GEOSYNTHETIC SEALING SYSTEMS IN LANDFILLS – A GLOBAL PERSPECTIVE

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OBJECTIVE

In several countries, the use of geosynthetic materials in landfills can be subject to an approval system anchored in regulations or recommendations through the national body, e.g. in Germany the LAGA (Länderarbeitsgemeinschaft Abfall) for geosynthetic clay liners or the BAM (Bundesanstalt für Materialforschung und -prüfung, Federal Institute for Materials Research and Testing) for other geosynthetic materials (geomembranes, geogrids, geotextiles or drainage geocomposites) or in South Africa the National Environmental Management: Waste Act 59 of 2008 and its corresponding regulations and/or technical notes. These often include requirements for geosynthetic products, their raw materials, installation, and external monitoring. This provides the owner of a landfill with standard construction methods for building sealing systems from approved or suitability-assessed components.

In international comparison, other local requirements and regulations might not be in that detail and such elaborate technical standards for selecting and applying soils and building materials in landfill sealing systems could also be an exception. Rather, differentiated standard construction methods result from a wide variety of hydrological and geological boundary conditions, geometric constraints, and the varying availability of soils, as well as the historical development of the respective national regulations.

This paper summarises a selection of international regulations and exemplary projects focusing on the geosynthetic components of the sealing system. It thus provides an insight into practices in landfill sealing that are common abroad.

How does South Africa compare? It is well known that South Africa has world-class environmental management legislation. This paper will briefly look at the history of the South African waste legislation and compare its current legislation to other leading countries, e.g. Germany and the USA.

In conclusion, the paper will focus on where global landfill sealing systems can improve and will discuss current and future trends for barrier systems in landfills.

KEYWORDS

Landfill, Regulation, Guideline, Base liner, Cap, Artificial liners, Geological barrier, Geomembrane, Geosynthetic clay liner, Polymers, PFA, Geosynthetics, Geosynthetic barriers, Multicomponent GCL.

INTRODUCTION

Waste management is the collection, transport, processing, disposal or treatment, managing, and monitoring of waste materials. It usually relates to materials produced by human activity, and the process is generally undertaken to reduce their effect on human health (Figure 1), the environment or aesthetics. All waste materials, whether they are solid, liquid, gaseous, or radioactive, fall within the remit of waste management. Landfills are used for the disposal of solid waste by burial and have been the oldest form of waste management.

Historically, landfills have been the most common method of organised waste disposal and remain so in many places around the world. Landfills are also used for waste management purposes, such as temporary storage, consolidation, and transfer, or processing of waste materials (sorting, treatment, or recycling) and are generally referred to as waste processing facilities or transfer stations.

HISTORY OF US SOLID WASTE MANAGEMENT

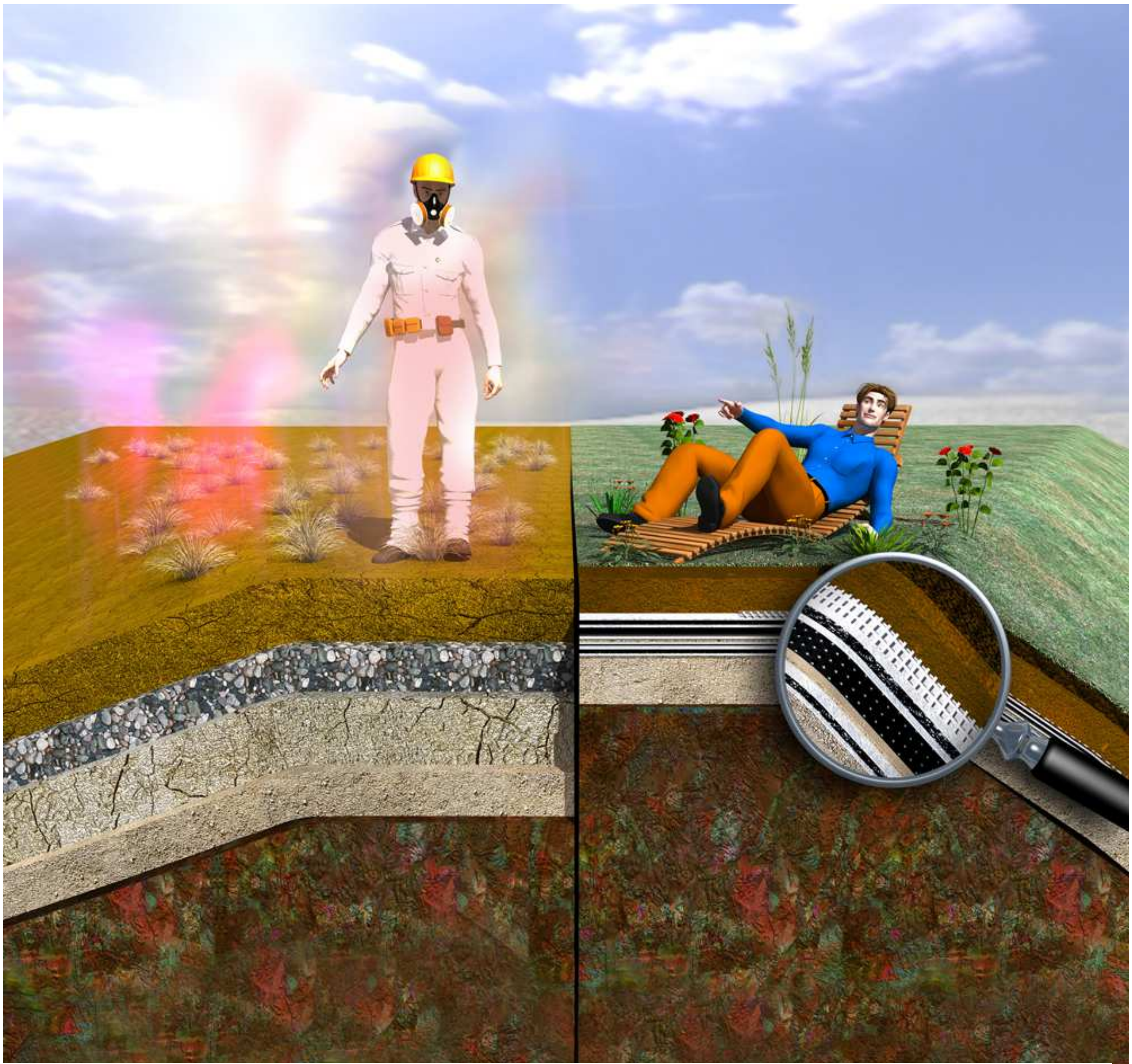

Figure 2: A safe landfill is supposed to protect the environment and human health (geosynthetic solution on the right side)

Humans have generated wastes since the dawn of mankind, but waste disposal only started to become an issue around 10,000 BC when humans began moving away from their nomadic habits and living in communities. Nomadic ways of life have successfully relied upon natural forces to manage their waste as sunlight and microbes in water and soils readily decomposed garbage and human waste as long as population densities remained low (Phillips [1]). The advent of non-transient communities, however, resulted in increased population densities. Hence, more waste is being concentrated in a smaller area (Niemczewski [2]). As settlements grew larger, development of cities started which increased the solid waste problems.

Around 500 BC, the first known municipal waste dump in the Western world was established in Athens, Greece. The citizens had to dispose of their waste at least one mile from the city limits. Dumping waste within cities, however, remained the primary disposal option in Europe and the US until the late 1800s when a connection was made between disease and filthy environmental conditions (NSWMA [3]). In the beginning, the priority was to protect public health and much later followed the desire to protect the environment.

A review of the history of waste management reveals that this evolutionary process can be divided into several relatively well-defined periods, each with a unique waste management perspective.

- Pre-1800: During colonial times, minimal sanitary regulations were common in American colonies. City dwellers simply disposed of their food waste (garbage) and refuse (trash) into city streets, alleys, and waterways. The government played a minimal role in the development of sanitary systems.
- The 1800s: After the Civil War, as cities grew, major sanitation problems developed and frequent, often devastating, epidemics occurred. The federal government began to realise its role in ensuring sanitation by creating the National Board of Health in 1879.
- Before the 1890s, there was little local government effort in providing an organised system for waste collection and disposal. Cities started to grow and people became more consumer-oriented. Waste dropped on the street became a more overwhelming problem and resulting from that public health from unsanitary conditions was an issue. Further it was realised that a clean city would attract more businesses, create jobs and then improve local economies. Waste collection and disposal was considered a natural extension of public services and local citizens increasingly began demanding solutions.
- During the interwar years, land disposal was still the primary method of solid waste management efforts and many locations had the city or town dump where their solid waste was disposed and affected the water quality of river waters. In 1929, the federal government issued the first location restriction for disposal sites, away from river banks because of its unsanitary impacts.
- In 1937, the first modern “sanitary landfill” in the US built on the British design began its operation in Fresno, California. This landfill innovated the techniques of trenching, compacting, and the daily covering of the waste with soil; this technique is commonly called “trench-and-fill” in the literature. The use of sanitary landfills slowly spread across the nation during the 1930s and 1940s.
- 1945 - 1964: In these decades, the composition of solid waste also changed as packaged goods (paper and plastic) became widely available as well as disposable goods. This and the increase in population growth resulted in a drastic increase in the amount and composition of solid waste.
- For most of the US, landfills continued to be the primary method for waste disposal. Open dumps, with the resulting fires, odors, and vermin problems, were still in use in many locations. Incineration was also popular until the 1960s when the Clean Air Act of 1963 forced many polluting incinerators to close.
- 1965 - 1991: In 1965, US President Lyndon Johnson recommended that the federal government helps states in solving pressing solid waste disposal problems that were causing serious environmental harm. In that year, Congress passed the Solid Waste Disposal Act (SWDA) which was enacted as Title 2 of the 1965 amendments to the Clean Air Act of 1963. This first federal legislation created a national office of solid waste and was designed to assist state and local governments with the technical and financial aspects of developing and managing waste disposal programs and to promote the development of guidelines for waste collection, transportation, recovery, and disposal.
- In 1970, Congress passed the Resource Recovery Act, shifting the emphasis of federal involvement from waste disposal to recycling, resource recovery, and waste-to-energy conversion. In that year, the US Environmental Protection Agency (EPA) was also established and brought

together environmental divisions from the Departments of Health, Education, and Welfare; Agriculture; and Interior; and other federal agencies.

- On October 21, 1976, US Congress passed the Resource Conservation and Recovery Act (RCRA) to address the increasing problems the nation faced from the growing volume of municipal and industrial waste (EPA [4]). It established a comprehensive federal involvement in solid waste management that included regulatory authority for the first time.
- In 1980, US Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or more commonly known as Superfund) directly in response to the Love Canal debacle. For over 30 years, the canal was used as the dumping ground for municipal garbage and chemical wastes from the City of Niagara, New York and surrounding municipalities. In 1978, toxic chemicals began to leak from the old canal into the yards and basements of the community and caused severe health incidents. CERCLA also imposed various taxes on chemical and petroleum industries, which were deposited into a trust fund (hence, the name "Superfund") to be used for remediations initiated under its provisions.
- In 1984, Congress amended RCRA by passing the Hazardous and Solid Waste Amendments of 1984 (HSWA). The HSWA put into effect tough, new requirements for hazardous waste management and disposal, as well as mandated EPA to develop criteria for new solid waste landfills. The EPA promulgated a comprehensive regulatory framework for the construction and operation of landfills receiving municipal solid waste in 1991.

For the past decades, solid waste management has significantly improved. Across the world, modern, well-designed landfills and waste-to-energy plants have replaced open dumps and polluting incinerators. In most communities, recycling has become an integral part of solid waste management. Conserving material and energy resources as part of solid waste management became a key consideration in achieving sustainable development.

GUIDELINES

For the comparison of international landfill barrier designs, only regulations are considered that also describe geosynthetic barrier systems and allow these to be used. Since both mineral and geosynthetic barrier components are suitable for use in the sealing systems, in many cases the regulations base their threshold value (typically thickness and permeability) on the mineral barrier system and ask for a technical comparison with an alternative solution, such as a geosynthetic clay liner (GCL).

When looking at the technical regulations for landfill construction, it becomes clear that a higher degree of differentiation exists between types of waste (low-level radioactive waste, hazardous waste, ore heap residual waste, hospital/research waste, municipal solid waste (MSW), incinerator ash, sewage treatment sludge, contaminated sludge, electric power-generation ash, mine spoil and construction and demolition debris), in the order of toxicity from high to low. The waste landfill classes to be assigned and resulting requirements for barrier systems increase in countries with higher prosperity. Therefore, it is not surprising that mainly requirements from industrialised countries can be compared, while in emerging and developing countries no standards exist or foreign standards are used as a reference.

In Europe, the basis for all regulations on sealing system requirements is the European Directive 1999/31/EC on the landfill of waste [5]. In this directive, basic statements are made on the required geological barriers and the necessary components of the base and capping sealing systems depending on the defined landfill classes (e.g. presence of an artificial sealing layer without a detailed description of its properties). The formulation of explicit requirements for components of the sealing systems regarding technical properties and their long-term durability were transferred to the member states' responsibility.

As of today, in some member states, there are no legal rules for landfill sealing systems beyond the European Directive 1999/31/EC [5] (Jovanović et al. [6]).

European Directive

Regulatory agencies around the world have long accepted geosynthetics as an alternative design solution or have out-right required their use in certain applications. The waste management sector has benefited more than any other sectors through the requirement to use geosynthetics in municipal solid waste containment and closure systems. There are many exemplary cases for the incorporation of geosynthetics into environmental regulations to prevent or reduce as much as possible, any negative impact from landfilling on surface water, groundwater, soil, air, or human health. This is achieved by introducing stringent technical requirements, such as in Europe with the EU Landfill Directive.

The Landfill Directive on the landfill of waste (Council Directive 1999/31/EC of 26 April 1999) [5] is a directive issued by the European Union to be implemented by its Member States by 16 July 2001. The Directive applies to all waste disposal sites and divides them into three classes: (I) landfills for inert waste, (II) landfills for hazardous waste, and (III) landfills for non-hazardous waste.

The EU Landfill Directive, section 3.1 requires the protection of soil, groundwater, and surface water, achieved by ensuring an efficient collection of leachate (in the base) and rainwater (on the cap), a combination of a geological barrier and a bottom liner, and in the passive/post closure phase by a top liner. The geological barrier shall meet the minimum requirements “Mineral layer or equivalent” listed in table 1. If these requirements cannot be met, the geological barrier can be completed artificially and reinforced by other means, giving equivalent protection, e.g. with a GCL in addition to the geological barrier.

An artificial liner (e.g. HDPE 2mm geomembrane) is required for hazardous (bottom and cap) and non-hazardous landfills (bottom only). The purpose of the artificial liner is to control leachate leakage from the base and rainwater in the cap and allow its controlled collection.

A set of rigorous operational and technical requirements are described as mandatory (Figure 2). In article 13 of the EU Directive the closure and after-care are the responsibility of the operator for at least 30 years.

However, landfilling is the least preferable option and should be limited anywhere in the world to a necessary minimum. Often the stages of waste minimisation are presented in a waste management hierarchy, which indicates an order of preference for the reduction of waste. The hierarchy captures the stages where a reduction of waste is possible (Figure 3).

The following route to achieve this goal is a circular economy, an economic closed-loop system in which raw materials, components and products hardly lose their value and where renewable energy sources are used. To support the EU’s transition to the circular economy, the European Commission rules aim to limit the amount of waste sent to landfill to the necessary minimum [7] and also

- introduces restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery from 2030,
- limits the share of municipal waste landfilled to 10% by 2035,
- introduces rules on calculating the attainment of municipal waste targets and requires EU countries to put in place an effective quality control and traceability system for municipal waste landfilled,
- requires the European Commission, with the European Environment Agency, to draw up early warning reports 3 years before each deadline to identify shortcomings in attaining the targets and recommending action to be taken,
- allows EU countries to use economic instruments and other measures to encourage applying the waste hierarchy.

Landfill bottom sealing

Landfill category	non hazardous	hazardous
Artificial sealing liner	required	required
Drainage layer ≥ 0,5 m	required	required

Landfill surface sealing

Landfill category	non hazardous	hazardous
Gas drainage layer	required	not required
Artificial sealing liner	not required	required
Impermeable mineral layer	required	required
Drainage layer > 0,5 m	required	required
Top soil cover > 1 m	required	required.

Mineral layer or equivalent

— landfill for hazardous waste: $K \leq 1{,}0 \times 10^{-9}$ m/s; thickness ≥ 5 m,

— landfill for non-hazardous waste: $K \leq 1{,}0 \times 10^{-9}$ m/s; thickness ≥ 1 m,

— landfill for inert waste: $K \leq 1{,}0 \times 10^{-7}$ m/s; thickness ≥ 1 m,

Figure 2: EU Landfill Directive requirements for bottom and surface sealing systems [5]

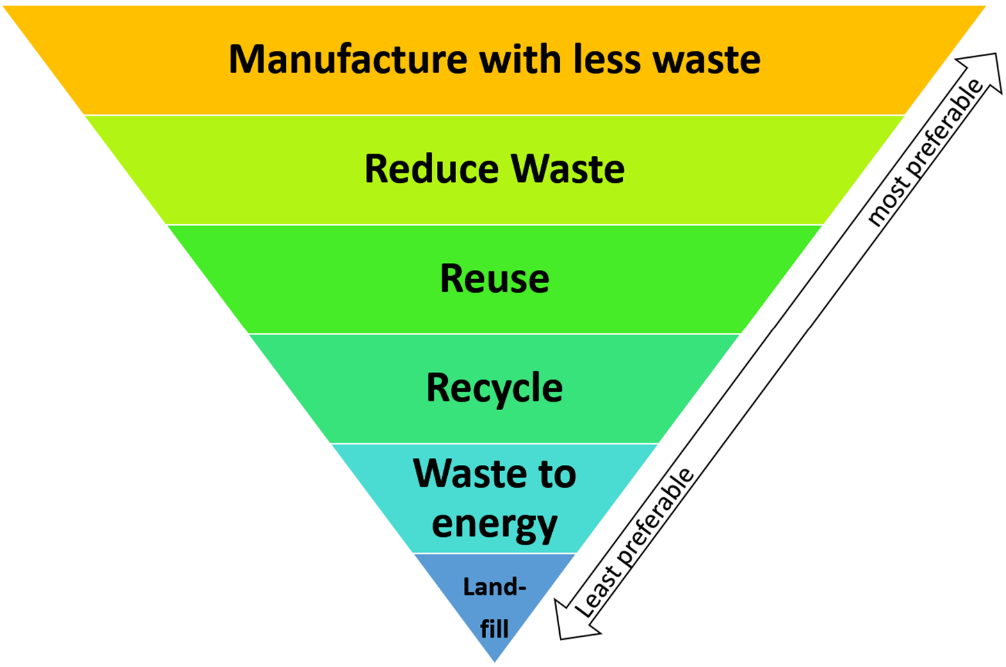

Figure 3: Stages of waste minimisation

Austria

Austria's regulations allow the (partial) replacement of the geological barrier and mineral sealing layer with a geosynthetic clay liner (GCL). Landfills are in general differentiated into inert waste (IW), construction waste (CW), and municipal solid waste (MSW). The corresponding requirements for the sealing elements are defined in the DVO [8].

Mineral sealing layers (thickness ≥ 0.50m for IW and CW landfills and ≥ 0.75m for MSW landfills) are required as a base seal. The permissible coefficient of permeability of the mineral sealing layer is $k_f \leq 10^{-9}$ m/s (in-situ samples) or for inert waste, landfills $k_f \leq 5 \cdot 10^{-8}$ m/s. A GCL can substitute the mineral sealing layer under the following conditions:

- Partial replacement of the mineral seal in areas with slopes (vertical to horizontal (v:h)) 1:h < 1:2.0 - the compacted mineral sealing layer must be ≥ 0.20m (inert waste and construction waste landfills) or ≥ 0.40m (residual or bulk waste landfills). The geological barrier cannot be improved or partially replaced by GCL.
- Complete replacement of the mineral seal with GCL in areas with slopes 1:h ≥ 1:2.0 permissible
- Complete replacement of the geological barrier by GCL in areas with slopes 1:h ≥ 1:2.0 permissible

The prerequisite for this replacement is proof of an equivalent level of protection compared with the DVO requirements [8].

The consideration of a GCL as a replacement for a compacted clay liner on steep slopes acknowledges the fact that an increasing slope inclination will challenge proper clay installation and compaction that is necessary to achieve a homogeneous clay impermeability or even make the installation impossible.

This passage leads to the fact that slope inclinations are almost exclusively planned with inclinations 1:h ≥ 1:2.0. It should be noted that the risk of permanent leachate head with the consequence of permeation of the mineral seal on steep slopes can also be classified as low with an **appropriately** dimensioned drainage layer.

Furthermore, geomembranes with thicknesses ≥ 2.5mm are used in the base sealing for residual or bulk waste landfills.

All geosynthetics must be tested and certified regarding their conformity to the corresponding standards of the Austrian Standards Institute (ÖNORM). Required mechanical and technical parameters must be proven. Unfortunately, long-term tests (e.g. tests on long-term shear behaviour) such as required in Germany are not a part of the ÖNORM.

Finland

Like all European countries, Finland also follows the minimum requirements from the EU Directive [5] and published with the country-specific requirements in the InfraRYL [9] guidelines.

Basal lining systems need to meet the following basic requirements (from bottom to top):

- Geological barrier: permeability ≤ 10^{-9} m/s, thickness ≥ 1.0m (non-hazardous waste) or ≥ 5m (hazardous waste) or bentonite-enriched mineral sealing layer with a permeability ≤ $6 \cdot 10^{-10}$ m/s and a thickness ≥ 0.5m (non-hazardous waste) and ≥ 1.0m (hazardous waste)
- Geosynthetic polymeric barrier GBR-P (geomembrane): thickness ≥ 2.0mm (additional requirements are defined in the federal environmental license or are written in the project specification. Typically, HDPE is used as geomembrane raw material but can be replaced by other raw materials (e.g. LLDPE, fPP, etc.) if e.g. the chemical attack is less critical. Thick asphalt barriers are also noted in the guidelines as an alternative.
- Protection layer for the geomembranes: mineral layer with a thickness ≥ 100mm or protection geotextiles
- The leachate collection layer with coarse mineral aggregate must have a thickness of ≥ 500mm and can be replaced on slopes by geosynthetic drainage mats in addition with mineral aggregate fulfilling the thickness requirements.

Capping systems need to meet the following basic requirements (from bottom to top):

- Levelling layer ≥ 300mm
- Gas collection layer (if suitable, the levelling layer can also be the gas collection layer): mineral layer thickness ≥ 100mm or a suitable geosynthetic drainage mat
- Compacted clay liner: thickness ≥ 0.5m, permeability ≤ 10^{-9} m/s or geosynthetic clay liner (GCL) with ≥ 4,000 g/m² sodium bentonite (at 0% moisture content)
- Hazardous waste landfills require additionally a geomembrane with a thickness of ≥ 1.5mm (typically flexible geomembrane HDPE, LLDPE, fPP, or EPDM are acceptable raw materials
- Drainage layer: mineral material (thickness ≥ 500mm) or geosynthetic drainage mat
- Vegetated cover soil thickness ≥ 1m

Germany

Since the late 1970s, Germany's LAGA (State Working Group on Waste) has issued recommendations for landfill liners. The administrative provisions of the Technical Guidelines on Waste (1991) and Technical Guidelines on Municipal Waste (1993) oversaw, inter alia, federal uniformity in landfill sealing system requirements. LAGA's work has included harmonisation between 40 relevant approval authorities in Germany to create uniform national quality standards (BQS) and product-specific suitability assessments. Alongside LAGA's work, BAM ((Bundesanstalt für Materialforschung und -prüfung, Federal Institute for Materials Research and Testing) released the NRW (North Rhine-Westphalia) Directive for geomembranes in 1986 and the Niedersachsen Barrier Code in 1989.

The transitional period set by the EU Landfill Directive [5] expired on 16 July 2009 – meaning that henceforth all European landfill sites were to meet harmonised requirements or be shut down. Germany had met these requirements for the most part by 2005 and published in 2009 the German Landfill Directive (DepV) [10] to establish full governing authority for BAM within the landfill sector's use of geosynthetics. Today, BAM oversees the relevant suitability assessments for geosynthetics, regulations which are enforced nationally, while the LAGA is responsible for mineral sealing systems, such as geosynthetic clay liners. Geosynthetic products in German landfill lining systems must offer a minimum of 100-year service life.

Figure 4: Approved geosynthetics being installed – geomembrane over the GCL and then covered with a geosynthetic drainage mat – on the left placement of cover soil (landfill cap Hanover, Germany)

All geosynthetics manufactured only with polymeric components have to be approved by the BAM to the fulfilment of the 100-year service life. The requirements for the assessment of a 100-year service life are elaborated by an advisory committee, formed by representatives of authorities, designers, landfill operators, manufacturers and consultants. The consensual findings of this expert committee on requirements that allow an assessment of 100-year service life are published in specific certification guidelines. The testing procedures defined in those exceed test durations of common index tests which are considered in most other standards by far – for example oven aging of materials for ≥ 1 year. The extrapolation of test results must show that the function is preserved also in challenging conditions, i.e., in the landfill basal lining system. The quality requirements of the BAM also go further beyond material certification: Both the geomembrane installer and the third-party supervision must be certified by the BAM in accordance to separate certification guidelines.

Upon closure, landfills must be capped. The specific requirements for permanent sealing systems for class I (inert waste), II (municipal solid, non-hazardous waste) and III (hazardous waste) landfills are typically outlined in the national regulations and allow LAGA certified geosynthetic clay liners as a stand-alone liner in class I and in class II and III in combination with a BAM certified ≥ 2.5mm thick HDPE geomembrane (Figure 4).

According to appendix 1, Nr. 2.1 of the DepV [10], a GCL may be used if it fulfills the LAGA requirements [11] or is approved by the local authority on a project-to-project basis.

The LAGA group set up a technical catalogue [11] with various requirements to fulfill, including short-term and long-term tests, covering the following main topics:

- Water permeability
- Mechanical resistance
- Durability
- Intimate contact
- Protective measures
- Manufacturability
- Controllability
- Quality management

Within each topic group, there are multiple tests to be carried out and the entire certification process can take several years. As a summary, it can be said that a LAGA certified product fulfills the GRI-GCL3 [12] recommendation and goes beyond, as it defines the raw materials, asks for more durability testing and several more specific requirements.

Great Britain

In the 1920s, the concept of a "sanitary landfill" has been developed in Great Britain. The British called this practice "controlled tipping" from which the term "tipping fee" was probably coined. While open dumping had been practiced for years, the concept of alternating layers of waste and either soil or another non-putrefying material gave rise to the idea of a pseudo-engineered fill. The belief was that vermin populations, odors, and fires could be reduced through this practice, thus making land disposal less smelly and more sanitary.

The EU Landfill Directive [5] was published in the Official Journal of the European Communities on 16 July 1999 (OJ L182, 16.7.1999) and the resulting requirements were implemented in England through Waste Strategy 2007 and across the UK through the Waste and Emissions Trading Act 2003.

The UK Environment Agency has formulated the implementation of requirements for landfill sealing systems in a series of geosynthetic guidance documents, e.g. LFE2 [13], LFE3 [14], and LFE5 [15]. For the geomembrane the EA-1 is specific on geomembrane properties for the polyethylene raw material HDPE and LLDPE and in the appendix refers to GRI standards GM13 [16] and GM17 [17]. On the other hand, LFE3 [14] is less specific with geosynthetic clay liner (GCL) requirements and contains terms as "Your design will need to take account of all of these issues and interactions" and "As specified …".

The decision on the choice of the sealing system is to be made after a risk assessment, see SEPA [18]. Project-specific boundary conditions are used to select the sealing system. Mineral basal liners improved by GCL are permissible if an underlying "attenuation layer" - i.e. a cohesive soil layer with sufficient pollutant retention capacity in a sufficient thickness - is present. In this case, the GCL is only intended to reduce the permeability of the mineral components of the combination sealing system. The requirements for thickness and permeability result from the risk assessment, considering, among other things, the contamination of the seepage water, the mobility of the pollutants, and the vertical distance of the seal from the groundwater horizon.

Hungary

Hungary should be mentioned as an example of a country that follows the parameters for sealing systems required in the European Directive [5]. This "minimum solution" was established in 2006 [19] after an existing set of rules in GoH, with specific requirements for geosynthetics, was amended in favour of a requirement, according to which alternative sealing systems must prove their equivalence to purely mineral sealing systems on a project-specific basis, utilising calculations and field tests.

The new Hungarian legislative sets for landfill classes: inert (A), inorganic non-hazardous (B1b), mixed non-hazardous (B3) and hazardous waste (C) and the requirements for basal liner systems are listed in Table 1.

Table 1: Base lining systems for Hungarian landfills [19] (Note: *Or artificially improved with compacted clay or a geomembrane)

	Class A	Class B1B	Class B3	Class C
Leachate collection	Required	Required	Required	Required
Mineral sealing*	1m thick $\leq 1 \cdot 10^{-7}$ m/s	1m thick $\leq 1 \cdot 10^{-9}$ m/s	1m thick $\leq 1 \cdot 10^{-9}$ m/s	5m thick $\leq 1 \cdot 10^{-9}$ m/s
Leak detection system	Not required	Not required	Required	Required
Geomembrane (2.5mm thick)	Not required	Not required	Required	Required
Leak monitoring	Not required	Not required	Required	Required

The Netherlands

The Netherlands has seen a major decrease in the amount of waste landfilled and the Dutch legislation stimulates recycling. Therefore, the last option is landfilling, if no other option is feasible.

The requirement for using a geosynthetic as a sealing element for landfills in the Netherlands is a certification by the testing and certification institute KIWA. Here, too, the focus is on index tests. Minimum thickness for a geomembrane is specified with ≥ 2.0mm.

Specific technical parameters of a composite lining system are not prescribed according to the Dutch regulations VROM [20]. The approach is target-oriented: Leakage rates are to be limited to ≤ 5mm/a (composite lining system) or ≤ 20mm/a for a single lining system. In this context, the assessment of the sealing system and the computational approach to determine the seepage rates, as well as the assessment of long-term nature, are the responsibility of the responsible designers and authorities.

Australia

Environment agencies in Australia have established landfill management guidelines prepared by the Australian States and Territories environment agencies, which cover landfill siting, design, construction, and operation.

According to Australian guidelines, the principal functions of a landfill liner system are to limit contaminant migration to groundwater and to control landfill gas migration. Different states may have different approaches and details for the liner system though. Queensland (QLD), New South Wales (NSW), and Victoria (VIC) state guidelines are discussed here as the main and most used guidelines.

QLD design guides are based on a risk-based approach. Risk assessments are undertaken to identify and determine the significance of the risks. A risk assessment helps to determine the level of environmental risk by looking at the probability (likelihood/frequency) of an event happening and the consequences (impacts). Some of the measurements and outcomes of the liner design in QLD guideline includes: Design and construct the most appropriate liner system practicable to contain leachate. Provide a geotechnically stable subgrade and liner, design the lining system based on the outcomes of the hydrogeological risk assessment, stability risk assessment, and landfill gas risk assessment, use industry design standards to show how the proposed lining system will limit contaminate migration from the site and achieve the objectives and outcomes for the site, ensure that the liner is sufficient to meet hydraulic coefficient, and maintain adequate separation between the base of the liner and the highest expected groundwater level. The suggested lining system in the QLD guideline is a combination of the subgrade, clay or GCL, geomembrane, and protection geotextile. It does not provide any specification or construction quality assurance (CQA) for the liner components though and leaves it to the designer to specify these based on the outcomes of the risk assessments.

The NSW guideline is more detailed compared to QLD one. The guideline suggests the liner system for general solid waste landfills to include a stable subbase, a 1m thick clay liner with hydraulic conductivity of 10^{-9} m/s or a reinforced GCL (with hydraulic conductivity less than $5 \cdot 10^{-11}$ m/s and other properties in compliance with GRI-GCL3 [12] and bentonite properties meeting the requirements specified in the guideline), a geomembrane (minimum 2.0mm thick with properties in compliance with GRI-GM13 [16] or GM17 [17]), a protection needle-punched nonwoven geotextile in compliance with GRI-GT12(a) [21] (max. stress strains to be measured in accordance with LFE2 [13] cylinder test (also described in GRI-GT12(b) [22] or ASTM D5514 [23]), minimum 300mm leachate drainage layer, and a filtration/separation geotextile (nonwoven needle-punched in compliance with GRI-GT13(a) [24], or GRI-GT13(b) [25].

For restricted solid waste cells according to the NSW guideline, the design of the leachate barrier system should be a dual barrier system. The primary barrier should contain a composite liner, comprising a lower geosynthetic clay liner and an upper geomembrane liner and the secondary barrier should contain either a 1m thick single compacted clay liner with a saturated hydraulic conductivity of $\leq 1 \cdot 10^{-9}$ m/s or a geomembrane/geosynthetic clay composite lining system.

For the sealing of landfill caps, NSW guideline suggests a minimum of 600mm of compacted clay layer with an in situ saturated hydraulic conductivity of $\leq 1 \cdot 10^{-9}$ m/s or a GCL, covered with a HDPE or LLDPE geomembrane, and should be adequately designed to accommodate any penetrations and protrusions (e.g. landfill gas controls and leachate risers). Equivalent capping systems can be used if they meet the capping requirements in the guideline.

The Victorian guideline, known as BPEM [26], suggests a basal lining system, comprising up to five components as sub-base: compacted clay (1m thick, hydraulic conductivity of less than $1 \cdot 10^{-9}$ m/s using both fresh water and 50,000 ppm NaCl solution) or geosynthetic clay liner (GCL), geomembrane (1.5 - 2.0mm thick, HDPE for the base and side slopes and LLDPE for caps), a protection layer, drainage layer/leachate collection system, and filter/separation geotextile. Geosynthetic clay liners (GCLs) are considered as an element for the composite base and side liners, and capping systems in landfills. BPEM [26] provides a comprehensive document for properties and minimum requirements of clay liner, GCLs, geomembranes, and geotextiles.

The BPEM [26] further requests a landfill design with a maximum seepage rate of 10 l/ha/day for type 2 landfills and 1000 l/ha/day for type 3 landfills.

BPEM [26] also provides a very tough CQA programme and test frequencies for on-site sampling and testing of shipped materials, e.g. mass per unit area and peel strength of the GCL each to be tested a sample every 500m². It also required that a leak detection test should be carried out to ensure that the geomembrane is not damaged.

China

The Chinese specification “CJJ113-2007 Technical code for liner systems of municipal solid waste landfill” [27] proposes four types of barrier systems:

- Geomembrane and compacted clay liner as a composite lining system
- Geomembrane and a geosynthetic clay liner as a composite lining system
- Compacted clay liner as a single lining system
- Geomembrane as a single lining system

The compacted clay liner should have a thickness of ≥ 0.75m, with a hydraulic conductivity of ≤ $1 \cdot 10^{-9}$ m/s, and the geomembrane should be HDPE and have a thickness of ≥ 1.5mm.

Japan

The Japanese guideline [28] specifies minimum design requirements for the liner system consisting of a 1 mm thick HDPE geomembrane and a 0.5m thick compacted clay liner with a hydraulic conductivity of ≤ $1 \cdot 10^{-8}$ m/s.

Russia

The Russian ordinance SP 320.1325800.2017 "Landfills municipal solid waste. Planning, operation and recultivation" [29], updated on 02/07/2018, stipulates that landfill base and slope barriers must be sealed with one of these materials: clay, concrete with bitumen layer, asphalt polymer concrete, polymeric materials, geosynthetic materials, and others. The requirements for the sealing systems are relatively low: permeability coefficient of less than 0.10 - 0.11 m/s (Note: this must be a mistake as it is very high!) and resistance of a minimum of 1.8kN to mechanical damage.

South Africa

South Africa is known to have excellent waste regulations, strategies and legislation in place when compared with neighbouring countries. The timeline below (Figure 5) outlines key waste management legislation over the past 30 years from 1989 to 2017.

The South African waste management story starts with the Environmental Conservation Act (Act 73 of 1989). This Act set out the requirements for the management of waste and provided the first legal definition of waste. This Act largely focused on the permitting, control and management of waste disposal sites. It intended to reduce the environmental impacts associated with many poorly operated landfills, many of which were in fact dumpsites (controlled and uncontrolled).

In 2008, the National Environmental Management (NEM): Waste Act (Act 59 of 2008) was promulgated, which resulted in numerous regulations that followed 2008 and 2017, including the NEM: Waste Amendment Act (Act 26 of 2014). The purpose of the Waste Act is to regulate waste management within South Africa across all levels of government, including national, provincial, municipal and local.

In South Africa, waste disposal landfills are grouped into four classes according to the waste types earmarked for disposal (Classes A, B, C and D) [30].

The classes of the landfill, their corresponding waste types and the minimum liner requirements are shown in Figure 6.

Figure 5: South African waste legislative timeline [30]

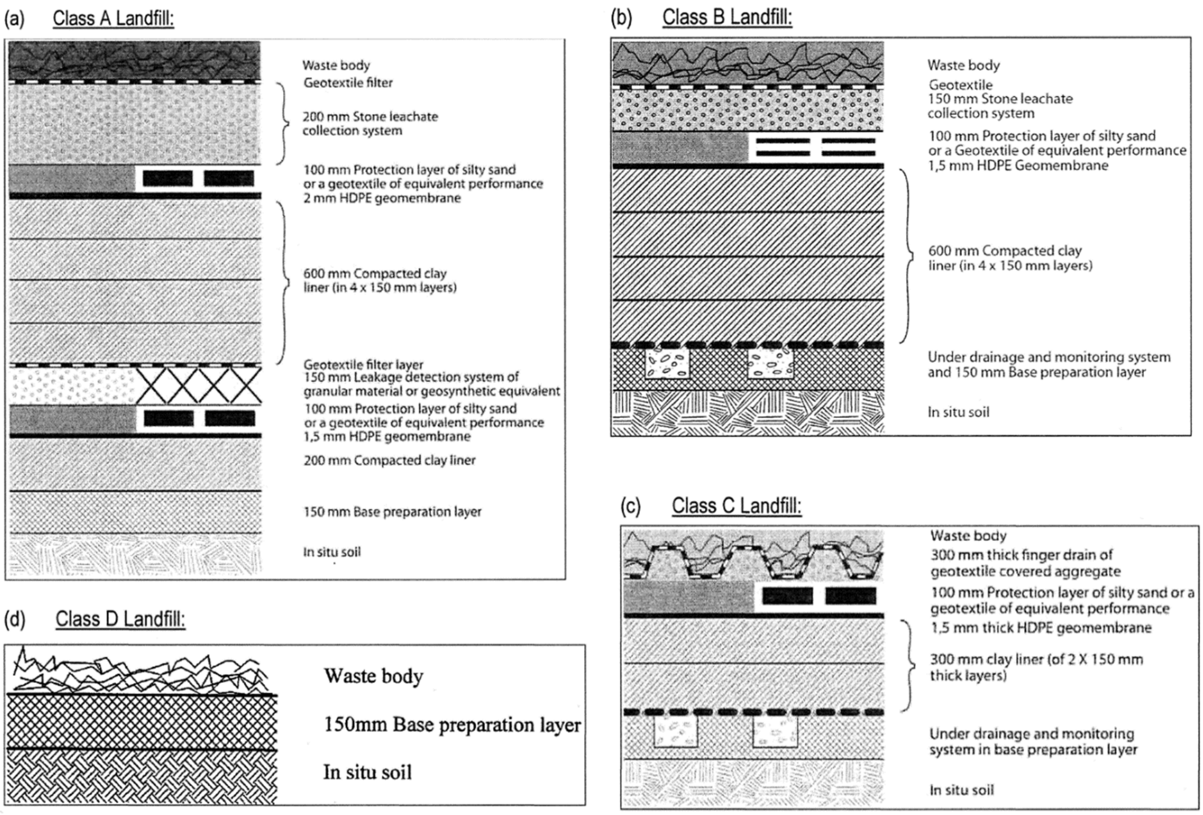

Figure 6: South African landfill classes, their corresponding waste types and the minimum liner requirements [31]

The liner detail in Figure 6 is a general minimum standard, and every containment facility needs to have its own fit-for-purpose engineered lining system that conforms to the class of facility and type of waste that it will receive. The various layers can be replaced by other layers of equal or improved performance, and the compacted clay layers are often replaced with a geosynthetic clay liner (GCL). The GCL layer generally has to have equivalent or improved performance demonstrated when replacing a Compacted Clay Liner (CCL), e.g. also in its permittivity and chemical resistance. However, in most cases a GCL outperforms a CCL. The leakage detection system normally made up of granular material can also be replaced by an approved geosynthetic equivalent alternative such as a cuspated HDPE drainage sheet or geocomposite drain. HPDE GMs have been widely used in landfills and waste containment barriers due to their high resistance to advective flow of leachate and resistance to chemical attack (Rowe et al. [32]). In South Africa, the minimum landfill liner thickness is 1.5mm, but this can be increased depending on the site-specific requirements for the design. This type of material can be smooth or textured depending on the stability requirements of the design.

Thailand

The Royal Thai Government Waste Management Strategy is managed by the local government with guidance, regulations and policies set by the central government. Current national policies for waste management are to promote participation in both public and private sector to increase awareness and reduce waste output, promote recycling and separation of waste streams.

The Environmental Engineers Association of Thailand (EEAT) works closely with a variety of stakeholders (in particular the central government Pollution Control Department PCD) on various working committees to promote the enforcement and uptake of guidance for waste management practices especially regarding MSW management policy.

However, of the estimated 15 million tons of waste produced each year in Thailand, approximately 12 million are placed in non-regulated and classified sites.

Thailand in 2012 had 96 operational landfills including recent 2021 projects such as landfills at Kanchanaber province and the Ratchaburi landfill site which consist of composite lining systems of a needle-punched geosynthetic clay liner with sodium bentonite powder and an HDPE geomembrane.

USA

Similar to European landfill legislation [5], the USA also differentiates between landfills for domestic waste and hazardous waste. Analogously, different minimum requirements are set for base and surface sealing systems.

Waste is defined to be hazardous and falls into the category EPA (Subtitle C of RCRA [33]) if it is listed as a hazardous waste; it is mixed with or derived from a hazardous waste; it is not excluded (some wastes, such as MSW, are specifically identified and excluded as hazardous waste); and it possesses any one of four characteristics: (i) ignitability; (ii) corrosivity; (iii) reactivity; or (iv) toxicity.

The RCRA Subtitle C [33] generally requires hazardous waste landfills to have a double-liner system with a leak detection system (LDS) between the two independent liners and a leachate collection and removal system (LCRS) above the primary liner. The purpose of the LDS is to allow monitoring of the primary liner (i.e. to identify whether, and to what extent, leakage is occurring through the primary liner) and to provide a mechanism for removing liquids that enter this system. The minimum double-liner system design standards for hazardous waste landfills as cited in 40 CFR 264, Subtitle C regulations [33] consist of the following, from top to bottom:

- LCRS that limits the head of the leachate on the primary liner to 0.3m or less;
- Geomembrane (GM) primary liner (typically 1.5mm thick);
- 0.3m thick granular LDS drainage layer with a minimum hydraulic conductivity of $1 \cdot 10^{-4}$ m/s or a geosynthetic LDS drainage layer with a minimum hydraulic transmissivity of $3 \cdot 10^{-5}$ m^2/s; and
- Composite secondary liner consisting of an upper GM overlying a 0.9m thick compacted clay liner (CCL) with a maximum hydraulic conductivity of $1 \cdot 10^{-9}$ m/s. (GCLs are often used to replace the CCL).

Requirements for final cover systems for hazardous waste landfills are also addressed in federal regulations (i.e. 40 CFR 264, Subtitle C of RCRA [33]). These regulations require in hazardous waste landfills the following minimum components from top to bottom:

- a top layer containing two components: (i) either a vegetated or armored surface layer; and (ii) a 0.6m thick protection layer, comprising topsoil and/or fill soil, as appropriate;
- a 0.3m thick granular drainage layer with a minimum hydraulic conductivity of $1 \cdot 10^{-4}$ m/s; and
- a composite hydraulic barrier, consisting of 0.5m thick geomembrane covering a 0.6m thick CCL with a maximum hydraulic conductivity of $1 \cdot 10^{-9}$ m/s. (GCLs are often used to replace the CCL).

US federal legislation applicable to municipal solid waste (MSW) landfills are contained in Subtitle D of RCRA [33]. MSW landfills generally receive household waste but can also receive non-hazardous sludge, industrial solid waste, and CDD waste. The minimum design standards stipulated in the federal Subtitle D of RCRA regulations for MSW landfills [33] require a single-composite liner system that consists of the following components, from top to bottom:

- an LCRS that limits the head of the leachate on the composite liner to 0.3m or less;
- 0.75mm thick GM (1.5mm thick if the GM is made of high-density polyethylene (HDPE)); and
- 0.6m thick CCL, with the CCL having a maximum hydraulic conductivity of $1 \cdot 10^{-9}$ m/s. (GCLs are often used to replace the CCL).
- The GM component must be installed in direct and uniform contact with the compacted soil component.

Final cover system requirements for MSW landfills must have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability $\leq 1 \cdot 10^{-7}$ m/s, whichever is less, and from top to bottom:

- a 0.15m thick vegetative soil layer as well as a 0.45m thick soil cover layer;
- single or composite lining system (GCLs are often used to replace the CCL).

THE STATE-OF-THE-ART OF MODERN LANDFILL DESIGN

Many modern landfills constructed over the past decades are performing extremely well and this is because the content of landfills is considered hazardous for the environment and the landfills are built with efficient barrier systems. Further, many landfills are also often located in cities or at least nearby to them, and have surrounding monitoring systems, so that the effect on the environment is noticeable in an early stage. Further regulations have been developed in the last decades, ensuring proper design and proper requirements to ensure that the barrier system will last far beyond the estimated design life of the landfill structure. There are several factors that contribute to the protection of the environment but one key factor is the use of a geosynthetic barrier system. The protection of water and the environment is a major consideration in the design of waste containment facilities (landfills) in many countries. Geosynthetic barriers have been and are increasingly being used and play a very important role in this application due to their technical effectiveness, versatility, cost-effectiveness, ease of installation, and good proven performances. However, their main advantages are that they seem to be technically better suited than traditional systems, such as compacted clay liners. In landfills, geomembranes and GCLs are used as bottom liners, for leachate ponds, cut-off walls, and closure and cover. While most regulations require a geomembrane or a clay liner as a single liner in construction waste landfills, GCLs as a replacement of the compacted clay liner are often used with the geomembrane as a composite lining system to form a high-effective barrier system in hazardous and most municipal solid waste (MSW) landfills. MSW landfills typically require a single composite liner comprised of a leachate collection and removal system and a geomembrane overlying either a GCL or compacted clay liner (Figure 7). Hazardous waste landfills generally require double-liner systems (two geomembranes), often incorporating both GCLs and compacted clay (von Maubeuge [34]).

Geomembranes and GCLs are used for landfill caps to prevent fluid migration into the landfill (Figure 7), thereby reducing or eliminating post-closure generation of leachate and the associated treatment costs. The cap is also designed to trap and properly vent the gases generated during the decomposition of organic wastes. Similarly, the closure system can prevent the seep of any fluids from the refuse body to the landfill surface. Often GCLs are added beneath the geomembrane to form a composite lining system. Geomembrane and GCL closure systems can also be designed to facilitate the future vertical expansion of the landfill, thereby enlarging the landfill capacity. By fully encapsulating the refuse, the completed cap enables the safe and efficient restoration, revegetation, and possible reuse of the land.

GCLs are an interesting combination of polymeric materials and natural soils. They consist of a layer of dry powder or granular sodium bentonite, typically 3,600 – 6,000 g/m², needle-punched encapsulated between two layers of geotextiles. GCLs are factory-fabricated and therefore available in rolls, and are often combined with a GM to form a composite liner or used individually as a single liner in landfill liner applications. GCLs have been demonstrated to be generally equivalent or superior to compacted clay liners (CCL) in waste containment system applications (Koerner et al. [35]; Giroud et al. [36]; von Maubeuge [37]).

Despite the enormous landfill technology development over the last decades the main issue has remained. The main purpose of a landfill has not changed. Landfills store materials that today are of no further use. During the storage of waste, the conditions within the landfill can change and cause different effects (temperature change, chemical concentration, etc.) on the barrier system. Especially, as likely not deeply investigated, incineration residues contain heavy metals which over time will "sink" to the basal lining system and dramatically increase the heavy metal concentration in leachate, directly over the lining system.

The good news for our current modern landfill tomb (or coffin) is that future generations will find methods how to extract these valuable raw materials, so that our current landfills will then be used in the future as a supply resource.

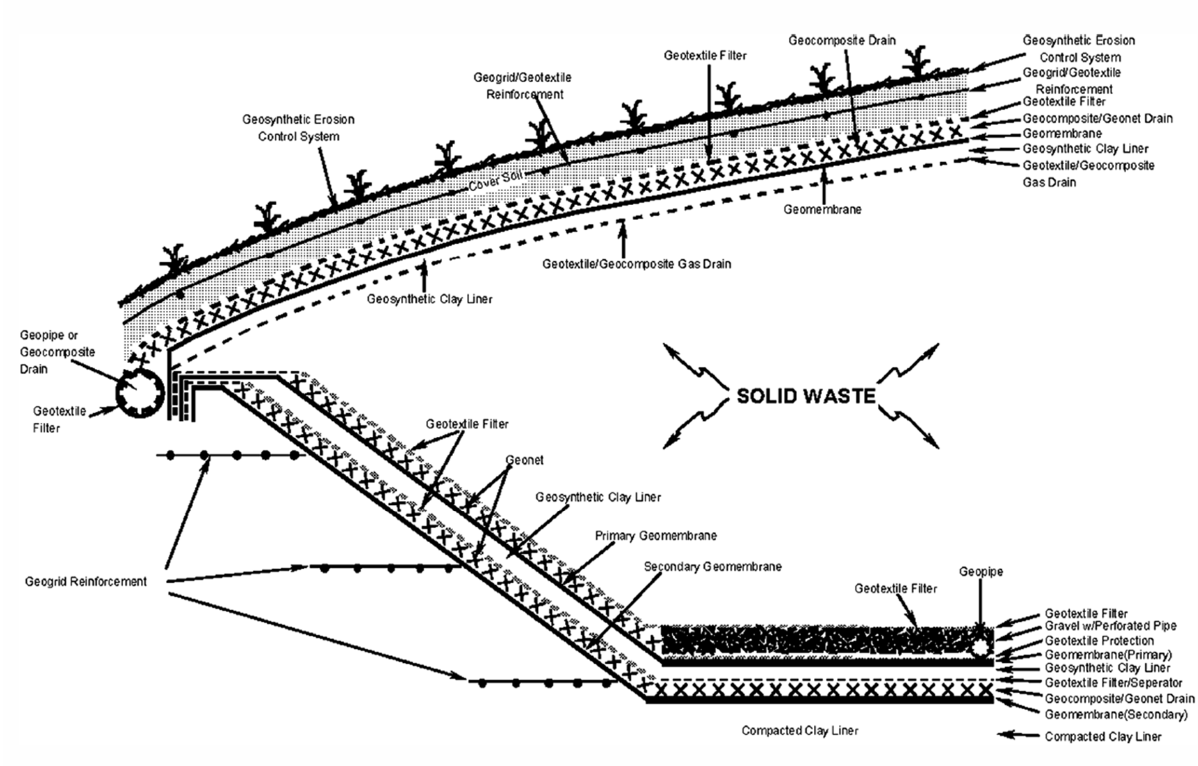

Figure 7: Geosynthetics used in a landfill base and as a cover/cap (Koerner [38])

Therefore, the main goal for every modern landfill should be a ‘zero leakage’ approach. This can only be achieved with strict regulations for landfill lining and capping systems. It then not only requires high-quality barrier materials with strict manufacturing quality control and assurance but also, e.g. a wrinkle-free installation of the geomembrane, direct, intimate contact with the compacted clay liner or geosynthetic clay liner, qualified and third-party-controlled installer, a site quality control and assurance of the material, installation, all geomembrane welding, as well as the placement of cover soil material, and last but not least a sufficient protection geotextile which fulfills its function over the service life of the landfill.

EXAMPLARY PROJECTS

As not all countries in the world have their own regulations or guidelines for landfill sealing systems, they still might want to have safe landfills. Therefore, often regulations or guidelines are used from other countries.

The Nyamasoga Landfill in Uganda

The Nyamasoga Landfill in Uganda is a critically important hazardous waste facility in the oil-rich Hoima District. The 44-ha site is close to drilling pads and a proposed refinery.

In the absence of guidance within Uganda’s environmental codes, the South African regulations and design specifications common to oil operations in the region were used to build a fully modernised landfill to handle drilling fluids, mud cuttings, and other industrial and processing waste not suitable for municipal solid waste burial. This produced designs for waste containment and stormwater management following South Africa’s Class A approach, which is a double liner system.

Figure 8: Installation of the base lining system [39]

The designer's technical specification finally led to the supply of geomembranes, geosynthetic clay liners (GCLs), and geogrids to solve the site's challenging parameters. The local soils were characterised by sandy clays with pockets of gravel interspersed. Weathered rock was present between 2.5 and 4.5m below the surface. This limited the maximum cell depth to 5m, to minimise rock excavation and prevent groundwater perching.

Additionally, the area was hilly, including being extremely steep at some edges (Figure 8). The design engineers created a C-shaped cell plan on the north side of the property, with the center points of the C having the lowest elevation. This is where the primary stormwater management cells were set, creating a very efficient design.

Due to a water table that perched at 5.2m, seepage was detected into the system during excavation. Thus, a geocomposite drainage layer was included in the design. Natural filter materials were too expensive to source for the site.

The absence of easily sourced filter material was only one of the sourcing challenges presented by the location. A bentonite-enhanced soil layer was expected, for example; but bulk sourcing such a clay layer was not possible in the area. Thus, the design was amended to include two GCL layers instead of just one.

This innovative design solution gave the site greater security, better economics, and a quicker, safer installation. It also underscored how geosynthetics provide exceptional performance and affordability for emerging infrastructures.

Senj Landfill - Sveti Juraj

The Senj landfill is located on the Croatian Adriatic coast near Senj in an abandoned quarry above the small village of Sveti Juraj between the main centers of Rijeka and Zadar.

The use of gravel for the leachate collection system, sand as a protection layer over the geomembrane or compacted clay on the slopes turned out to be impossible, due to the approximately vertical walls that form the embankment of the quarry. Flattening the terrain would have meant expanding the landfill area, which was technically not possible due to property ownership. It was also too expensive considering the amount of rock removal. Further, there would have been no nearby deposit location or use for the material, and landfilling it in the new landfill would have further reduced the new waste storage capacity. Therefore, a geosynthetic solution has been assessed by designers and authorities as to the best option in terms of safety and environmental impact.

Figure 9: Sealing of the nearly vertical side slopes of the base lining system in the Senj landfill

The challenging boundary condition of the project was the sealing of the steep wall of the former quarry, which is very steep and up to 20m high (Figure 9). The first step was to create a flat supporting surface for the sealing elements. This was done with a facing shell of shotcrete, which leveled the highly fissured surface of the rock face and additionally stabilised it with a reinforcement of structural steel mesh and a tie-back into the rock with additional anchors.

Above the shotcrete layer, a geosynthetic protection and drainage layer was installed to divert small amounts of potential seepage water, minimising an additional hydraulic pressure against the sealing system. The actual base and side-wall lining system consisted of a composite lining system of a geosynthetic clay liner and a 1.5mm thick geomembrane. A geosynthetic protection layer of a needle-punched nonwoven was installed above the geomembrane to prevent any damage to the geomembrane from the leachate collection layer and the pressure from the waste.

Tahwa landfill, Sultanate of Oman

In the Sultanate of Oman, the Oman Environmental Service Holding Company S.A.O.C (be'ah) has strongly promoted the establishment of controlled landfill management in recent years. In the last decade, more and more landfills with technical barriers have been built. The previously common unregulated dumping without sealing away from populated areas has been transferred to central collection points.

The standard structure for the base of these landfills consists of a composite lining system. Due to geological and climatic conditions, the use of locally extracted mineral materials for the compacted clay liner was not possible, the decision was made to specify a geosynthetic clay liner (GCL) in combination with a ≥ 2.0mm thick HDPE geomembrane (Figure 10). Mechanically bonded nonwovens were used as a protective layer above the geomembrane and a geosynthetic drainage mat supplemented the gravel leachate collection layer.

An advantage for the location of the Tahwa landfill is the hydrogeological situation, as the distance between the aquifer and the bottom of the landfill is high and there is no threat of possible water pressure from the aquifer. However, there were other challenges. One was the difficulty to excavate rocky subsoil. Another challenge was the high temperature and temperature gradient, as this influenced the geomembrane welding procedure. Therefore, welding was mainly carried out at night or in the early morning. Additionally, the composition of the waste, with its high organic content attracts rare carrion birds such as Egyptian Vultures.

Figure 10: Geosynthetic base lining system with GCL and geomembrane as a composite lining system

FUTURE IMPROVEMENTS FOR LANDFILLS

For future landfills different developmental stages of alternatives in landfill engineering, e.g. improvement of a landfill, a barrier material, or use of waste material as a construction material are possible. It is obvious that the selected examples are only a small part of suggested improvements and should leave room for improvement for further thoughts and discussions.

MSE Berms for Landfill Capacity Enhancements

The mechanically stabilised earthen (MSE) technology consists of utilising geosynthetic reinforcing elements in combination with soil and a wide selection of facing elements to create safe and cost-effective grade separations for highways, and most recently, waste containment facilities. Figure 11 shows examples of MSE berm applications to increase the capacity of a containment facility, for highway applications, and steep soil slopes.

The MSE berm around the perimeter of the landfill footprint to gain additional disposal capacity has already been utilised in several landfill expansion projects around the world. An example is the Cherry Island Landfill (CIL) expansion project in Wilmington, DE, USA where a 2,440m long, 21m high MSE berm was built to facilitate the vertical expansion of the CIL (Geosyntec [40]; Espinoza et al. [41]). This landfill vertical expansion project not only provided an additional 20 years of disposal life, but also became one of the five finalists in the 2012 Outstanding Civil Engineering Achievement (OCEA) award by the ASCE.

In the future, this practice is likely to be extensively considered especially on sites where the availability of landfill space is limited or at a premium. Also, due to the difficulty or opposition to siting new landfills, existing landfill facilities would have to rely on this technology to continue in operation.

Figure 11: MSE berm around the perimeter of the Hanover landfill, Germany

Remediation Capping with Multicomponent GCLs

Remediation tasks may not require highly sophisticated designs as requested for landfills, but still require low permeability capping solutions capable of meeting multiple key performance criteria. Critically, it would be required to provide an immediate and permanent gas barrier, be compatible with the chemical contaminants, and be resistant to long-term degradation.

Additionally, they should avoid the formation of toxic leachate by preventing fresh-water ingress, and in some cases, it might be necessary to tie and connect to side slurry walls around the site.

Rather than using an expensive composite lining system or just a single lining system, a multicomponent geosynthetic clay liner could be an effective and economic solution. An added polymer coating to the needle-punched GCL improves the GCL performance and opens more applications where GCLs can be used in. Advantages of the extruded polymer-coated barriers are: prevention of root penetration; increasing resistance against desiccation; bentonite piping resistance under high water gradients; lower permeability; barrier against chemicals and ion exchange; gas barrier, etc. (von Maubeuge [42]).

The former industrial site to the north of Glasgow contains calcium sulphide solid waste, known as 'galligu', which released toxic, foul-smelling, hydrogen sulphide gas.

A multicomponent GCL (MGCL) material has been instrumental in the remediation of a former industrial site to the north of Glasgow, in preparation for a new urban development which includes infrastructure works, around 800 new homes, a new education and community facility, green space and streetscapes, as well as retail and commercial units (Figure 12). The MGCL securely capped the contaminated area.

Figure 12: A protection nonwoven geotextile is being installed over a multicomponent GCL and then covered with soil material

Using Waste Construction Material for a Better Purpose

There is a growing awareness of the need to divert construction and demolition waste from landfills and reuse or recycle them. The use of excavated soil, industrial waste products, and recycled construction materials in earthworks contributes to the conservation of resources and the currently necessary reduction of landfill space. Nevertheless, there is a special need for action for the selection of technical safety measures which are necessary for the use of soils and construction materials with environmentally relevant contents (so-called substitute construction materials), which otherwise would need to be stored in a landfill.

In its current version, the Code of Practice on Construction Methods for Technical Safety Measures when Using Soils and Construction Materials with Environmentally Relevant Contents in Earthworks (M TS E) [43] regulates various construction methods that can be used as technical encapsulation measures and in some cases are even stricter than the landfill barrier system requirements.

The German replacement construction materials ordinance, which is to be applied nationwide in the future as part of the framework ordinance and which is intended to create for the first time nationwide and legally binding requirements for the recycling of mineral waste and its use in technical structures, refers to the construction methods of the M TS E guide.

Consequently, for example, a mineral barrier component such as a geosynthetic clay liner (GCL) or a geomembrane can be assigned as a barrier system.

The expanded U-shaped protective wall at the shooting club SSC Schale, Germany is 475m long and 20m high, one of the largest reinforced earth structures in Germany and structurally groundbreaking for the problem-free and safe sealing of the dam core on steep slopes (Figure 13). Over 200,000m^3 of soil were moved, mostly with environmentally relevant contents. This "waste" material forms the core of the wall, with a steel mesh front-facing. The polyester geogrids used in the system are anchored up to 11m in the dam core and thus enable the steep front facing. The geosynthetic clay liner, with the German LAGA approval for landfills, seals the waste core material against the environment and thus prevents the escape of any contaminants.

Figure 13: GCL used as an encapsulation barrier for waste construction material in a MSE structure

Additionally, the front facing is designed in such a way that flying clay target residues and lead bullets/pellets fall down and can be picked up at regular intervals, properly disposed or recycled.

New product development

Advances in technology have made geosynthetics well-established in landfill applications and allowed engineers and designers to build safe and long-lasting landfills.

Innovative materials for geosynthetics and designs can be expected in future, especially when new questions arise. The creative use of new raw materials or geosynthetic products in landfill engineering, especially if new questions on their performance are brought up, will continue to expand.

PFAS

Geosynthetic barriers, such as geomembranes and geosynthetic clay liners, play a very important role in landfill applications due to their technical effectivity, versatility, cost-effectiveness, ease of installation, and good proven performances and have world-wide an excellent track record. The storage of PFAS (Per- and polyfluoroalkyl substances) within modern landfills is a fairly recent question and issue and the goal with PFAS is to isolate the contaminate from the environment and thus protect human health and the environment (Ramsey, [44]). Specific testing and research are underway for PFAS type materials containment, initial results are positive and suggest that containment of PFAS can be achieved at levels similar to that of hazardous chemicals examined previously, such as benzene and other aromatic compounds. This research should continue and be completed, further the results of this research can contribute to sound environmental engineering and the creation of realistic regulations protecting human health and safety and the environment. The existing materials and systems will be used for PFAS containment as they provide the best track record and utility. New material developments (barriers and/or sorption materials) are also underway to further optimise the solutions for PFAS containment. However, the release of PFAS from sorbent materials is highly undesirable, as they can likely become a secondary source of PFAS in the environment.

Polymer modified GCLs

In recent years, bentonites modified (amended) with polymers have been introduced to the market, stating that they can improve the chemical compatibility and hydraulic conductivity performance of GCLs when e.g. permeated with aggressive liquids. It is claimed that the addition of polymers into the bentonite improves or maintains the hydraulic conductivity, likely increases bentonite swelling capacity, prevents cation exchange due to modification of the smectite minerals or clogging of the pores. However, performance of enhanced bentonite depends upon the mixing procedure and might significantly vary even at same composition.

In practice, the addition of polymer (chemical) additives is generally a very small percentage (0.5% to 5%) of the overall bentonite mass to be modified. However, several research data also show higher percentages of polymers used. Therefore, it is clear that research data, which are used to verify the use of a polymer amended bentonite type in an application, must contain the exact polymer type and amount, as well as the comparable mixing procedure. To allow manufacturing quality control (QC), construction QC and acceptance auditing, it is necessary to be able to identify the type, quantity, distribution and consistency of the polymer additive (regardless if the bentonite supplier or the GCL manufacturer adds the polymer).

Therefore, as a minimum requirement, the chemical makeup of a polymer (chemical) additive should be detailed, with a material safety data sheet (MSDS) provided and in the data sheet of the geosynthetic clay liner (GCL) with polymer-modified bentonite it must be noted that polymers have been added and at least the type and quantity of polymer should be outlined. The manufacturer should also provide in advance quality control data proving the addition and the quantity and numbers of polymers as well as method statements on how they can be identified and quantified in quality assurance testing.

Especially the mid- and long-term effects of the polymer modification need to be investigated. Chen et al. [45] investigated the interface shear strength between a polymer-amended bentonite geosynthetic clay liner (GCL) as well as a GCL containing sodium bentonite and a 1.5mm textured high-density polyethylene (HDPE) geomembrane (GM). All tests were conducted with normal stresses of 20, 100, 250, and 400 kPa and ended at a maximum displacement of 50 mm.

The poor interface shear performance of the polymer-amended/modified bentonite GCLs, due to polymer extrusion out of the bentonite to the GCL surface, was an interesting outcome of this research:

- “Interface shear strengths corresponding to peak and large-displacement conditions were lower for the B-P GCL than the conventional GCL at same normal stress, even though both GCLs had similar physical properties.” [45]
- “Effect of the polymer hydrogel on interface strength increased with increasing normal stress, with lower interface strengths obtained at a normal stress of 400 kPa relative to 250 kPa.” [45]

The main issues with polymer (chemically) modified bentonites in GCLs are the long-term performance and durability of the GCL. The polymer additive may provide a benefit during the first swell cycles but after that and during future drying/hydration the performance is unknown and cannot be guaranteed. The referenced paper regarding polymer modified bentonite by Gardam et al. [46] clearly states that the achieved test results for modified bentonites are short-term only. It also notes in the conclusion that “Further tests are required to validate these results over longer time periods and larger flow volumes and to influent-effluent chemical equilibrium”. Other studies on polymer-modified bentonite GCLs by Scalia et al. [47] with cooperation of Colorado State University shows that after two years the polymer has been lost from the polymer-modified bentonite GCL during permeation. In addition, documented long-term performance results should be presented and not only short-term index bench tests.

This will enable the design engineer to be able to make informed decisions and for stakeholders to be aware of potentially harmful chemical additives to people and the surrounding natural environment.

CONCLUSION AND FINAL REMARKS

In many parts of the world, governmental agencies have mandated the use of geosynthetics in landfill applications. In Europe, the Construction Products Directive (89/106/EEC; M/107) has to be followed or exceeded. South Africa, Australia, Germany, UK, the USA, and other countries have excellent to very good guidelines. If not done yet, their use must be made mandatory in regulations to have efficient solutions with large potential on cost savings, the safety of the designed structures and a minimum of environmental pollution including a large reduction of the use of natural resources.

Most regulations describe material properties in detail or refer to existing specifications. However, some regulations show a shortage of other relevant design parameters, such as design issues, external effects, durability issues, installation considerations and/or quality control/assurance. Improvement is needed for those.

The comparison of international regulations and requirements shows no such detailed assessment of physical properties, service life, and defined application rules for geosynthetics in landfill construction analogous to the regulations applicable in Germany, where suitability tests, in-house and external monitoring of geosynthetics for landfill construction cover not only the actual product but also the specific raw materials and the processed product on the construction site. This comprehensive consideration is not included in many normative regulations in international comparison.

Nevertheless, methodological procedures for the installation and testing of geosynthetics from higher-level regulations or international standards are also adapted internationally in project-specific quality assurance plans. There are numerous examples which prove that geosynthetics can be used to produce effective sealing systems for landfills even with difficult geometries and/or difficult climatic boundary conditions. In this context, high-quality products with consistent properties, a well-coordinated and dimensionally accurate installation, and competent supervision of the installation are crucial for the success of the construction measures.

Nearly worldwide a modern municipal solid waste landfill is designed as a composite lining system with an HDPE geomembrane and a compacted clay liner (often and more and more replaced by a more efficient geosynthetic clay liner). Double-lined base sealing systems with two composite lining systems and an integrated leachate detection system are also used in a few countries in landfills for very hazardous waste, but the majority of countries still built these with a single composite lining system.

The benefits of geosynthetic materials have been recognised and are gaining more popularity and often are even finding their way into regulations as a standard system.

The development of landfill designs is ongoing and one trend is mechanically stabilised walls around landfills to increase the waste volume.

In non-regulated landfills, in coal ash storage areas [48] or for encapsulation of contaminated soils multicomponent geosynthetic clay liners are also specified, rather than a single lining system.

The challenges for the designer and the geosynthetic manufacturers are new product developments, e.g. as a barrier against PFAS or the use of new or modified materials, such as polymer-modified bentonites. However, some of these products are still in the development stage and likely more research is needed.

Overall, geosynthetics play an important role in landfill projects and they have proven their versatility, cost-effectiveness, ease of installation, sustainability (compared to mineral materials). Additionally, they are easy to quality control, have a very good homogeneity in manufacturing and compared to traditional natural materials a much better cumulative energy demand and a much lower CO_2 output [49].

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