). Note that all these thickness are the minimum ones required by the applicable law.

However, the applicable law includes a possibility to replace the mineral materials of the typical section by alternative ones provided that the alternative system is at least equivalent to the replaced one. This concept of “equivalence” is applicable both for the sealing passive barrier and the drainage layer at the active barrier.

However, concerning the design and construction of piggy-back landfills and particularly and their piggy-back lining system (PBLS), there is actually, a lack of regulations or guidelines specific to this mode of building.

Given this situation, several works were initiated in France at the end of 2015 in order to provide minimal technical requirements for the design of piggy-back landfills. These works concern (i) the new French regulation on landfills which includes a specific section concerning piggy-back landfills, (ii) the revision of the French guide of good practices for the geological, hydrogeological and geotechnical survey of landfills which should also address the type and the size of the survey specific to piggy-back landfills and (iii) a new technical guide devoted entirely to piggy-back landfills. These works should require a complete passive barrier at the bottom and side slopes of the new landfill when the existing landfill liner system does not meet the requirements of the new French regulation on landfills. The concept of equivalence for bottom lining systems should be also applicable to the PBLS. As regards the reinforcement GSY are necessary to bridge possible voids and withstand the forces induced by differential settlements should be designed according to Eurocode 7 (partial factors). The design should include reduction coefficients for taking account of the physical damage during installation, the creep and the chemical degradation of the product.

Table 1. Typical section of a lining system of a standard landfill according to the French regulation

Barrier system	Cell bottom		Cell side slopes	
	Function	Material	Function	Material
Active	Drainage	Granular materials* (thickness: ≥0.5 m)	Drainage	Geosynthetic
	Active permeability	Geomembrane**	Active permeability	Geomembrane**
Passive	Passive permeability	Clay*** (thickness: ≥1 m)	Passive permeability	Clay soil (thickness: ≥1 m) or 0.5 m of clay*** on the lower 2 m from cell bottom
	Attenuation + subgrade layer	Natural materials existing on the site (thickness : ≥5 m)	Attenuation + subgrade layer	Natural materials existing on the site (thickness : ≥5 m)

* Can be associated with drainage geocomposites with reduced thickness to 0.3 m for the equivalence;

** Geotextile necessary on the upper face of the geomembrane for protection;

*** Can be associated with Geosynthetic Clay Liner or treated soil (Sand-Bentonite-Polymer for example) in the context of equivalence.

4 STATE-OF-THE-ART OF PIGGY-BACK LINING SYSTEMS WORLDWIDE

Depending on the site conditions and country practices, major differences between the designs of the PBLS can be found. In order to highlight the various similarities and differences between the designs, this section presents the current state of practice around the world. The analysis is made based on 22 case studies among 6 countries. These case studies and the general structure of their PBLS are summarized in Table 2. The classification in Table 2, is completed with a statistical view (Figure 2) in terms of percentage of use of the various GSY components (structure, nature and function of GSY) within the PBLS.

The analysis of Table 2 and Figure 2 is performed below for each function of the lining system component: active barrier, passive barrier, reinforcement of the barrier and the drainage of gas stream and leachate flow from the old waste.

4.1 *Active containment barrier*

Concerning the drainage at the active barrier system, a layer of sand or permeable granular materials like gravels is always implemented. The thickness of this granular material layer among the reviewed sites varies from 0.15 m (e.g. Danes Moss site in U.K.) to 0.6 m (Maine site in USA). It could also be noted that the granular layer is often associated with a drainage GSY like a geonet or a geocomposite drain (GCD). This drainage GSY, aside from its drainage role, protects the underlying GMB from puncture. The granular materials also protect the drainage GSY against Ultra-Violet radiations and from mechanical actions of construction site machinery during the waste filling (Golder Associates 2011).

As regards the sealing function of the active barrier, a GMB is always implemented. But, different polymers, types and number of GMB can be found.

For the nature of the polymer, Table 2 shows that all the GMBs used in the PBLS are made of either high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE). HDPE GMBs are the most used with almost 80% of the GMBs used on the reviewed sites. This is presumably because HDPE is known as an excellent chemical inertness material (Sadlier and Frobel, 1997). In France, only HDPE GMBs have been used on the identified sites while LLDPE GMBs are used abroad for 18% of the case studies. Indeed, in some countries like Australia, China or USA, LLDPE GMBs are used for their high flexibility which should be more suitable for potential differential settlement hazards. This is the case for example of the Peabody site, Johnston County site in USA, and the MLRMC site in Australia.

Other polymers like polypropylene (PP) or flexible polyvinyl alcohol (PVC) exhibit similar properties to LLDPE in terms of flexibility (similar multiaxial behavior) (Stulgis et al., 1996) to set up a flexible PBLS for differential settlements. These polymers, however, exhibit several drawbacks and are not suitable for a use in leachate environment (except PP). This point will be further discussed in section 5.

As regards the type of GMB surface, even if smooth GMBs have been widely used (70% of the reviewed sites), textured GMBs are also considerably used. As an example, textured GMBs were used on the Maine, RIEDSBM and Danes Moss sites, in order to increase the interface stability by increasing the interface shear strength. Beyond that, both smooth and textured GMB can be used on a same site depending on the slope gradients. This is the case for the Blydenburgh landfill (first landfill expansion), Maine landfill and MLRMC landfill. For the first landfill expansion, textured GMBs were implemented on the slopes steeper than 6H/1V (≈ 9.5°) while smooth GMBs were placed on the lower gradients. In France, textured GMBs are almost never used. Only the site D has used a double-sided textured GMB because of significant slope gradients.

Furthermore, the common practice is to use only one GMB within the PBLS. In some cases (Johnston County, Maine and RIEDSBM sites), however, two GMBs separated by a drain are implemented. This double-lining system aims to establish a leak detection system (Richardson et al. 2008). In case the top GMB would be defective, the leachate would be directed trough the drain towards a collector, so the leak can be detected. The use of a double GMB at Johnston County and RIEDSBM landfills was motivated but the fact that the old landfills did not have any base liner system (Blond et al. 2005; Pieter, 2010). This justification is approved by Vogt (2006) and Golder Associates (2011) who state that a double-lining GMB should be incorporated in the PBLS when the old base liner system does not meet modern regulations.

The Maine regulations require a double liner system when landfills are established on weathered or fractured subgrade, so the piggy-back landfill in Maine used a double GMB in view of an unstable existing landfill (Grillo et al. 2001).

Table 2. Structure of the 22 piggy-back liner systems case studies (Tano et al., 2015)

State	Year and site	Type	GGR	HDPE[1]	Text[2]	GVL[3]	LDL[4]	References
France	2011, Site A	L						Communauté d'agglomération de Montpellier (2011)
	2011, Site B	M	×	×				Ecogeos (2011) unpublished
	2012, Site C	V	×	×				Ecogeos (2012) unpublished
	2013, Site D	M		×	×			Unpublished
	2013, Site E	M	×	×		×		Ecogeos (2011) unpublished
	2014, Site F	M	×	×				BRGM (2009) Ecogeos (2010) unpublished
USA	1987, Blydenburgh	V	×	×	×[6]			Barbagallo and Druback (1997)
	1990, Frederick County	V	?	×	?	?	?	Law et al. (2013)
	1991, South. Alleghenies	M	×	×				Dayal et al. (1991)
	1995, Peabody	M		×[5]	×		×	Stulgis et al. (1996)
	1996, Colonie	M	×	×				Barbagallo et Druback (1997)
	1999, Johnston County	M		×[5]	×			Pieter (2010)
	2001, Maine	L	×	×	×[6]		×	Grillo et al. (2001)
	2004, Nobles County	M		×		×		Lynott (2004)
	2012, South Hadley	V		×				Wehler (2011), Sochovka et al. (2012)
	2013, Kekaha	M	×	×				AECOM (2013)
Canada	2003, RIEDSBM	M	×	×	×			Bouthot et al. (2003), Blond et al. (2005)
	2010, Regina	M		×				Mihial and Wright (2011)
U.K.	2005, Danes Moss	V?	×	×	×			http://www.trisoplast.fr/downloads/2005_Danes_Moss_EN.pdf
China	2009, Qizishan	M	×			×		Chen et al. (2009), Chen et al. (2011)
	2011, SENT	M		×		×	×	http://www.epd.gov.hk/eia/register/report/eiareport/eia_1432007/html/Section3.htm
Australia	2015, MLRMC	M	×		×[6]	×		Golder associates (2011), AECOM (2012)

[1]: high-density polyethylene geomembrane;
[2]: textured geomembrane;
[3]: gas venting layer;
[4]: leachate drainage layer;
[5]: LLDPE GMBs were also used;
[6]: smooth GMBs were also used.

4.2 *Passive containment barrier: clay, geosynthetic clay liner (GCL) and sand-bentonite-polymer (SBP) mix*

Most mineral liners include a clay layer of thickness of about 1 m with a permeability $K \leq 10^{-9}$ m/s to provide a passive sealing in case of a GMB failure (leakage). The clay layer can be associated with a GCL (45% of the case studies) or a SBP (5% of the case studies). The extensive use of GCL could be explained by the fact it exhibits good resistance to stress cracking and is relatively easy to be installed.

4.3 *Reinforcement function*

This is surely one of the components of the PBLS which is not commonly used in the lining system of standard landfills. In 1987, for the construction of the first landfill expansion (Blydenburgh), designers were considering several subgrade reinforcements to deal with the differential settlements that may occur during and after piggy-back waste fillings. For economics and required construction time reasons, they choose to use 2 polyethylene uniaxial reinforcement geogrids (GGR) to withstand these settlements. The two GGRs were installed perpendicular to each other in order to multidirectional support a potential non-symmetrical depression (Tieman et al., 1990). The design was based on conservative assumptions assuming a 2.4 m circular void beneath the PBLS. This was likely the first time of using GGR in landfills for this application (Berg, 1987 and Whelton and Wrigley, 1987).
Even if, some case did not include a GGR in the PBLS, it can be noted that, this innovative practice of providing reinforcement GGR to support the whole PBLS (Sharma and Lewis 1994), has been widely adopted by designers (63% of the case studies in Table 2). 2 different layers of GGRs were sometimes set up at different levels of the PBLS in order to increase the mechanical strength (e.g. Southern Alleghenies landfill).

4.4 *Leachate and gas drainage system beneath the passive barrier*

It is not rare to find in old landfills a high level of leachate because of ineffective drainage systems. In such cases, the construction of a piggy-back landfill on top of the old landfill would create a rise in the leachate level under the surcharge load. This leachate could not only create slope instability but could also reduce the shear strength of GSY interfaces by exerting an under-pressure on the PBLS. The flow of gas produced in old waste can have the same effect if there is no proper gas venting system. To address these points, a GCD with perforate pipes or a drainage layer is sometimes implemented beneath the passive layer, between the old landfill and the new one. But these provisions (gas and leachate drainage under the PBLS) have been adopted by only about 20 % of the case studies.

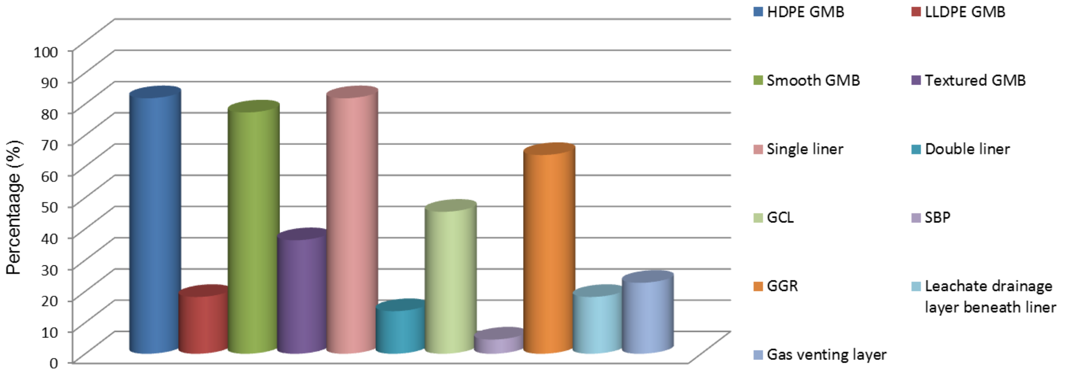


Figure 2: Distribution of the piggy-back liner system practices (Tano et al., 2015)

5 GENERAL GUIDELINES FOR THE SELECTION OF THE GEOSYNTHETICS WITHIN A PIGGY-BACK LINING SYSTEM

To be effective, the different layers of GSY and their arrangement within the PBLS should be carefully studied. Given the actual lack of recommendations regarding the design of PBLS, it is important to give minimal technical requirements for the design of the PBLS. Here, some general guidelines are given for the selection of the protective geotextile (GTX) or GCD + GMB (active barrier), the GCL or SBP (passive barrier) and finally for the reinforcement GGR.

5.1 *Selection of the protective geotextile or geocomposite*

For the drainage of the leachate at the landfill bottom, the applicable regulation in France (ministerial order 31-12-2001 amending the order 09-09-1997) requires to implement a drainage layer with a thickness of at least 0.5m above the sealing system (GMB). To avoid the puncture and perforation of the GMB by the aggregates, a protective GTX is traditionally installed between the GMB and the granular layer. Generally, this protective GTX is a PP nonwoven needled GTX. The applicable regulation also allows replacing the 0.5m drainage layer by an alternative equivalent system which is typically a GCD + 0.3m of drainage layer. In this situation, there is no more a protective GTX, but only a GCD which plays both a protective and a drainage role.

To limit the puncture of the underlying GMB, the protective GTX or GCD must be properly selected depending on the applied load of the overlying waste, the grain shape (round, angular) and the particle size of the drainage granular materials. The key criteria for the selection of the protective GTX or GCD are the mass per unit area (can be > 2000 g/m²), the thickness (can be > 20 mm), the static or CBR puncture strength (can be > 20 kN), the resistance to pyramidal punching (can be > 10 kN), the dynamic perforation strength (can be = 0 mm). According to Croissant and Touze-Foltz (2012), the length of the GTX or GCD fibers has also an effect on its protective performance. Based on several experimental tests, the authors concluded that short fibers are more efficient than long fibers. Moreover, virgin fiber-based are preferred to recycled fibers.

Moreover and very often, the selection of the protective GTX or GCD is performed based on the designer experiences or on analytical approaches such as that proposed by Narejo et al. (1996). However, a real test simulating the GMB punching using the intended aggregates, the real load (like field conditions) and the intended protective GTX or GCD could allow for more realistic results. These types of test is described in several works such as those of Reddy and Saichek (1998), Budka et al. (2006), Aufrère et al. (2009) and Stoltz et al. (2013).

5.2 *Selection of the geomembrane*

There is actually a wide range of GMBs differing by the polymer nature (HDPE, LLDPE, PP, PVC, EPDM, etc.), their surface structures (smooth or textured) and their mechanical properties (stiff, flexible). The selection of a GMB has to be made based on a comprehensive analysis of its mechanical and chemical characteristics, its temperature resistance, of its ability to be installed and of the site conditions. For a use in piggy-back landfill, the selected GMB must be chemically resistant to leachate and able to withstand the potential voids or differential settlements (hence tensile forces). Given these requirements, flexible ethylene-propylene-diene-terpolymer (EPDM) and PVC GMBs cannot be used because they respectively exhibit

a limited mechanical resistance (strength) and a low chemical inertia (Lambert, 1997). Moreover, PVC can lose its flexibility on the long term and become stiff. PP GMBs cannot also be used because they have a low tear resistance and, as EPDM, PVC, they generally have a greater permeability than polyethylene (PET).
Therefore, only PET GMBs (HDPE and LLDPE) could be suitable for a use in piggy-back landfill context. The choice between HDPE and LLDPE seems to be not obvious because each polymer has its advantages and limitations. It should also be noted that only one type of GMB cannot be suitable for all cases. The main properties of the HDPE and LLDPE GMBs are given on Figure 3

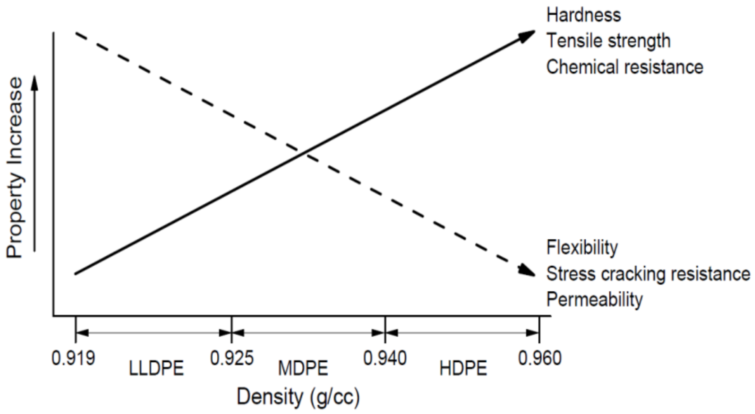


Figure 3: Comparison between HDPE and LLDPE properties (from Hsuan et al., 2008)

For example, HDPE exhibits a high chemical resistance to leachate and is expected to have an excellent ability to reduce advective and diffusive flow of contaminants. HDPE GMB also has a good tensile strength. However, in piggy-back landfill context, the flexibility of the liner to deform with minimal impact on its integrity is a major concern while HDPE GMB is stiff. Moreover, HDPE is a material potentially subject to stress cracking and its long-term flexibility and tensile behaviour can be altered over time. It is true that HDPE has excellent strain capabilities under uniaxial strain (or elongation) but it exhibits relatively poor multiaxial (out-of-plane) strain performance. On the contrary, LLDPE show excellent both uniaxial and multiaxial strain behaviours (BPEM, 2010) and can accept large deformation due to its higher flexibility. However, even if Simpson and Siebken (1997) have shown that LLDPE GMBs are as chemically resistant to leachate and mechanically resistant (tensile strength) as HDPE GMBs, LLDPE GMBs are generally somewhat less permeable than HDPE GMBs. The allowable maximum strains for each type of GMB, are given in Table 3.

Table 3. Maximum allowable strains for various geomembranes (from Peggs, 2003)

Geomembrane nature	Maximum allowable strain (%)
HDPE randomly textured	4
HDPE smooth	6
HDPE structured profile	6
LLDPE randomly textured	8
LLDPE structured profile	10
LLDPE density > 0.935 g/cm^3	10
LLDPE density < 0.935 g/cm^3	12

Furthermore, in the same site conditions, a textured GMB would be subject to more tensile stress compared to a smooth GMB because of a higher surface friction. But a smooth GMB could cause interface instability in case of high slope gradient because of its low friction interface. In France, the regulations and standards (CFG, 1995; MEDDE, 2007; AFNOR, 2010:

XP G38-067) tend to encourage the use of smooth GMB by requiring to not to submit the GMB to any stress. But, in reality, a smooth GMB will be very likely subject to a certain degree of tensile force since its surface friction is not zero. Therefore, because both smooth and textured GMBs have advantages and limitations, the choice of the type of GMB remains open and has to be made depending on the site conditions. However, the designer has to choose a GMB with an appropriate surface friction to avoid interface instability while limiting as far as possible, the tensile forces within the GMB.

5.3 *Selection of the passive barrier*

In order to improve the sealing function of the clay layer as passive barrier, a GCL or SBP is often implemented on top of the clay layer in the framework of sealing equivalence. As previously seen, GCLs are often selected instead of clay layers presumably because GCLs are easier to install. Concerning the GCL, it is generally admitted that they can withstand significant tensile strains (under confinement) and are suitable for a use on steep slopes rather than a mineral sealing material like clay. Some SBP mix can also exhibit good shear strength characteristics. Sodium (natural sodium and activated calcium) bentonite GCLs are preferred to natural calcium bentonite GCLs because natural calcium is more sensitive to cation exchange processes that could alter the sealing performance. Generally, the following requirements are provided for GCL: a mass per unit area of bentonite at 0% of water content > 5000 g/m², a cation exchange capacity ≥ 70 meq/100 g, a CaCO3 content ≤ 5% and a tensile strength > 10 kN/m. Like SBP, the permeability of GCL is excellent and below 10-10 m/s. But, this GCL permeability could be not homogeneous due to the fact that the distribution of the bentonite within the GCL is not uniform. However, it is possible to get more uniform permeability with the use of a SBP. But, the implementation of SBP requires an on-site manufacturing station.

5.4 *Selection of the reinforcement geosynthetic*

The design of the reinforcement geosynthetic is a key step to ensure the integrity of the PBLS. High strength woven GTXs and geogrids (GGR) are the two main types of reinforcement GSY. Generally, GGRs are preferred because they exhibit a better interface shear strength. This is due to their open structure that leads to a soil-soil contact and aggregates interlocking in the GGR plane. There is a wide range of polymers that may constitute a GGR. These are mainly PP, PET, polyester (PE), Aramide (AR) and alcool polyvinylique (PVA). But they are not all suitable for a use in piggy-back landfill context. Indeed, the following main criteria are required to ensure the integrity of the PBLS: a high stiffness and tensile strength, a long term low creep and a good chemical resistance.

- High stiffness and tensile strength: The higher the stiffness, the lower strain of the GGR. Hence the PBLS would be subject to limited strains and forces and its integrity would be preserved. Beyond the stiffness, the GGR should be able to withstand significant tensile forces induced by a potential collapse or differential settlements.
- Low creep: For the construction lifespan, the reinforcement must limit the strains within the PBLS to an acceptable level. This means that the GGR should not be subject to a considerable creep with an altered stiffness under the site conditions (temperature up to 50° and tensile forces). Therefore, the GGR long-term or residual stiffness should remain high over time. The allowable strain is generally fixed to less than 6 % based on the allowable strain of the 2 mm HDPE GMB. These requirements strongly restrict the use of polymers PP and PET which are more sensitive to the creep and temperature (Kongkitkul and Tatsuoka, 2006; Kongkitkul et al., 2012).
- Chemical resistance: The pH of fresh leachate is generally around the neutrality between 5.5 and 8. But, over time, the pH could become basic and reach a value of 9. The selected

GGR should then be compatible with these chemical conditions. Because PE and AR are sensitive to the hydrolysis phenomena at basic pH > 9, it is not recommended to use these polymers in this situation.
Given the requirements above, the PVA GGR appears to be the most suitable reinforcement for a use in piggy-back landfills. However, since each site is a particular case (different waste nature and thickness, existing barrier, etc.), only one product cannot be suitable for all cases. Hence, the design of the PBLS should be site specific and the selection of the reinforcement GSY should be scientifically and technically justified according to the mentioned above criteria.
Furthermore, to guarantee the durability of the reinforcement, it could be preferable to have a technical agreement from a well-recognized organization like the British Board of Agreement (BBA).

6 CONCLUSION

This study has addressed the current state of practice in the design of PBLS through an overview of 22 case studies worldwide. The aim was to show the various design practices and the related key issues (settlement assessment, veneer system stability and gas/hydric issues).
It was noticed several differences in the design of the various PBLSs. The provision of a reinforcement geosynthetic (GSY) and leachate/gas drainage systems beneath the PBLS have been also discussed when they are potentially required. Based on the safety practices, some general guidelines for the selection of the various GSYs within and beneath the PBLS have been provided as a base for the design.
Beyond the above considerations, the actual works related to piggy-back landfills should provide best compliance regulations and a more efficient design. New understandings, research works and field experiences would be also helpful to improve the design of piggy-back landfills.

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