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TESI DI LAUREA

Environmental sustainability assessment of Geosynthetic Clay Liners

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Summary

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INTRODUCTION

The principal aim of the forthcoming thesis is to assess the environmental sustainability of bentonite geocomposite mineral barriers (GCLs) in comparison to more conventional design solutions comprising compacted clay (CCL).

Despite sharing the objective of preventing the migration of hazardous substances, these two solutions diverge significantly in terms of composition, performance, installation methods, design thicknesses, costs and environmental impacts.

This activity forms part of a wider research programme conducted by the Department of Structural, Building and Geotechnical Engineering (DISEG) at the Polytechnic University of Turin. The programme concerns the use of bentonite barriers for the control of PFAS in the subsoil and is entitled 'Theoretical-experimental study on the transport processes of perfluoroalkyl substances (PFAS) in waterproofing systems consisting of bentonite barriers (e.g., bentonite geocomposites), taking into account coupled phenomena (e.g., 'Chemical osmosis' in collaboration with Eni Rewind, for which Professor Andrea Dominijanni assumes responsibility for the scientific aspects, and Professors Mario Manassero and Eng. Nicolò Guarena is contributing to the project.

Barriers formed by compacted clay (CCLs) were developed and used first; they consist of layers of clay compacted directly in situ, whose thickness can exceed one metre, offering a permeability that varies between 10^{-9} and 10^{-10} m/s.

GCLs, on the other hand, were introduced recently, between the 1980s and 1990s. They are composed of layers of bentonite alternating with geotextiles, which, enclosed in a package with an overall thickness of around 20-30 cm, offer a permeability of between 10^{-10} and 10^{-12} m/s.

The aforementioned properties render mineral barriers particularly suitable for the construction of hydraulic bottom barriers or the covering of waste dumps. They are effective in impeding the passage of contaminants in both liquid and gaseous solutions.

The objective of the study was to provide a clear representation of the equivalence of the two design solutions in terms of contaminant containment and to conduct a comparison of the environmental impact linked to all phases of the life cycle of the two barriers in terms of carbon footprint, diffusive gas flux through the covers, and contaminant flux in liquid solution that passes through the landfill bottom barriers, flowing into the water table.

In this regard, we examine the semi-permeable membrane behaviour of GCLs, which effectively restricts the movement of contaminants in solution through the pores.

The efficiency of semi-permeable membranes is quantified in terms of ω, chemical-osmotic efficiency, which is primarily influenced by the porosity of the material and the concentration of contaminant.

The study is divided into two sections. The initial section is entirely theoretical, wherein the chemical and physical characteristics, as well as the applications, of the two distinct types of barriers are elucidated. Additionally, environmental considerations pertaining to mineral barriers are presented, and the theoretical methodologies for evaluating the environmental impact of the selection of bentonite geocomposites (GCLs) as barrier layers for waste containment in landfills are delineated.

Thereafter, attention in the second phase of the paper is directed towards the detailed description of the analysis and careful study of gaseous emissions by assessing the carbon footprint of CCLs versus GCLs at all stages of their life cycle.

The evaluation of the gaseous diffusive flux through the cover is also deepened and it is shown how the effective diffusion coefficient $D_e$is sensitive to changes in water content and thus to the degree of saturation of the GCLs; in particular, it is illustrated how correct hydration of the bentonite layer causes the values of D_e to the order of 10^{-11}, translating as an excellent ability to contain the gaseous diffusive flows contained within the landfill towards the external environment.

The initial chapter is devoted to an examination of the characteristics of mineral barriers. Here, the focus is on the properties, applications, and installation procedures, which are markedly distinct between compacted clay liners and geosynthetic clay liners.

Furthermore, Legislative Decree 121/2020 is summarised, which introduces substantial amendments to the Italian regulatory framework on waste management. The objective of these amendments is twofold: firstly, to advance the principles of the circular economy and, secondly, to mitigate the environmental impact of landfills.

The second chapter presents a discussion of the theoretical approaches that can be employed for the assessment of the environmental sustainability of bentonite geocomposites.

The chapter makes reference to the relevant regulations and provides theoretical background to the issues addressed in the environmental assessment. In particular, it considers the carbon footprint of the two design solutions throughout their entire life cycle, from the production of raw materials or quarrying in the case of clays, through to the transportation phase, which represents a significant difference between the two cycles.

The considerable discrepancy in the volumes of material to be transported between the two solutions is evident, with clay solutions requiring hundreds of times more heavy vehicles than GCLs.

This is followed by the construction or assembly phase of the barrier system, which differs in terms of the quantity of material to be handled between the two solutions due to the preparatory nature of this phase in relation to the previous transport phase.

Two fundamental topics are addressed in this chapter, which represent the core business of the work. The first is the quantification of diffusive gas flux, which delves into the theory of M. Aubertin et al. The second is the contaminant liquid flux through the bottom layer of the barrier, which makes reference to the work of Prof. Dominijanni and Prof. Manassero in Influence of membrane behaviour on contaminant transport.

Chapter 3, from which the analytical part of the thesis begins, illustrates the calculation of gaseous emissions and provides an initial comparison of the different design alternatives.

The quantification of emissions at each stage of the process, from the initial extraction of raw materials through to the construction site, provides a deeper insight into the Bentonite Barrier Research Project.

The principal stages of the process encompass the initial phase, which encompasses the various carbon footprint entities referenced in the studies conducted by Raja et al. and the data from the Geosynthetic Institute consulted for the purpose of quantifying emissions in the raw material extraction and production phase.

The project layout is that of a landfill site with a surface area of one hectare.

In considering emissions during the transport phase, the equation proposed by Raja et al. (2015) was employed to calculate emissions for both the outward journey, with vehicles loaded with material to be transported, and the return journey from the site.

The results obtained consider the tonnes of CO_2 emitted per unit distance travelled. Subsequently, an average distance from the site, indicative for the case study, of 20 km was taken into account.

As will be explained subsequently, the emissions resulting from the construction of the bottom barrier and the final landfill cover are insignificant in comparison to those arising from the construction of clay barriers (Raja, 2014).

The third chapter concludes with an examination of the diffusive flow of gas through the final covers.

Despite the extensive literature on the subject and the widespread use of mineral barriers, there is a paucity of studies examining the efficacy of these barriers in controlling gas flow. This is an important yet challenging area of research due to the potential risks associated with the gases generated within landfills.

In this context, we elaborate on the theory proposed by M. Aubertin et al. The objective is to quantify the magnitude of emissions in hazardous gas coverage by experimentally studying the diffusion properties of gas flow through barriers. This will be achieved by starting with Fick's law, which is expressed for gas flow, and rewriting it in terms of partial pressure gradients (Hillel, 1980; Fredlund and Rahardjo, 1993). This will establish a dualism with Darcy's law, which is used for advective transport. The effective diffusion coefficient, D_e, plays a similar role to that of hydraulic conductivity k.

Although Fick's law can be generalised for three-dimensional conditions, in this context only uniaxial flow will be considered. This implies a change in flow at the corresponding position, with the concentration varying in time and space.

The flow of gas, and thus the change in concentration, is proportional to the effective diffusion coefficient, which is an intrinsic property of materials and is highly dependent on porosity and water content, as previously mentioned.

The following calculation is designed to quantify the flow of gases through landfill cover systems, with a particular focus on the gases that, in terms of volume, are most prevalent in municipal waste landfills: carbon dioxide (CO_2) and methane (CH_4) (Katerina Babikova, 2018).

The present study focuses exclusively on the GCL and CCL layers. While this analysis hypothesis may yield results of an order of magnitude higher than those observed in the real case, it serves to focus greater attention on the environmental assessment of the two barrier layers and the performance that GCL and CCL can provide. It also questions the equiparate nature of the two design solutions.

The final conclusions and comparisons are preceded by Chapter 4, which provides a detailed examination of the efficiency of the bottom barrier layer. This considers the behaviour of semi-permeable membranes in GCLs and calculates the contaminant flux through the bottom barrier with iterative calculation through a bistrate configuration. This configuration is composed of GCL+attenuation layer and CCL+attenuation layer, with the aim of increasing the hydraulic gradient.

The semi-permeable membrane behaviour serves to impede the migration of solutes or contaminants, thereby preventing their passage to areas of lower concentration, such as the exterior of landfills.

It is demonstrated that GCLs, which utilise the properties of bentonite as the primary component for hydraulic resistance, can exhibit notable membrane behaviour, performing effectively as bottom barriers in waste dumps (Shackelford et al.).

The objective of this chapter is to examine the findings of the research project, evaluating the membrane behaviour of GCLs and contrasting it with established techniques such as compacted clay barriers.

1 PROPERTIES OF MINERAL BARRIERS

Mineral liners fall mainly into two categories: Compacted Clay Liners (CCL) and Geosynthetic Clay Liners (GCL).

CCLs, developed first, consist of compacted clay layers with a specific density, whose thickness can exceed one metre, offering a permeability that varies between 10^{-9} and 10^{-10} m/s. GCLs, introduced in the 1980s and 1990s, are composed of layers of sodium bentonite alternating with geotextiles, enclosed in a package whose overall thickness is around 20-30 cm, with a permeability ranging between 10^{-10} and 10^{-12} m/s.

The principal objective of these barriers is to effectively confine substantial quantities of waste and pollutants over extended periods of time. In addition to impeding the flow of pollutants due to their low permeability, these barriers must be capable of retaining the pollutants within them. This is accomplished through the structure of clay, which, with its multitude of unconnected voids and electrostatic forces, in conjunction with other materials, effectively traps pollutants.

In the present era, these solutions represent one of the few technologies that can guarantee an effective combination of low liquid permeability, long life and relatively low construction costs, particularly in the context of handling substantial volumes of waste or water. It is, however, important to note that, regardless of the low permeability of these structures, they remain permeable. It is therefore essential to conduct comprehensive studies in order to ascertain both the quantity of fluid that may potentially leak over time and the extent of any deterioration in the physical and mechanical properties of the insulating material.

The permeability of a material is typically evaluated in a laboratory setting, under conditions that simulate one-way flow on small samples. However, it is important to note that the measured properties may differ significantly from those observed in laboratory conditions. This can often result in a reduction in the actual permeability of the material by one or two orders of magnitude.

This description emphasises the necessity of a comprehensive investigation prior to the implementation of a mineral barrier intended to regulate fluid transmission. This study must take into account a number of factors, which will be discussed in greater detail in the following paragraphs. It is also essential to recognise that the complete elimination of fluid flow is unfeasible. Instead, the objective is to impede its escape from the confined area, thereby minimising the potential environmental impact.

In the following, the legal framework governing the confinement of landfills will first be analysed, illustrating how the designer can select the most suitable hydraulic barrier for each specific case, and then the main types of hydraulic barriers will be examined.

1.1 LEGISLATIVE DECREE 121/2020

Legislative Decree 121/2020, which implements Directive (EU) 2018/851, introduces substantial amendments to the Italian regulatory framework on waste management. These amendments are designed to advance the principles of the circular economy and to mitigate the environmental impact associated with landfills.

While the primary objective of the legislation is to progressively reduce the use of landfills, the decree introduces fundamental provisions to ensure the sustainable management of existing landfills, with a focus on waste confinement and protective measures to avoid contamination of water and soil.

In this context, background barriers and coverage play an essential role in the overall framework.

The containment of waste within landfills represents a pivotal aspect in the mitigation of detrimental impacts on the surrounding environment.

In accordance with European directives, Legislative Decree 121/2020 establishes rigorous regulations pertaining to the confinement of waste. These stipulate the implementation of sophisticated technological solutions, aimed at enhancing the safety and durability of containment barriers.

The lowest barrier is of paramount importance in preventing the contamination of groundwater by leachates, which are the result of waste decomposition. The decree stipulates that these barriers must be constructed from highly impermeable materials, such as compacted clay liners (CCL) or geosynthetic clay liners (GCL).

A detailed analysis of the technical requirements for the bottom barrier, as set forth in Legislative Decree 121/2020, reveals the imposition of exceedingly rigorous standards pertaining to the permeability of bottom barriers. These standards stipulate that the hydraulic permeability of bottom barriers, whether constructed with a clay liners (CCLs) or a geosynthetic clay liner (GCL), must not exceed 10^{-10} m/s and 10^{-11} m/s, respectively.

It is imperative that these materials be installed with a minimum thickness to ensure effective confinement and prevent leachate infiltration into the subsoil.

The backing barrier is constructed with a layering of both natural and synthetic materials. In addition to the mineral barrier, the use of an HDPE (high-density polyethylene) geomembrane with a minimum thickness of 2 mm is mandatory. The second layer serves to enhance the confinement capacity, thereby reducing the risk of breakage and damage.

The barrier cover, on the other hand, serves to isolate the waste deposited within the landfill, restrict the emission of gases such as methane and prevent the infiltration of rainwater. Legislative Decree 121/2020 sets out precise technical requirements for the construction of the cover, with the objective of minimising the environmental impact of landfills during and after the operational phase.

The waste landfill cover must comprise a number of distinct layers. One of the principal layers is the mineral barrier (CCL or GCL), which must exhibit a hydraulic permeability comparable to that of the underlying barriers (10^{-9} m/s for CCLs and 10^{-11} m/s for GCLs).

Furthermore, an HDPE geomembrane must be installed on the mineral barrier to provide additional protection against seepage.

Furthermore, the regulations stipulate the necessity of a drainage layer situated above the geomembrane, which is designed to facilitate the drainage of precipitation, and a vegetation layer, which is intended to enhance water absorption and soil stability.

One of the key aspects in landfill management is the control of gas emissions, especially methane (CH_4), produced by the anaerobic decomposition of organic waste.

The decree stipulates that landfills must be equipped with biogas capture systems, which can be used for energy production or treated to reduce their environmental impact. The implementation of covering barriers serves not only to prevent seepage but also to contribute to a reduction in greenhouse gas emissions into the atmosphere.

In conclusion, it can be stated that Legislative Decree 121/2020 represents a significant advancement in the field of sustainable landfill management, as it introduces more rigorous standards for bottom and cover barriers.

These structures, composed of advanced materials such as GCLs and HDPE geomembranes, are designed to guarantee the secure containment of waste and to prevent contamination of the surrounding environment. Furthermore, the decree introduces new measures to reduce greenhouse gas emissions and mandates rigorous monitoring to guarantee the safe and sustainable operation of landfills. The integrated approach of Legislative Decree 121/2020 represents an effective response to the challenges currently facing waste management in Italy.

1.2 COMPACTED CLAY LINERS (CCLS)

Compacted Clay Liners (CCLs) represent one of the most established solutions in environmental engineering for the construction of impermeable barriers for the containment and safe management of waste and contaminants. Historically used as barrier layers in waste containment facilities, CCLs play a crucial role in limiting the infiltration of surface water into the waste (in cover barriers or 'caps') and in preventing the migration of leachate into the surrounding environment through bottom barriers.

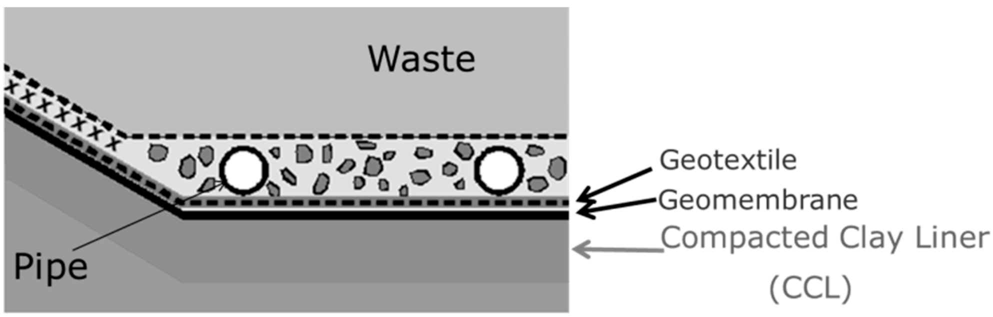

Figure 1.1 Bottom barrier stratigraphy using CCL - IGS

Figure shows the typical stratigraphic structure of a confined landfill using a CCL (Compacted Clay Liner).

Proceeding from the surface to the deeper layers, the following can be distinguished:

- Waste: the top layer is the waste delivered to the landfill.
- Filter layer: generally composed of gravel and/or crushed stone, this layer has the function of filtering and diverting the leachate generated by the passage of rainwater, guiding it into the soil.
- Geotextile: Also known as nonwoven fabric (TNT), geotextile is mainly used to prevent clogging of drainage systems. In fact, leachate is not a fluid without particles, but contains microparticles that are partly retained by the nonwoven fabric.

- Drainage: Consisting of perforated pipes inserted in a layer of gravel, this system is designed to collect leachate and convey it to treatment plants, where the necessary operations will be carried out to allow the safe release of the liquid into the environment.
- Geotextile: A second layer of geotextile is placed for additional filtration and protection functions.
- Geomembrane (GMB): This waterproof synthetic layer offers additional protection against the dispersion of liquids.
- CCL (Compacted Clay Liner): The compacted clay layer acts as a final barrier for leachate not collected by the drains.

The CCL has a dual function: on the one hand, it slows down the passage of leachate towards the water table, and on the other hand, in certain cases, it can help reduce the polluting potential of the fluid, thanks to its chemical-physical interaction with the clay.

1.2.1 Properties of Compacted Clay Liners

CCLs are generally designed using the Proctor method, which is a standardised procedure for determining the optimal density and ideal water content required to compact soils, particularly clays, in order to achieve low permeability. This characteristic is crucial in the design of Compacted Clay Liners (CCLs), which are used as impermeable barriers in landfills and other confinement systems. CCLs must ensure extremely low hydraulic conductivity, generally less than 10^{-9} m/s, to prevent the migration of leachates into the soil and groundwater.

The Proctor method is founded upon a laboratory test in which soil samples are compacted with varying water contents with the objective of obtaining a curve that delineates the relationship between soil dry density and water content. The maximum point on the curve represents the maximum dry density that can be achieved with a given water content, which is referred to as the optimum moisture content. This parameter is of great consequence in the design of CCLs, as it ensures that the material is compacted correctly, thereby achieving the highest possible density and minimising permeability.

In the design phase of CCLs, the Proctor method is employed to ascertain the optimal water content to be incorporated into the soil and the requisite compaction energy to achieve the maximum density. Once the Proctor curve has been established, the clay is compacted in the field in layers of varying thickness, typically between 15 and 30 cm. This ensures that the moisture and density values obtained in situ are consistent withhose determined in the laboratory.

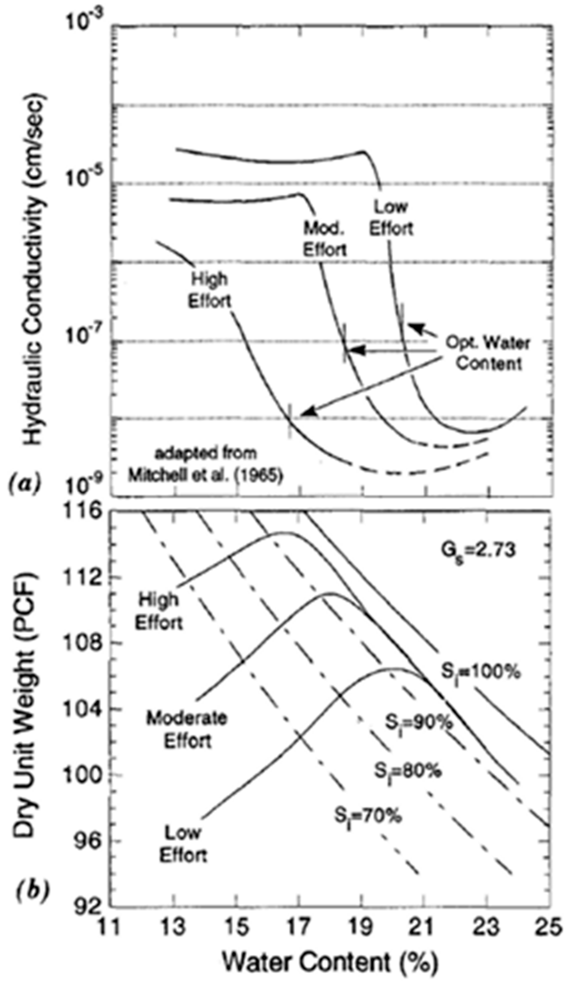

Figure 1.2 Correlation between soil compactability and hydraulic conductivity - Mitchell et al. (1965)

As illustrated in the figure above, there is a direct correlation between soil compaction and the hydraulic conductivity of the soil.

The hydraulic conductivity of a soil is significantly affected by its density and water content. The implementation of the Proctor method for soil compaction effectively reduces the porosity and tortuosity of the soil, thereby limiting the ability of fluids to pass through the material.

The permeability of clay compacted to approach maximum dry density with the appropriate water content is markedly low, which is of great consequence for the efficacy of CCLs. In the event that the soil is not optimally compacted or has an inadequate water content, there is a significant potential for an increase in hydraulic conductivity, which could ultimately compromise the performance of the barrier. Consequently, there is an inverse correlation between the soil density obtained by the Proctor method and soil permeability: the higher the density, the lower the soil permeability.

It is of paramount importance to conduct on-site assessments during the construction of CCLs to ascertain that the moisture and density values are in close alignment with those determined in the laboratory through the Proctor test. This guarantees that the permeability of the soil remains within the anticipated parameters, thus ensuring the efficacy of the waterproof barrier.

CCLs are composed primarily of clays and minerals, including kaolin and montmorillonite, which are distinguished by their exceptionally fine particles, typically measuring less than 2 micrometres in diameter.

The fineness of the clay gives rise to a lamellar structure with a high specific surface area and a very low interconnected porosity. The aforementioned structural characteristics render the movement of fluids through CCLs to be highly tortuous and complex. This necessitates the expenditure of greater energy from the fluid in order to traverse the barrier, which consequently results in significantly longer travel times and a reduction in effective permeability.

CCLs must meet strict regulatory requirements, including a minimum thickness of 0.6 metres and a maximum hydraulic conductivity of 10^{-7}cm/sec. These parameters ensure that the barrier is sufficiently effective in preventing the migration of contaminating fluids over the long term.

To achieve these standards, it is often necessary to use clays or loamy soils from external sources (borrow sources), which must be carefully characterised to ensure their quality and suitability for compaction.

1.2.2 Applications

CCLs are used in several critical applications, including:

- Landfills: Used as bottom and cover barriers to contain solid waste and prevent contamination of surrounding aquifers.
- Containment Basins: Used in basins designed to contain wastewater or other hazardous fluids, ensuring that chemicals do not seep into the ground below.
- Hydraulic Works: Used in dams, embankments and other hydraulic structures to prevent water leakage and maintain the stability of the infrastructure.
- Environmental Remediation Projects: Essential for isolating contaminated soil and preventing the spread of harmful substances during remediation operations.
- Tunnel Coatings: Applied as coatings for tunnels and galleries to prevent water infiltration and reduce the risk of corrosion or structural instability.

1.2.3 CCL Installation Procedure

The design and installation of CCLs require a number of methodical steps to ensure the effectiveness and durability of the barrier. The main steps in the process are described below:

Preliminary Investigation and Soil Characterisation:

A significant preliminary investigation is required to characterise the extent and quality of the soil at the borrow source. This includes analysis of the mineralogical composition, fine particle content and plasticity index. In some cases, if the borrow source soil is deficient in clay, it may be necessary to add bentonite to achieve the required hydraulic conductivity.

Transport of Material:

The clay is mined using standard construction equipment and loaded onto three-axle trucks with some bulk soil transport capacity. The distance between the source of supply and the installation site can vary, significantly influencing transport-related carbon emissions.

Preparation of the Subfloor

The subgrade must be properly prepared to provide stable support for the CCL. This includes ground levelling and levelling operations using bulldozers and graders, ensuring that the ground is free of mass movements that could compromise compaction.

Clay compaction:

The clay is spread in thin layers, generally between 15 and 20 cm thick, using bulldozers. Each layer is mechanically compacted using sheepsfoot rollers to eliminate voids and large pores, creating a homogenous, dense mass. During compaction, water is added to achieve the optimum moisture content, determined using the Proctor method. This method involves compacting clay samples with varying amounts of water to identify the moisture content to achieve maximum dry density.

Finishing and Protection of the CCL:

The surface of the final clay layer is compacted and smoothed with smooth-drum rollers to prepare a suitable base for the application of an HDPE geomembrane. Once the CCL is complete, it is covered with an HDPE geomembrane, followed by a sand drainage layer. This additional layering further enhances the effectiveness of the barrier, providing protection against any residual seepage and facilitating the drainage of leachate.

1.2.4 Environmental and Project Considerations

The installation of CCLs also involves significant environmental considerations.

Emissions associated with clay extraction and transport are generally not included in the carbon footprint analysis, but are an important factor to consider, especially in large-scale projects. The sensitivity of the overall carbon footprint to site-specific variables, such as transport distance, is closely examined to optimise efficiency and reduce environmental impact.

Furthermore, the long-term stability of CCLs depends on the quality of the design and installation, as well as continuous monitoring of barrier performance. It is essential to ensure that the substrate is properly prepared and that clay compaction is performed correctly to prevent dehydration or swelling that could compromise the integrity of the barrier.

1.3 GEOSYNTHETIC CLAY LINERS (GCLS)

Geosynthetic Clay Liners (GCL) represent an innovative solution in the field of barriers for waste containment and environmental protection, emerging as a versatile and efficient alternative to traditional compacted clay barriers (CCL).

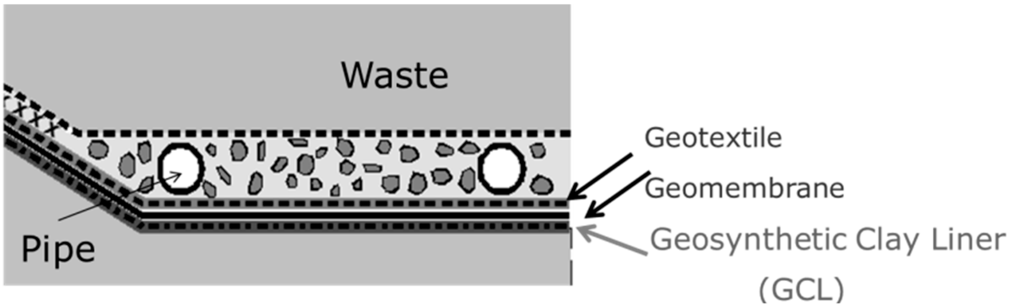

Figure 1.3 Bottom barrier stratigraphy using GCL - IGS

As shown in the figure, GCLs consist of a layer of natural bentonite, usually sodium, enclosed between two layers of geosynthetics, which may include geotextiles, geomembranes, or a combination of both:

- Refusal to confine;
- Filter layer;
- Geotextile;
- Dreni;
- Geotextile;
- GCL

A comparison of the stratigraphies presented in the figure suggests that GCLs may offer an alternative to CCLs, exhibiting a notable reduction in thickness. Furthermore, GCLs are more straightforward and time-efficient to install than CCLs.

A noteworthy attribute of GCLs is their intrinsic capacity for self-healing, which is enabled by the swelling of bentonite in the presence of water. This property enables the closure of micro-cracks, enhancing the durability and resilience of the material.

These characteristics have contributed to the growing popularity of GCLs over CCLs in recent years. The following section will provide a more detailed examination of the key considerations involved in the sizing of GCLs, along with an analysis of the factors that affect their properties over time.

The thin and flexible structure of GCLs offers a number of advantages, including low hydraulic permeability, straightforward installation, and greater adaptability to differential ground movements.

1.3.1 Properties and Characteristics of Geosynthetic Clay Liners

GCLs are renowned for their low permeability, which can be less than 10^{-10} m/s, rendering them highly efficacious in the confinement of contaminating liquids. This property is primarily attributable to the capacity of bentonite to expand and form an impermeable gel in the presence of water.

It is important to note, however, that the hydraulic conductivity of GCLs can vary depending on the composition of the bentonite and the type of geosynthetic used, as well as the applied confining pressure. This is illustrated in the figure below, which relates hydraulic conductivity and applied confining pressure (A. Bouazza / Geotextiles and Geomembranes 2002).

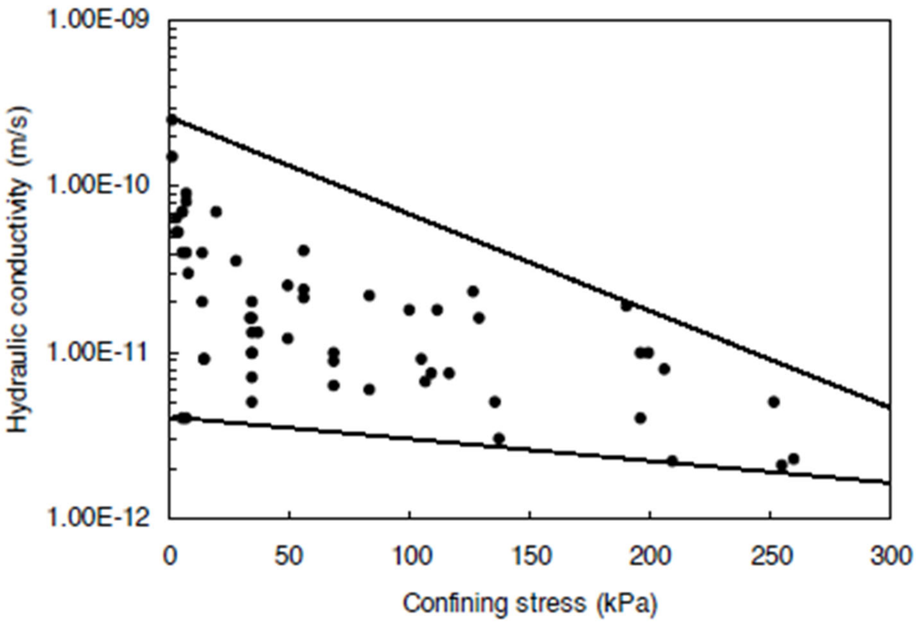

Figure 1.4 Hydraulic conductivity and confining stress - A. Bouazza

Bentonite is highly compatible with a wide range of contaminants and is effective in the presence of a variety of chemical compositions, although its effectiveness can be affected by the chemical composition of the leachate. For instance, the presence of divalent cations, including calcium and magnesium, can diminish the swelling capacity of the bentonite, thereby enhancing the permeability of the barrier. This phenomenon, known as cation exchange, is of particular relevance in the context of sites with elevated levels of chemical contamination.

GCLs are capable of self-repair in the event of perforations or minor damage, due to the ability of the bentonite to expand and seal holes.

Nevertheless, the self-repair capacity may be undermined in the event of thinning or loss of material, for instance as a consequence of mechanical stress or internal erosion.

They demonstrate high resistance to freezing and thawing cycles, maintaining their structural and hydraulic integrity even in extreme climatic conditions. This characteristic renders them suitable for utilisation in regions characterised by variable climates, where traditional barriers may be susceptible to compromise.

In conditions of low velocity flow, diffusion represents the primary mechanism of transport.

Conversely, in coarse-grained materials, with permeabilities in the range of 10^{-3} to 10^{-4} m/s, convection and dispersion phenomena are the primary transport mechanisms.

In addition to the aforementioned transport mechanisms, a number of chemical and biological processes exert a significant influence on both the motion of the fluid and the properties of the porous medium. Such processes include:

- Absorption
- Precipitation
- Hydrolysis
- Biodegradation
- Radioactive decay

These processes not only alter the flow dynamics within the porous medium, but also change the chemical and physical characteristics of the bentonite contained in the GCL.

The structure of the GCL consists of a bentonite layer, between 5 and 10 mm thick, enclosed between two thin layers of polymer geotextile. Bentonite, a clayey material characterised by high swelling capacity and very low permeability (approx. 10^-9 m/s), consists mainly of montmorillonite (up to 70 per cent by weight), quartz, feldspars, mica, carbonates, cristobalite and volcanic glass.

A distinctive property of bentonite is its ability to increase its volume by 15-18 times when hydrated, absorbing an amount of liquid equal to 200-700% of its dry weight. This characteristic is crucial in the self-repair and shrinkage processes of the material.

The porous structure of the GCL consists of three levels:

- Micropores: cavities inside bentonite granules
- Mesopores: intergranular spaces
- Macropores: voids present in the overall structure of the GCL

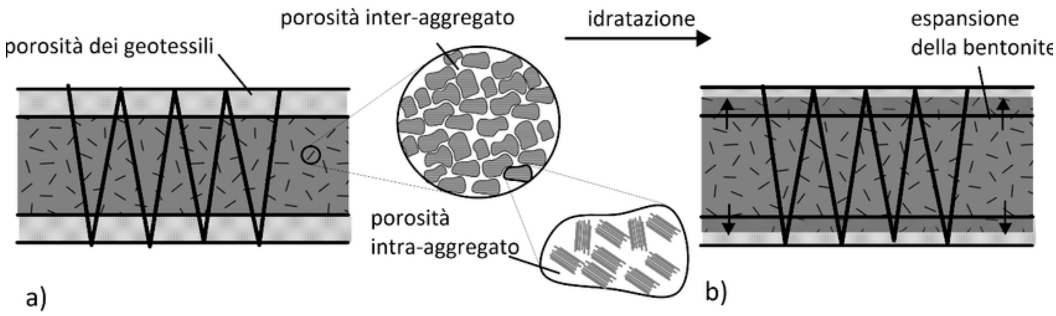

Figure 1.5 Schematic of the microstructure of the geocomposite with the three orders of porosity; conceptual model of hydration - Source - Modelling the water retention curve of benthic geocomposites Asli S. Acikel

The effectiveness of GCL as an impermeable barrier depends critically on its degree of hydration, which affects both gas and liquid permeability.

The hydration process can take place by capillary rise from the foundation soil or, in the case of draining substrates, through specially made holes in the overlying geomembrane.

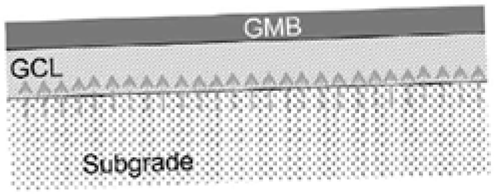

Figure 1.6 Hydration of GCL by capillary rise from the foundation soil - IGS

The water retention curve (WRC) of bentonite exhibits considerable variation contingent on the particle size of the material and the production method employed.

The findings of Professor Beddoe's research indicate that coarser-grained bentonites tend to accumulate greater amounts of water than fine-grained bentonites, due to the differing intergranular compaction modes.

An analysis of the hydration curves indicates that the process of complete saturation of the bentonite requires a considerable amount of time, approximately 35 weeks.

Moreover, the attainable hydration level is markedly affected by the water content of the foundation soil, with considerable implications for the long-term efficacy of the barrier.

In considering the behaviour of GCLs in relation to gaseous flows, it is notable that, although they are primarily used as barriers for liquids, they are also effective in counteracting gaseous flow, a property that is worthy of mention.

In an open environment, the motion of a gas is driven by pressure or concentration gradients, in a manner analogous to liquids in the presence of a hydraulic potential gradient.

In porous media with low conductivity, the flow assumes the characteristics of laminar flow, with a parabolic velocity profile. This phenomenon is described by Darcy's law.

Conversely, the compressibility of the fluid introduces further complexity in the context of gaseous flows through porous media, necessitating the utilisation of alternative flow models.

Nevertheless, for limited pressure differences, the incompressibility approximation allows the application of Darcy's law.

Bouazza and Vangpaisal conducted significant trials in this area, introducing the concept of permectivity (ψ), defined as the ratio of permeability to material thickness:

$$\psi = k/s$$

Studies have shown an inverse correlation between the degree of hydration of GCLs and their gas permeability.

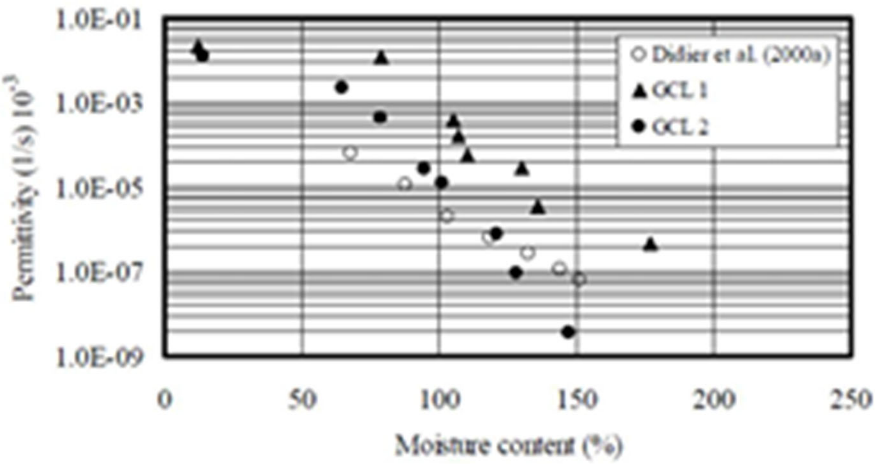

Figure 1.7 Permittivity and hydration, different types of GCL - Source Gas permeability (Didier et al.)

As the water content increases, there is a reduction in permeability that can reach five or six orders of magnitude. This phenomenon is attributable to the occupation of the pores by water, which hinders the passage of gases.

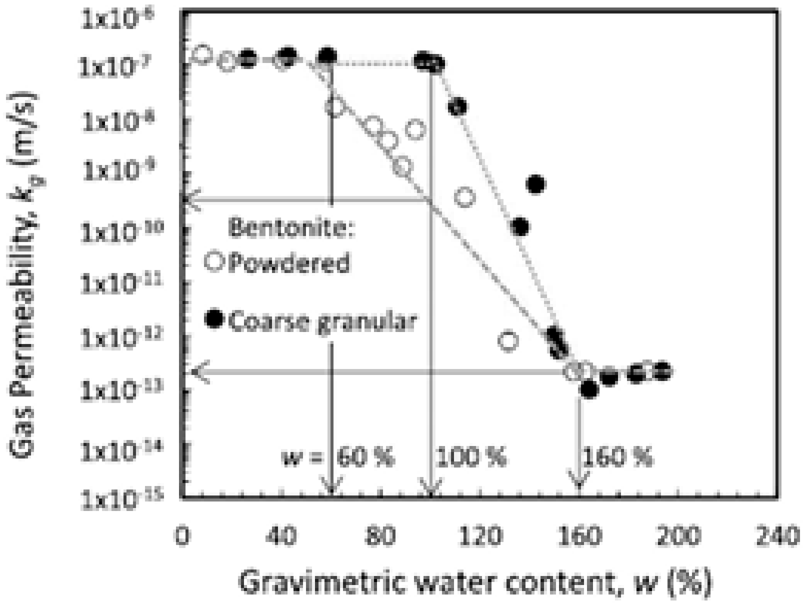

Figure 1.8 Gas permeability in function of hydratation (powdered bentonite and coarse granular bentonite), Source Gas permeability (Didier et al., 2000)

It is crucial to acknowledge that there is a threshold moisture content beyond which further increments do not result in substantial enhancements in barrier efficacy. Furthermore, fine-grained bentonites demonstrate a more consistent decline in permeability than their coarse-grained counterparts, likely due to a more uniform distribution of hydration.

One conclusion of the study is that it is essential to maintain the hydration of GCLs at a constant level to guarantee their efficacy as a gas barrier. A GCL that is initially well hydrated but subsequently subjected to dehydration may paradoxically facilitate the escape of gases from the soil.

It is important to note that the hydration process of GCLs is a time-consuming one, reaching its maximum level over an extended period. This aspect must be taken into account when designing and implementing these barriers.

It is important to note that the effectiveness of GCLs as a barrier for both liquids and gases is contingent upon the ability of the foundation soil to ensure adequate and constant hydration. In the event of insufficient hydration, there is a notable increase in gas permeability, which ultimately compromises the functionality of the barrier.

Equally important is the phenomenon of GCL withdrawal.

The phenomenon of shrinkage in Geosynthetic Clay Liners (GCL) represents a significant challenge in the field of environmental geotechnical engineering.

Despite the relative simplicity of their installation, GCLs are subject to dimensional variations that may compromise their effectiveness as impermeable barriers. In light of this, an additional amount of GCL layer is considered for each project, with an approximate increase of 10 per cent.

Furthermore, prolonged exposure to weather conditions during the period between installation and final covering, which can last for months, subjects GCLs to cycles of hydration and dehydration. The drying process is significantly accelerated by sunlight and wind action.

The geomembrane (GMB) enclosing the bentonite, which is typically dark in colour, serves to amplify this effect by absorbing a greater quantity of solar radiation and converting it into heat, thereby further promoting shrinkage.

The significance of shrinkage is not merely confined to the reduction in dimensions caused by thermal and hygrometric cycles; it also encompasses differential displacements between adjacent GCL panels. These relative movements have the potential to generate discontinuities or 'gaps' in the joint areas, which could compromise the integrity of the barrier and create localised points of weakness.

To address this challenge, Brachmann et al. proposed an innovative methodology involving the mutual adhesion of bentonite panels, with the objective of preventing the formation of gaps induced by environmental cycles.

A particularly interesting aspect that emerged from the studies by *Koerner & Koerner and Thiel et al. is* the correlation between the extent of shrinkage and the slope of the surface on which the GCL is installed. Their results, reported in a comparative table, show an inverse relationship between slope and shrinkage: on shallowly sloping surfaces (around 4°) significant shrinkage is observed already in the first months of exposure, while on steeper slopes the phenomenon is significantly attenuated, even after prolonged periods.

In summary, the main factors influencing GCL withdrawal, as identified by *Rowe*'s research, include:

- The moisture content of GCL
- The particle size distribution of the substrate
- The intensity and frequency of thermal cycles
- The inclination of the laying surface

These parameters interact in complex ways, determining the long-term behaviour of GCLs under operating conditions. A thorough understanding of these dynamics is essential to optimise the design and implementation of effective and durable barrier systems, minimising the risk of compromising their waterproofing functionality.

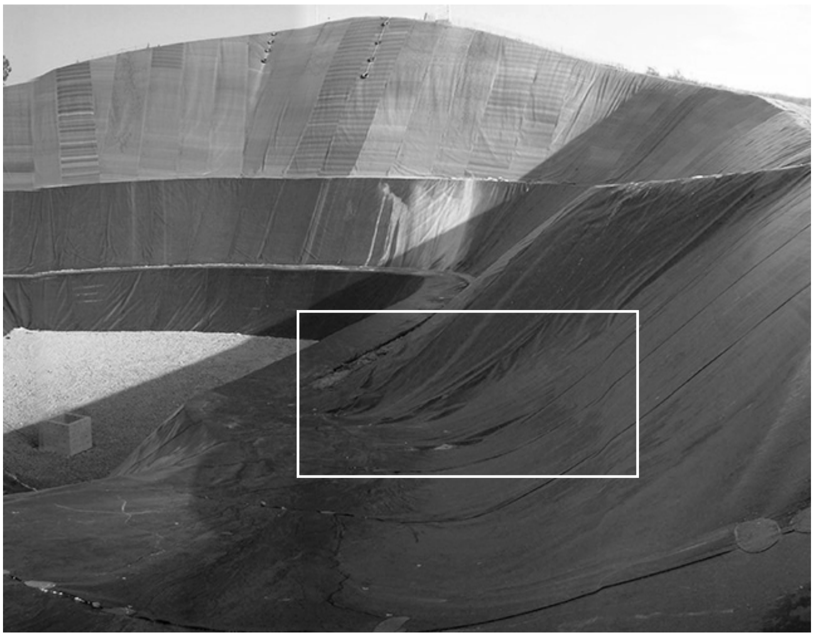

Figure 1.9 Application defects and wrinkles of GCLs - source - www.investgabions.it

The image above illustrates one potential defect that may be observed in the application of geocomposites.

It should be noted, however, that folds may also be created in the geomembrane as a result of shrinkage, as was first observed. The presence of folds in the geomembrane precludes the possibility of considering the flow as unidirectional; instead, it must be regarded as two-dimensional.

The generation of a multidimensional flow is contingent upon the presence of folds and their intersection from disparate directions.

Another significant defect is the presence of holes, which tend to concentrate the flow at that point, thereby representing a hydraulic weakness of the barrier.

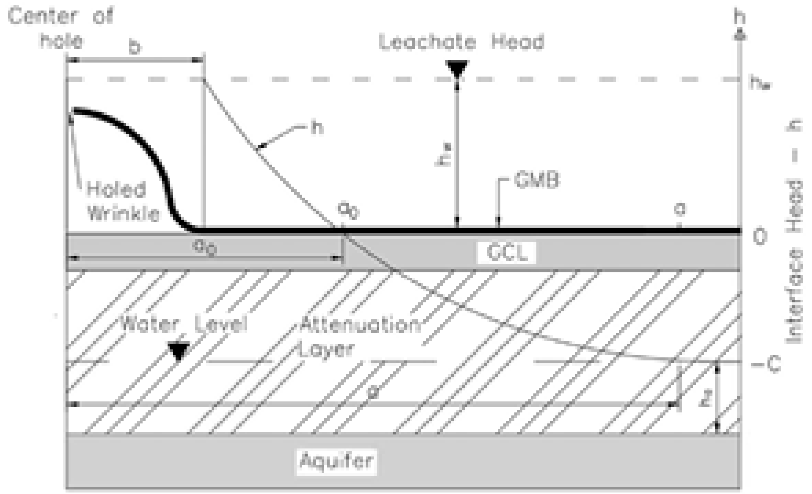

Figure 1.10 Influence of holes on the hydraulic potential - IGS

It is essential to pay special attention to the formation of defects, which can be created especially during the installation phase of GCLs or during the roofing process.

If such defects are not excessive in size, they will tend to repair themselves thanks to the bentonite's 'self-healing' capacity.

Self-repair occurs through expansive behaviour, which can increase in volume by up to 15-18 times if properly hydrated.

This process can, in many cases, completely seal the hole or significantly reduce its size.

As the results of experiments vary, there is a tendency to consider more conservative hole sizes in favour of safety.

In their respective reports, Shan and Daniel specify a maximum diameter for a circular hole of 30 mm, whereas Rowe and Li indicate a maximum size for a cut of 15 mm x 120 mm.

These values have been tested with different fluids, in addition to water, and have been shown to result in complete self-repair of the defect. Rowe and Barakat postulated that the number of holes in a geomembrane can vary from five holes per hectare for GCLs installed by skilled workers, up to 20 holes per hectare for GCLs laid by less skilled personnel.

It is possible for a hole to be present at a fold in the GCL. In such a scenario, the flow of liquid follows the pattern depicted in the above figure.

The aforementioned hole thus constitutes a preferential pathway for the leachate to traverse the GCL and reach the underlying soil. Once the fluid has passed the hydraulic barrier, it continues to move through the soil at a velocity that is proportional to the permeability of the substrate itself.

1.3.2 Types of GCL

There are several variants of GCL, which differ mainly in the type of bentonite used (sodium or calcic), the type of geosynthetic (woven or non-woven geotextile, geomembrane) and the production methods (needle-punching, stitch-bonding, thermal-locking).

Reinforced GCLs: These GCLs are produced using methods such as needle-punching, where the fibres of the upper geotextile are punched through the bentonite layer to bond with the lower geotextile. This process creates a more robust and displacement-resistant structure, making reinforced GCLs particularly suitable for steep slope applications.

Unreinforced GCLs: These products are simpler in their construction and are generally used in situations where large differential movements or high loads are not expected. However, they may be more susceptible to mechanical damage during installation or use.

1.3.3 Applications

Figure 1.11 Application example of bentonite geosynthetics - source: 'Geosynthetics and sustainability GEO kunst special 2022'.

GCLs are employed in a multitude of applications, including landfill lining systems. These are frequently utilised as bottom and cover barriers in controlled waste landfills, where they serve to impede the migration of leachate and contaminants present in it into groundwater. In such applications, GCLs can be combined with geomembranes to create composite lining systems that offer superior protection against leaks by increasing the hydraulic gradient and significantly increasing the design thickness.

In hydraulic works and reservoirs, they are ideal for lining reservoirs, canals and ponds, providing an impermeable barrier that minimises water infiltration and protects groundwater resources.

The capping of landfills and the containment of hazardous waste are also utilised in landfill cover systems. In such applications, the materials in question serve to reduce the migration of gases and limit the infiltration of rainwater, thereby contributing to the long-term stability of the site.

In addition to their primary functions, GCLs can also be employed as secondary linings to safeguard underground storage tanks from potential leakage that could result in groundwater contamination. This is particularly pertinent in the context of fuel and chemical storage facilities.

1.3.4 Environmental and Project Considerations

The installation of geosynthetic clay liners (GCLs) has significant environmental implications, with notable distinctions from those observed in the use of clay linings (CCLs).

One of the principal elements in the environmental assessment of GCLs is the production and transportation of the materials. Indeed, GCLs are composed of a thin layer of bentonite encapsulated between two geotextile layers, which significantly reduce the volume of material required and generate much lower transport-related emissions than CCLs.

A number of studies have demonstrated that the life-cycle efficiency of GCLs is significantly influenced by the distances they are transported and the source of energy used in their production. Consequently, these variables represent a crucial aspect in the assessment of the environmental impact and the design of GCLs.

The efficacy of a GCL barrier is contingent upon the quality of the interface between the bentonite and the substrate, which must be free of irregularities to prevent the formation of gaps that could compromise the watertightness.

Furthermore, the behaviour of the GCL is also influenced over time by the hydration-dewatering cycles of the bentonite. A study by Koerner et al. (2012) demonstrated that prolonged exposure of GCLs to wet-dry cycles can result in a reduction of their waterproofing capabilities, particularly in environments with variable climates.

Another crucial factor is the protection of GCLs from damage incurred during the installation process. The thin nature of bentonite renders GCLs vulnerable to damage, such as tears or punctures, which have the potential to significantly impair the performance of barrier layers.

It is therefore imperative that rigorous control is exercised during the installation process, and that preventive measures, such as the use of protective geotextiles, are implemented.

As Bouazza et al. (2016) have observed, it is of the utmost importance to guarantee that the barrier retains its insulating properties over time, thereby reducing the probability of failure resulting from mechanical damage or chemical alteration of the material. In conclusion, the design of GCLs necessitates an integrated approach that considers both the environmental impact during production and transportation and the long-term integrity of the barrier through meticulous installation and monitoring.

Technological advancements in this domain, such as the utilisation of more resilient geosynthetics and less energy-intensive manufacturing processes, may facilitate enhanced environmental efficiency and performance of GCLs in prospective environmental engineering endeavours.

2 THEORETICAL APPROACHES TO ENVIRONMENTAL SUSTAINABILITY ASSESSMENT

In the global context of the fight against climate change, geotechnical engineering is confronted with a significant challenge: that of harmonising design specifications with regulatory obligations pertaining to environmental sustainability.

This challenge is aligned with the overarching Sustainable Development Goals (SDGs) established by the United Nations, which place significant emphasis on curbing greenhouse gas emissions, particularly carbon dioxide (CO_2).

In this context, geosynthetics, and in particular bentonite geocomposites (GCL), present themselves as an innovative and potentially sustainable solution. The growing utilisation of these materials in civil and environmental engineering projects is indicative of their functional versatility and potential for reducing the overall environmental impact of infrastructure.

Over the past four decades, there has been a notable shift towards the systematic integration of geosynthetics in geotechnical design.

This trend is supported by a substantial body of scientific and technical knowledge, including standardised norms for material characterisation and established design methodologies.

The International Geosynthetics Society (IGS), through its 'Educate the Educator' initiative, is playing a pivotal role in advocating for the integration of these competencies into the curricula of civil and environmental engineering programmes at universities across the globe.

In order to assess the environmental impact of GCLs and other geosynthetics in an objective manner, it is necessary to apply rigorous and standardised methodologies.

In this context, Life Cycle Analysis (LCA) emerges as a significant tool, offering a systematic approach to quantify the energy and environmental loads associated with a product or process throughout its life cycle, from the initial stage of raw material extraction to the final stage of disposal.

In the context of LCA, the concept of the carbon footprint assumes a central role in the assessment of environmental impact.

This indicator, which quantifies the greenhouse gas emissions associated with a product or process in terms of CO_2 equivalent, provides a clear and comparable metric for the assessment of the contribution of LCGs to climate change mitigation.

The application of LCA in the environmental assessment of GCLs allows for the following: To comprehensively quantify the environmental impact throughout the life cycle, taking into account phases such as production, transport, installation, maintenance and disposal. The identification of the life cycle phases with the greatest environmental impact enables the implementation of targeted interventions for optimisation.

It is possible to make an objective comparison between the environmental impact of GCL and that of alternative solutions based on natural materials and traditional methods. It is recommended that alternative end-of-life scenarios, including recycling and reuse, be evaluated in order to minimise the overall impact.

Recent studies such as '*Christos Athanassopoulos & Richard J. Vamos (2011), Carbon footprint comparison of GCLs and CCLs*' have shown that the use of GCLs to replace traditional natural materials can lead to significant reductions in carbon footprint. This advantage is primarily attributable to a number of key factors, including:

The necessity for a reduced volume of material results in a decrease in the level of mining and transportation activities.

The installation processes are more efficient, which results in a reduced reliance on heavy machinery and, consequently, lower emissions on-site. The potential for increased durability may result in a reduction in the frequency of required maintenance and replacement. It is, however, essential to emphasise that the actual environmental benefit of utilising GCLs can vary considerably depending on the specific project conditions.

The overall environmental balance can be significantly influenced by a number of factors, including the distance that materials must be transported, the characteristics of the site in question, and the performance requirements of the work in progress.

In the specific context of controlled landfills, the use of GCL in final cover systems represents a particularly interesting case study. The recent Italian legislative decree (DL 121/2020) has introduced new avenues for the utilisation of geosynthetics in these applications, contingent upon their functional equivalence to conventional solutions being substantiated.

A comparative analysis between design solutions based on natural materials (such as clay and gravel) and alternatives using GCL provides a concrete opportunity to assess the potential contribution of these materials to the environmental sustainability of geotechnical works. By quantifying the carbon footprint, it is possible to provide planners and decision-makers with the requisite tools to make informed, sustainability-oriented choices. The assessment of the environmental impact of GCLs through carbon footprint analysis represents a pivotal aspect of the advancement of genuinely sustainable geotechnical engineering.

This approach enables the quantification and minimisation of the environmental impact of works, while also facilitating the promotion of a more conscious and responsible design culture in alignment with global sustainable development goals.

2.1 CARBON FOOTPRINT COMPARISON

The carbon footprint is a metric used to quantify the environmental impact of activities or products, expressed in terms of carbon dioxide equivalent (CO_2 eq). This parameter is fundamental to the evaluation of the impact of diverse technologies and processes on the greenhouse effect and subsequent climate change. In the specific context of confinement systems, such as Geosynthetic Clay Liners (GCL) and Compacted Clay Liners (CCL), carbon footprint analysis provides crucial insights into the overall environmental impact of these materials throughout their entire life cycle.

The disparity in greenhouse gas emissions between GCL and CCL can be attributed to a multitude of factors encompassing the entirety of these systems' life cycles. These encompass the extraction of raw materials, production processes, transportation, installation, and even maintenance and the end-of-life phases. A comprehensive examination of these factors demonstrates that GCLs offer notable advantages in terms of reduced environmental impact when compared to CCLs.

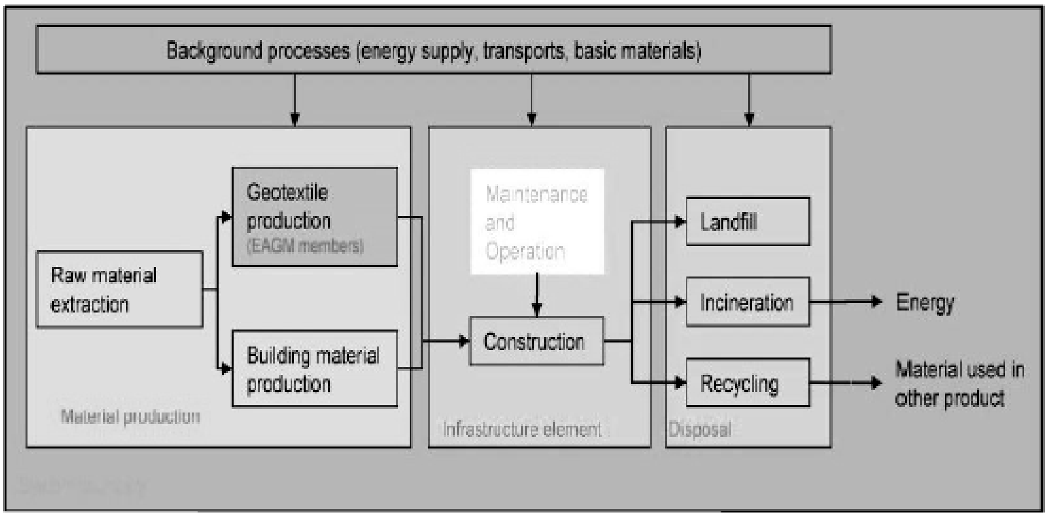

Figure 2.1 System boundaries, Background processes - source: LCA of GCL versus conventional construction materials - E.A.G.M. - 5th European Geosynthetics Congress. Valencia 2012'

The production of GCLs, which consist of layers of geotextiles and bentonite, typically necessitates the utilisation of lesser quantities of material in comparison to CCLs, which rely on the incorporation of considerable volumes of compacted clay. This discrepancy in production results in a reduction in emissions, not only associated with the extraction of raw materials but also with the energy and environmental costs of transportation. It is important to note that although the production of GCLs involves specific industrial processes, such as the processing of bentonite and the assembly of geotextiles, the total impact of these processes is often mitigated by the higher efficiency and lower material quantities required.

The transportation process represents a pivotal element in the evaluation of the carbon footprint. CCLs, which require large volumes of compacted clay, necessitate a considerable number of transportation trips, resulting in elevated CO_2 emissions. In contrast, GCLs, being of a lighter and more compact nature, offer substantial advantages in terms of logistical efficiency. This distinction is especially pertinent in contexts where construction sites are situated at a distance from the source of raw materials, a scenario in which the environmental benefits of GCLs are markedly amplified.

It is evident that the installation phase has a considerable impact on the overall carbon footprint. CCLs necessitate on-site compaction operations that require the utilisation of heavy machinery, resulting in elevated fuel consumption and associated emissions. The pre-assembly of GCLs in a factory setting necessitates the utilisation of less energy-intensive installation procedures, thereby reducing the CO_2 emissions associated with this phase.

Recent studies, such as that conducted by Athanassopoulos & Vamos, have confirmed that, under identical conditions, CCLs typically result in a higher carbon footprint than GCLs. It is important to note, however, that the relative impact may vary depending on the specific project conditions. To illustrate, in scenarios where clay deposits are situated in close proximity to the site of utilisation, the benefit of GCLs in relation to transport-related emissions may be diminished.

A frequently neglected, yet crucial element in carbon footprint analysis is the assessment of long-term durability and maintenance requirements. GCLs have been observed to retain their waterproofing properties for longer periods than CCLs, which may result in a reduction in the frequency of maintenance or replacement. This factor can contribute to a further reduction in the carbon footprint over the life cycle of the containment system.

In conclusion, the comparative carbon footprint analysis between GCLs and CCLs demonstrates that, in the majority of scenarios, GCLs offer considerable environmental benefits. These benefits primarily originate from the minimisation of emissions associated with the extraction, transportation and installation of materials. Nevertheless, it is imperative to underscore the necessity of a case-by-case evaluation, taking into account particular variables such as the proximity to material sources, the characteristics of the site, and the long-term performance requirements. These factors contribute to the conclusion that GCLs represent a more environmentally sustainable choice in many contexts, although not in all cases.

In order to make informed decisions aimed at reducing the overall environmental impact, it is essential to adopt a holistic approach to the assessment of the carbon footprint, which considers the entire life cycle of containment systems.

Life cycle assessment (LCA) represents a fundamental tool in the field of environmental management.

The Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with a product, process, or service throughout its life cycle.

This approach is guided by the UNI EN ISO 14040 standard, which assesses the environmental impacts associated with a product, process, or service throughout its life cycle, from the extraction of raw materials to production, distribution, use, and final disposal.

The objective of LCA is to provide a comprehensive view of environmental impacts, enabling science-based decisions that promote environmental sustainability (*STEFANIA BILARDI, NICOLA MORACI) (*Prof. Andrea Dominijanni - *Research Project).*

The LCA methodology is developed in four main steps, all interconnected and described in detail in the UNI EN ISO 14040 standard.

The following study presents four approaches to the procedure, each of which considers a different aspect of the life cycle of the product. The first, from cradle to gate, considers the emissions associated with the extraction of raw materials and the production of the product. The second, from cradle to site, also includes the emissions associated with the transport of the product to the place of use. The third, from cradle to end of construction, considers the energy and emissions associated with the construction process. Finally, the fourth approach, from cradle to grave, also covers the demolition and disposal stages, which are not considered in this thesis study.

This measure provides essential data for the evaluation of environmental impacts associated with the utilisation of energy resources and the production of materials.

The CI is frequently employed at the international level for the comparison of diverse design solutions, particularly within the construction and industrial product sectors, with the objective of promoting more sustainable options (Prof. Andrea Dominijanni - Research Project, Bentonite barriers for the control of PFS in the subsoil).

The Carbon Footprint (CI), or Embodied Carbon (EC), is sometimes combined with the concept of Embodied Energy (EE) or Cumulative Energy Demand (CED), which expresses the energy embedded in the product during its life cycle or that required in the process.

The conversion is dependent upon the quantity of CO_2 emitted in order to generate the energy utilised in production processes, which may originate from fossil, nuclear or renewable sources.

Recent studies have demonstrated that the utilisation of geosynthetics can markedly diminish CO_2 emissions and other environmental impacts in comparison to the deployment of natural materials. The reduction in emissions is particularly significant in the transport and installation phases, as well as leading to a decrease in the consumption of non-renewable resources (Stefania Bilardi, Nicola Moraci – The Use of Geosynthetics in the Sustainable Design of Controlled Landfills).

This analysis considers a range of landfill covering solutions, from those utilising natural materials to those employing geosynthetics. It demonstrates that geosynthetics can reduce CO_2 emissions in comparison to traditional solutions.

This reduction is achieved through a reduction in the need for natural materials and a reduction in energy consumption during the construction phase (Prof. Andrea Dominijanni, Research Project, Bentonite barriers for the control of PFAS in the subsoil).

As previously outlined, the carbon footprint of the products under examination can be summarised as follows:

Estrazione	Produzione	Trasporto	Costruzione
Dalla culla al cancello			
Dalla culla al sito			
Dalla culla alla fine della costruzione			

Figure 2.2 Schematisation of the boundary conditions of the carbon footprint analysis conducted - CNG 2021 Bilardi and Moraci

Referring precisely to the three stages depicted according to the activities under consideration:

1. Extraction of raw materials, in the case of clays, and in-plant production of GCLs ;
2. Transport of materials from the extraction site (CCLs) or the plant (GCLs) to the construction site of the landfill barrier layers;
3. Cotruzione del sistema di strati di barriera di fondo e di copertura finale della discarica.

2.2 EVALUATION OF DIFFUSIVE GAS FLUX

The function of waste landfill covers is to safeguard the surrounding environment from contamination by preventing the migration of contaminants from the site.

These final covers, also referred to as 'caps', are composed of different materials arranged in layers, each of which fulfils a specific function within the overall system.

A variety of configurations have been developed with the objective of optimising efficiency, long-term stability and durability. These employ a range of materials, including fine-grained soils, geomembranes, cement products, bitumen and even treated waste.

A fundamental aspect of an effective roofing system is the capacity to restrict the penetration of water into the underlying waste.

In order to achieve this, it is common practice to include at least one layer of material that is characterised by low hydraulic conductivity, namely bentonite clay geocomposites (GCL).

GCLs are becoming increasingly prevalent in roofing applications, having previously been employed primarily in the construction of basic barriers.

GCLs are composed of a thin layer of granular or powdered bentonite sandwiched between two layers of geotextiles. The bentonite, due to its high affinity for water, provides the desired hydraulic properties, while the geotextiles guarantee the mechanical stability of the entire system.

Despite the extensive literature devoted to the hydraulic properties of GCLs, there is a paucity of studies concerning their effectiveness in controlling gas flow, which is a crucial aspect for several types of waste that can generate or interact with potentially hazardous gases.

The following section reviews the theory of gas diffusion and describes an experimental method for measuring the diffusion properties necessary for calculating the gas flow through roof systems (M. Aubertin et al. / Geotextiles and Geomembranes - 2000). This method is used to quantify the emission of hazardous gases.

2.2.1 Diffusive transport in gas flux

Diffusion is a generic transport process observed in fluids (liquids and gases). It is characterised by the random movement of molecules, which redistribute themselves until they reach a state of equilibrium, characterised by uniform concentration.

The diffusing element progresses from the region of higher concentration to that of lower concentration.

Given that analogous random molecular motions are also linked to conductive heat transfer, the identical mathematical equations have been employed to describe both heat and diffusive flow in isotropic substances.

The principal diffusion equation, designated as Fick's first law, can be expressed in the following form with regard to gas flow:

$$F_g = -D_e \frac{\partial C}{\partial Z}$$

Where F_g, is the mass transferred per unit area (M/L^2 T), C is the concentration of the diffusing substance (M/L^3), Z is the spatial coordinate (L) measured perpendicular to the unit cross-sectional area D_e is the effective diffusion coefficient of the substance (L^2/T).

The negative sign in the equation indicates that the flow occurs in the opposite direction to the increase in concentration.

The equation suggests that there is a linear relationship (for a given D_e) between the mass flux and the concentration gradient between two points.

When Fick's equation is rewritten in terms of partial pressure gradients (Hillel, 1980; Fredlund and Rahardjo, 1993), a dualism can be established between Fick's first law and the well-known Darcy's law used for advective transport, with D_e which plays a similar role to that of hydraulic conductivity k.

The value of D_e varies depending on the characteristics of the fluid and the porous medium (such as molecular weight, porosity and degree of saturation).

The expressed Fick's law can be generalised for three-dimensional conditions (analogous to how Darcy's law was extended), but here only uniaxial flow is considered.

Under transient conditions, concentration can vary in time and space. Continuity conditions imply that a change in concentration over time is balanced by a change in flux at the corresponding position.

For a one-dimensional flow in an isotropic non-reactive medium, one can therefore write (Crank, 1975):

$$\frac{\partial C}{\partial Z} = D_e \frac{\partial^2 C}{\partial Z^2}$$

Which represents Fick's usual second law.

For the purposes of this analysis, the equations just outlined will be sufficient for the determination of the effective diffusion coefficient D_e and for the simplified calculation of the gas flow through the GCLs and covering systems.

To obtain flow and concentration profiles, Fick's laws can be solved analytically for relatively simple boundary conditions (e.g. Crank, 1975), whereas more complex applications often require numerical calculations (e.g. Rowe and Booker, 1985, 1987; Rowe et al., 1994; Aachib and Aubertin, 1999).

In any case, the starting point is the determination of the value of the effective diffusion coefficient.

2.2.2 The effective diffusion coefficient

According to Fick's laws, gas flow and concentration change are proportional to the effective diffusion coefficient D_e

This represents a state-dependent property of the material, as it varies depending on fundamental characteristics such as porosity and water content.

In a porous medium, gas diffusion occurs much more rapidly in air-filled pore spaces, characterised by their volumetric air content:

$$\theta_a = n(1 - Sr)$$

where n is the total porosity and Sr is the degree of saturation, with respect to water-filled spaces, characterised by the volumetric water content of

$$\theta_w = n - \theta_a = n \cdot Sr$$

The volumetric water content represents the ratio of water volume to total volume (e.g. when Sr=1, $\theta_w = n$, e $\theta_a = 0$).

θ_w can be related to the water content w by the following expression:

$$\theta_w = w(1 - n)\rho_s$$

where ρ_s is the relative density of the solid.

When the gas phase in a partially saturated medium is continuous, a condition that occurs when the degree of saturation is less than 85-90% (e.g. Corey, 1957; Matyas, 1967), gas diffusion occurs mainly in air-filled pores. In this case, D_e can only be expressed as a function of θ_a since diffusion in the liquid phase is very limited.

However, at higher saturations, as can be expected in a GCL, the gas phase becomes discontinuous and the gas diffuses both through air (if present) and into water, implying a solubilisation process

When diffusion occurs simultaneously in pores filled with air and water, the resulting effective diffusion coefficient can be expressed as a sum of the contributions of both phases, and can be written:

$$D_e = D_a + HD_w$$

with

$$D_a = \theta_a D_a^0 T_a$$

$$D_w = \theta_w D_w^0 T_w$$

So we recall that $\theta_w = n$.

In these equations, D_a , D_w represent the components of the diffusion coefficient corresponding to the air and water phases, respectively, while H is the Henry's law constant for the equilibrium concentration (H=0.03 for oxygen). The coefficients D_a^0 e $D_w^0$are the diffusion coefficients in an open (unobstructed) medium, for which at room temperature (RT=20°C), they are respectively assumed to be $2.20\ x\ 10^{-5}\ m^2$ /s and $1.80\ x\ 10^{-9}\ m^2$ /s.

Finally, the parameters T_a , T_w are tortuosity coefficients reflecting the non-linear path of the gas flow in the air and water phases, respectively.

Of considerable importance in the calculation of diffusive gas flow through barriers is the water content and porosity as well as the confining pressure.

The performance of barriers formed by Geosynthetic Clay Liners in relation to gas flow is strongly dependent on their degree of saturation.

It is shown that as the saturation of GCLs increases, gas permeability decreases dramatically, making them more effective as barriers.

To achieve low permeability, a GCL must be adequately hydrated and this hydration is often considered to be the result of moisture absorption (suction) from the soil or hydration resulting from geomembrane defects that cause water infiltration.

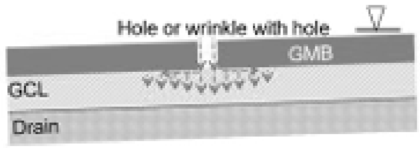

Figure 2.3 Local hydration of GCL from hole in GMB - IGS

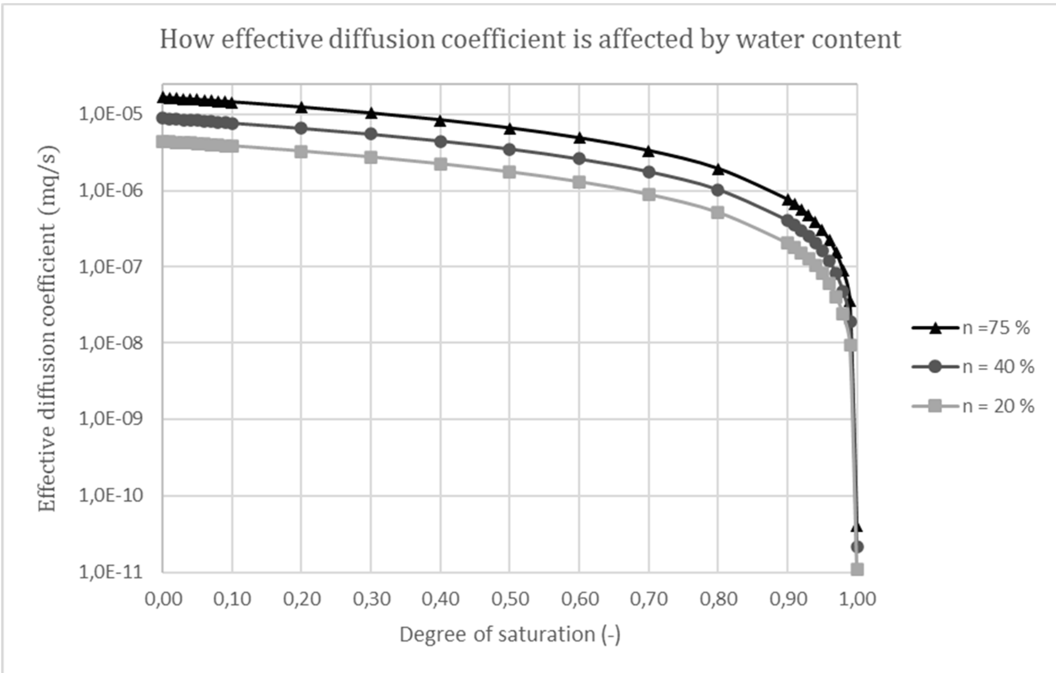

Figure 2.4 Sensitivity of the effective diffusion coefficient to water content and porosity

It is shown in the parametric study shown in the graph above, how the effective diffusion coefficient is sensitive to the variation in the degree of hydration of GCLs.

The graph shows how the effective diffusion coefficient D_e tends to decrease dramatically when the degree of saturation exceeds percentages greater than 70% (also typical of GCLs), until collapsing to values in the order of 10^{-11}, which translates as an excellent ability to contain diffusive flows of the gases contained within the landfill towards the surrounding environment.

Additionally, the graph illustrates the porosity index's suitability as a pivotal element in evaluating the capacity of a material, such as GCLs (Geosynthetic Clay Liners), to impede gas diffusion. The porosity index (n) represents the fraction of the material's total volume occupied by pores and is a key parameter affecting both advective flow and gas diffusion through the material. A high porosity index indicates that the volume of the pores is greater, thereby allowing for greater movement of gases. In this instance, the effective diffusion coefficient is observed to increase, as the presence of fewer physical impediments facilitates the movement of gases through the open pores. Conversely, a low porosity index indicates that the material is more compact, with a reduction in the available space for gas transport, which consequently results in a decrease in the diffusion coefficient. A GCL with high porosity but saturated with water will exhibit reduced gas diffusion, as the pores will be filled mainly with liquid. Nevertheless, in conditions of low saturation, a material with a high degree of porosity facilitates the diffusion of gases. It is therefore essential to understand the interaction between the porosity index and the degree of saturation in order to comprehend the overall diffusion process.

It can be hypothesised that GCLs with a higher porosity, for example those containing coarse granular bentonite, may demonstrate a greater effective diffusion coefficient under conditions of low hydration than GCLs with a lower porosity, for example those containing powdered bentonite. Bouazza et al. (2017c)

However, as previously discussed, as hydration increases and pores are filled with water, diffusion becomes severely limited.

2.3 CONTAMINANT LIQUID FLUX THROUGH BOTTOM LAYER

The transport of contaminants in liquid solution through porous media is primarily determined by the processes of diffusion, advection (convection), and dispersion.

In conditions of low flow velocity, the phenomenon of diffusion is the prevailing mechanism. Conversely, when flow velocity is high, the processes of advection and dispersion become dominant.

2.3.1 Advection

The advective process refers to the movement of contaminants (or solutes in general) along with the fluid in which they are contained. This movement is driven by a hydraulic gradient, with the solvent responding to this gradient and moving in accordance with it.

In this phase, solutes are transported with an average velocity that can be expressed by the following relationship:

$$v_f = q/n$$

Where v_f is the filtration rate of the solute, q the hydraulic flow per unit area (or Dracy flow) [L/T], and n is the porosity of the medium.

Darcy's flow is given by the relationship:

$$q = \frac{Q}{A} = -k\frac{dh}{dx} = k \cdot i$$

With Q representing the volumetric flow or flow rate $[L^3/T]$, A is the cross-section and k the hydraulic conductivity or permeability coefficient $[L^2/T]$, with h hydraulic load [L], x flow direction and i hydraulic gradient.

When it is assumed that all particles of the solute are transported along with the fluid, at the filtration rate, the transported mass can be derived as:

$$J_A = q \cdot c = k \cdot i \cdot c = n \cdot v_f \cdot c$$

With J_A mass flowing through the unit cross-sectional area per unit time, [M/(L^3T)].

2.3.2 Diffusion

The diffusive process can be described as a transport mechanism whereby an ion or molecule moves in response to a concentration gradient that is higher than that which would otherwise be expected.

This process occurs even in the absence of a hydraulic gradient and ceases only when the concentration gradient is completely nullified.

In the event that the solution is in motion, for instance as a consequence of a hydraulic gradient, molecular diffusion represents one of the phenomena involved in the transport of contaminants.

The governing law of this process is Fick's first law (1885), which, in a one-dimensional situation, can be expressed as follows:

$$J_D = -D_0 \cdot \frac{dc}{dx}$$

With J_D diffusive mass flow, [M/(L^2T)], and D_0 diffusion coefficient in free solution [L^2/T].

The following are values of D_0, diffusion coefficient in free solution [L^2/T], at 0°C, 18°C and 25°C for different species of anions and cations commonly contained in landfill leachate.

Cation	D_j^0 (10^{-6} cm²/sec) 0°C	18°C	25°C	Anion	D_j^0 (10^{-6} cm²/sec) 0°C	18°C	25°C
H^+	56·1	81·7	93·1	OH^-	25·6	44·9	52·7
Li^+	4·72	8·69	10·3	F^-	—	12·1	14·6
Na^+	6·27	11·3	13·3	Cl^-	10·1	17·1	20·3
K^+	9·86	16·7	19·6	Br^-	10·5	17·6	20·1
Rb^+	10·6	17·6	20·6	I^-	10·3	17·2	20·0
Cs^+	10·6	17·7	20·7	IO_3^-	5·05	8·79	10·6
NH_4^+	9·80	16·8	19·8	HS^-	9·75	14·8	17·3
Ag^+	8·50	14·0	16·6	S^{2-}	—	6·95	—
Tl^+	10·6	17·0	20·1	HSO_4^-	—	—	13·3
$Cu(OH)^+$	—	—	8·30	SO_4^{2-}	5·00	8·90	10·7
$Zn(OH)^+$	—	—	8·54	SeO_4^{2-}	4·14	8·45	9·46
Be^{2+}	—	3·64	5·85	NO_2^-	—	15·3	19·1
Mg^{2+}	3·56	5·94	7·05	NO_3^-	9·78	16·1	19·0
Ca^{2+}	3·73	6·73	7·93	HCO_3^-	—	—	11·8
Sr^{2+}	3·72	6·70	7·94	CO_3^{2-}	4·39	7·80	9·55
Ba^{2+}	4·04	7·13	8·48	$H_2PO_4^-$	—	7·15	8·46
Ra^{2+}	4·02	7·45	8·89	HPO_4^{2-}	—	—	7·34
Mn^{2+}	3·05	5·75	6·88	HP_4^{3-}	—	—	6·12
Fe^{2+}	3·41	5·82	7·19	$H_2AsO_4^-$	—	—	9·05
Co^{2+}	3·41	5·72	6·99	$H_2SbO_4^-$	—	—	8·25
Ni^{2+}	3·11	5·81	6·79	CrO_4^{2-}	5·12	9·36	11·2
Cu^{2+}	3·41	5·88	7·33	MoO_4^{2-}	—	—	9·91
Zn^{2+}	3·35	6·13	7·15	WO_4^{2-}	4·27	7·67	9·23
Cd^{2+}	3·41	6·03	7·17				
Pb^{2+}	4·56	7·95	9·45				
UO_2^{2+}	—	—	4·26				
Sc^{3+}	—	—	5·74				
Y^{3+}	2·60	—	5·50				
La^{3+}	2·76	5·14	6·17				
Yb^{3+}	—	—	5·82				
Cr^{3+}	—	3·90	5·94				
Fe^{3+}	—	5·28	6·07				
Al^{3+}	2·36	3·46	5·59				
Th^{4+}	—	1·53	—				

Figure 2.5 Tracer and self-diffusion coefficient of ions at infinite dilution - source' Diffusion of ions in sea water and in deep-sea sediments' - Yuan-Hui Li, Sandra Gregory'

For diffusion in a saturated porous medium, Fick's law is expounded as follows:

$$J_D = -\tau \cdot D_0 \cdot n \cdot \frac{dc}{dx}$$

And accordingly:

$$J_D = -D^* \cdot n \cdot \frac{dc}{dx}$$

Where is introduced τ tortuosity coefficient, and D^* effective diffusion coefficient.

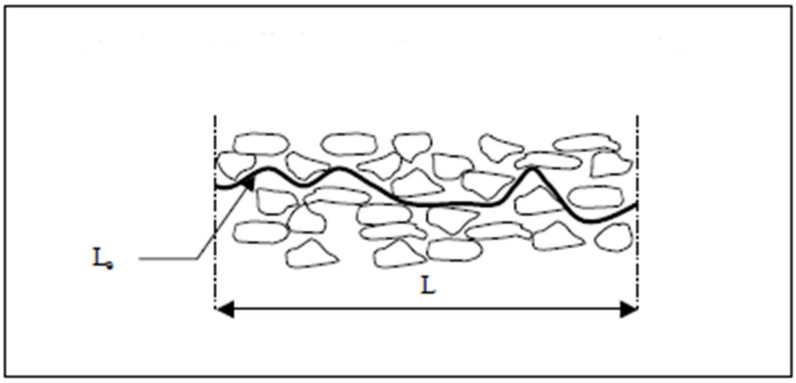

Figure 2.6 Effective contaminant pathway - Geosyntheticsociety

Tortuosity is the ratio of the length L in a straight line to the actual contaminant flow path Lc.

Lc>L being τ<1 e $D^* < D_0$, diffusive mass transport in the porous medium occurs at low velocities.

Usual tortuosity values vary between 0.01 and 0.67 (Perkins and Johnson, 1963; Freeze and Cherry, 1979; Daniel and Shackelford, 1988; Shackelford, 1989; Shackelford and Daniel, 1991).

2.3.3 Membrane behaviour in Geosynthetic Clay Liners

Bentonite geosynthetics (GCL), employed as barriers in waste disposal facilities for geo-environmental applications, enhance their capacity to contain contaminants when they function as semi-permeable membranes.

This behaviour enables bentonite geocomposites to restrict the migration of solutes, or contaminants, preventing their passage to areas of lower concentration, such as the exterior of landfills.

It has been demonstrated that conventional GCLs, which employ bentonite as the primary component for hydraulic resistance, exhibit considerable potential for membrane behaviour.

This is of particular importance in order to reduce the dispersion of contaminants into the surrounding environment.

The semi-permeable membrane behaviour prevents the passage of pollutant solutes through the GCL layer, thereby contributing significantly to the barrier function.

This property, largely attributable to the bentonite content, has been widely discussed in the literature, for example in the study conducted by Shackelford et al. (2003).

The objective of this chapter is to provide a synthesis of the findings from the research conducted, with a particular focus on the analysis of membrane behaviour in GCLs and its comparison with established solutions such as compacted clay barriers.

The restriction of solute passage and the phenomenon of chemico-osmosis (i.e. the movement of water from a solution with a low solute concentration to one with a higher concentration) are two key manifestations of membrane behaviour in clays (Shackelford et al., 2003).

The capacity to impede the passage of electrolytes (anions and cations) is contingent upon the dimensions of clay pores, which must be sufficiently minute to engender electrostatic repulsion between ions. This prevents anions from entering the pores and curtails cation migration due to electroneutrality, as elucidated by Fritz (1986).

In the presence of more spacious pores, both anions and cations are able to migrate freely through solutions via the pores, where they are not affected by the negative charges of the surfaces of adjacent particles.

Although the arrangement of clay particles is conceptualised as being parallel, in reality this is not always the case, resulting in variations in pore size.

It is possible that some solutes may pass through the wider sections, while narrower sections may remain impermeable to them due to overlapping electrical potentials.

The pores, designated as "blind pores," exert a precise influence on the semi-permeable membrane behaviour of clay layers. This characteristic is quantified by an efficiency coefficient representing the degree of solute restriction, which is also known as the "reflection coefficient" (ω), the "membrane efficiency coefficient," or the "chemico-osmotic efficiency coefficient."

The value of ω ranges from 0, indicating no membrane behaviour, to 1, indicating total solute blockage.

Membranes with an efficiency of 100 per cent ($\omega = 1$) are considered ideal, while membranes made of natural clays, with varying pore sizes, have efficiencies ranging between 0 and 1, making them non-ideal or imperfect membranes.

To demonstrate that a GCL is a suitable replacement for a compacted clay lining (CCL), it must be proven that the proposed GCL will perform at least as well as the existing CCL. A prior assessment of the GCL's performance can be obtained through an analysis of contaminant migration based on advective-diffusive transport theory.

Despite the low hydraulic conductivity typical of GCLs (less than 10-^{10} m/s) when permeated with low concentration (<0.1 M) monovalent electrolyte solutions, a higher solute flux through GCLs than CCLs is observed.

This is due to the reduced thickness of the GCL (layer thickness of the order of a few cm) and the resulting high concentration gradient, which drives the diffusive flow (Manassero et al., 2000).

Therefore, to achieve performance comparable to that of CCLs, it is essential to supplement GCLs with an attenuation layer (AL), which reduces contaminant migration and improves the overall functionality of the barrier system.

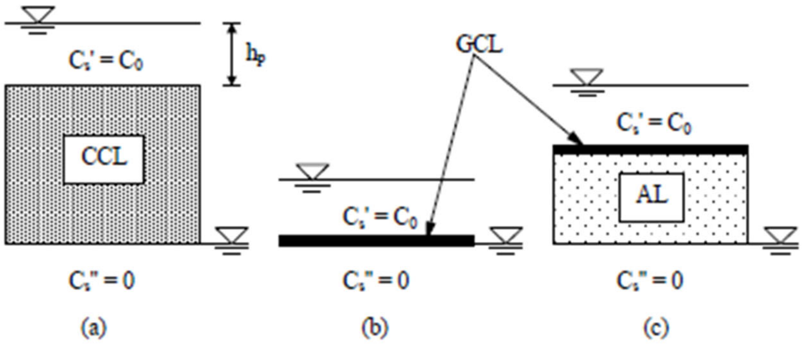

Figure 2.7 Setup landfill barrier-prof Dominijanni & prof Manassero, Influence of membrane behaviour on contaminant transport

The attenuation layer (AL) may comprise natural or artificial materials and exhibits a relatively high hydraulic conductivity.

The primary objective of the attenuation layer is to diminish the concentration gradient within the barrier system by increasing the distance between the leachate collected in the basin and the base of the barrier.

In this way, the attenuation layer plays a pivotal role in decelerating the transport of contaminants to underlying areas, enhancing the efficacy of the lining and providing supplementary protection to groundwater resources.

The steady-state mass flow, J_s, through a composite barrier is given by the following equation, proposed by Manassero et al. (2000):

$$J_s = q\frac{C'_s\exp(P_L) - C''_s}{\exp(P_L) - 1}$$

With

$$q = \frac{1}{\sum_{i=l}^{N}\frac{L_i}{k_i}}(h_p + \sum_{i=l}^{N} L_i)$$

$$P_L = q \sum_{i=l}^{N} \frac{L_i}{n_i D_i^*}$$

In the above equations N is the number of layers that make up the barrier layer, q is the flow in m/s of the solution, k is the hydraulic conductivity (m/s), L in m represents the thickness of the layers, h_p is the leachate height, n denotes the porosity and $D_i^*$the effective diffusion coefficient:

$$D^* = \tau \cdot D_0 \ [\frac{m^2}{s}]$$

The salt concentrations inside and outside the barrier are respectively C'_s e C''_s. Finally, P_L is the Peclet number, a dimensionless parameter quantifying the relationship between advective and diffusive transport.

2.3.4 Coupled flux transport theory

Spiegler and Kedem (1966) derived equations for a semi-permeable membrane permeated by a solution containing a single salt (e.g. NaCl or CaCl2), which describe the flow rate

$$q = -P_{v\lambda}\frac{dP}{dx} - \omega_{\lambda}\frac{d\Pi}{dx}$$

And the flow of salt (mol $m^{-2}s^{-1}$) through it:

$$J_s = (1-\omega)qC_s - P_{v\lambda}\frac{dC_s}{dx}$$

The virtual osmotic pressure (N/m2) within the relationship is given by

$$\Pi = (\nu_a + \nu_c)RTC_s$$

With ν_a, ν_c stoichiometric coefficients of the anion and cation, R the universal gas constant of 8.314 N m $mol^{-1}K^{-1}$, T the absolute temperature in Kelvin.

The specific hydraulic conductivity $P_{v\lambda}$ is given by:

$$P_{v\lambda} = \frac{k}{\gamma_w}$$

With γ_w solvent unit weight in N/m^3.

By linearising the flow equations, an analytical solution can be obtained under steady-state conditions (*Steady-state analysis of pollutant transport to assess landfill liner performance - Andrea Dominijanni PhD and Mario Manassero PhD*):

$$q = \frac{k}{\gamma_w}(\frac{dP}{L} - \omega \quad \frac{\Delta\Pi}{L})$$

$$J_s = (1-\omega)q\frac{C'_s \exp(P_{L\Pi}) - C''_s}{\exp(P_{L\Pi}) - 1}$$

With

$$P_{L\Pi} = \frac{(1-\omega)qL}{P_s}$$

Which respectively represent the flow rate q, the flow of contaminant (or salt) passing through the mineral barrier J_s.

3 ANALYSIS AND STUDY OF GASEOUS EMISSIONS

3.1 CARBON FOOTPRINT EVALUATION

The utilisation of bentonite geocomposites (GCL, geosynthetic clay liners) in the construction of base sealing and landfill cover systems presents a number of notable advantages over conventional solutions that employ compacted clay liners (CCL). These benefits extend to both the containment performance of contaminated fluids and biogas, as well as to the environmental sustainability aspects of the disposal facility.

The utilisation of GCLs in lieu of CCLs confers a number of advantages, including:

- an increase in waste storage capacity due to the reduced thickness of GCLs (about 1 cm);
- the optimisation of barrier costs and time;
- decreasing consumption of non-renewable mineral resources;
- the reduction of air emissions, including greenhouse gases such as carbon dioxide (CO_2), which are responsible for ongoing climate change.

In order to objectively quantify the improvement in landfill sustainability resulting from the use of GCLs in comparison to CCLs, an analysis of the carbon footprint of both product life cycles is an effective methodology.

This methodology permits a comprehensive life cycle analysis of both barrier solutions, encompassing the extraction of raw materials, the implementation and commencement of the waterproofing system, and all intermediate steps.

The two design alternatives for the base sealing system and the final cover, the subject of the study, were defined in accordance with the requirements set forth in Legislative Decree 36/2003 of 13/01/2003 (subsequently amended by Legislative Decree 121/2020 of 03/09/2020) for non-hazardous waste landfills.

A schematic representation of these solutions is illustrated in the following figures, which elaborate on the study of the Research Project of Prof. Andrea Dominijanni, the scientific head of 'Bentonite barriers for the control of PFA in the subsoil, Theoretical-experimental study on the transport processes of perfluoroalkyl substances (PFAS) in sealing systems consisting of bentonite barriers (e.g., bentonite geocomposites), taking into account coupled phenomena'.

<u>CCL profile of the landfill bottom barrier system</u>

Figure 3.1 CCL profile of the landfill bottom barrier system - Prof. Dominijanni - Research Project

<u>Profile with GCL of the landfill bottom barrier system</u>

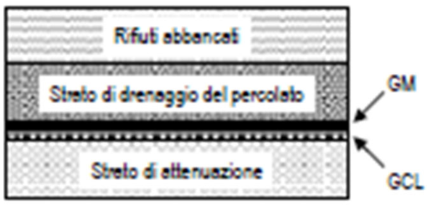

Figure 3.2 Profile with GCL of the landfill bottom barrier system - Prof. Dominijanni - Research Project

Profile with CCL of the landfill cover system

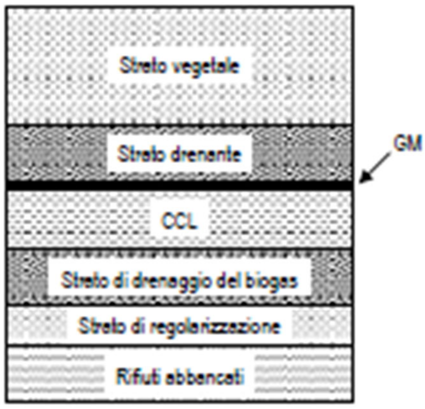

Figure 3.3 Profile with CCL of the landfill cover system - Prof. Dominijanni - Research Project

Profile with GCL of the landfill cover system

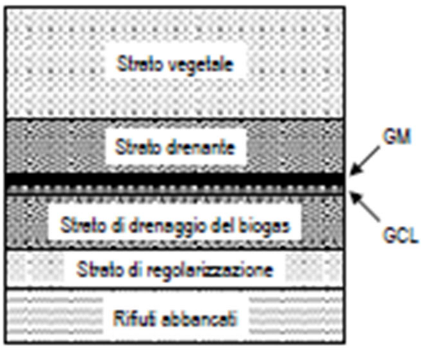

Figure 3.4 Profile with GCL of the landfill cover system - Prof. Dominijanni - Research Project

As illustrated in the figures just shown, the design solutions feature a multi-layer background barrier whose elements used are:

- leachate drainage layer, having a thickness s ≥ 0.5 m and hydraulic conductivity $k \geq 10^{-5}$m/s;
- HDPE geomembrane, thickness s > 2.5 mm;
- compacted clay barrier (CCL) or bentonite geocomposite (GCL);
- attenuation layer.

The covering system, illustrated immediately after the barrier system described above, is also characterised by a solution perforated by several layers, consisting of:

- surface covering layer;
- rainwater drainage layer;
- HDPE geomembrane;
- compacted clay barrier (CCL) or bentonite geocomposite (GCL);
- biogas drainage layer;
- layer of regularisation;

The two design solutions presented differ solely in regard to the selected mineral layer, which is either a GCL or a CCL.

As a result, the discrepancy in the environmental impact assessment between the two design solutions under consideration is attributable to the distinct characteristics of the bentonite geocomposite barrier in comparison to the compacted clay barrier. In this regard, all elements common to both design solutions were excluded from the environmental quantification.

A carbon footprint (CI) analysis emphasises the three stages of the product life cycle described above.

- The extraction of raw materials and, in the case of GCLs, the production of geosynthetics;
- The transport of materials from the extraction or production site to the landfill construction site;
- The construction of the bottom barrier system and the final landfill cover.

The study quantifies greenhouse gas emissions in terms of tonnes of CO2 equivalent per unit area of the barrier system and is structured as follows.

3.1.1 Emissions in the raw material extraction and production phase

The results of the calculation of the CO2 equivalent emissions per unit area of the E-barrier, whether it is a cover or a background barrier, referring to the phase of raw material extraction and production of GCL in the plant, are summarised below

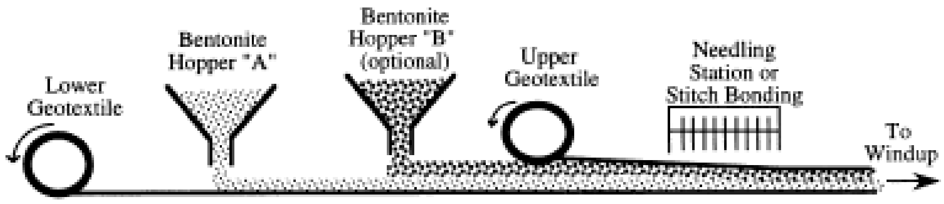

Figure 3.5 Manufacture of Different Types of Geosynthetic Clay Liners - Koerner & Daniel (1997) - Final Covers for Solid Waste Landfills

Additionally, the study by Stefania Bilardi and Nicola Moraci, which discusses the use of geosynthetics in the sustainable design of controlled landfills, considers the emissions related to the extraction of raw materials and the production of the product under discussion, which are collectively referred to as cradle-to-gate emissions.

The calculation was conducted on the basis of a mass per unit volume of clay of 1.9 tonnes per cubic metre and 5.4 kg per square metre, with regard to bentonite geocomposites.

Figure 3.6 Processing of Clay - Source 3-K-VON-MAUBEUGE-Naue

With reference to the studies conducted by *Raja et al. in 2014 and 2015*, and from the source https://geosynthetic-institute.org/papers/paper41.pdf, the carbon footprint related to CCLs and thus clay was assumed to be 0.00003 tCO2e/t (this value is lower than the value in the ICE database and equal to 0.005 tCO2e/t as this takes into account the crushing and screening processes), while considering GCLs 0.22 tCO2e/t is assumed.

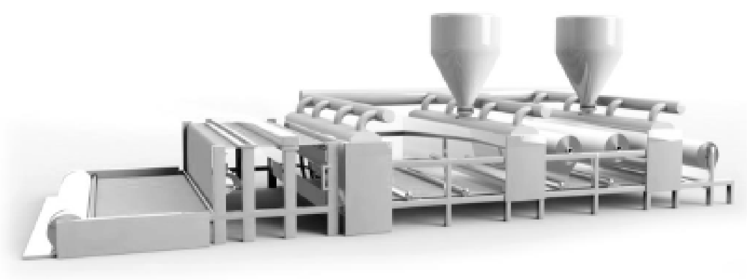

Figure 3.7 GCLs production scheme - Source 3-K-VON-MAUBEUGE-Naue

The design solutions presented consider a mass of the bentonite geocomposite used to cover 1 hectare of landfill surface area M increased by 10% so as to consider the joints between the GCL sheets.

Figure 3.8 Raw materials mining/production - Source 3-K-VON-MAUBEUGE-Naue

The total CO2 emissions (tCO2e/hectare of surface area) with reference to the bottom barrier system (cradle-to-gate phase) are summarised in the table below:

Materiali	IC	M	E
	(tCO2e/ton)	(ton/ettaro)	(tCO2e/ettaro)
CCL	0,0003	19000	5,7
GCL	0,22	59,4	13,07

Table 3.1 First stage emissions in tCO2e/hectare bottom barrier - source - Prof. Andrea Dominijanni (Research Project, BENTONITIC BARRIERS FOR PFAS CONTROL IN THE UNDERGROUND)

Turning instead to total CO2 emissions (tCO2e/hectare of surface area), with reference to the roofing system (cradle-to-gate phase) we have

Materiali	IC (tCO2e/ton)	M (ton/ettaro)	E (tCO2e/ettaro)
CCL	0,0003	9500	2,9
GCL	0,22	59,4	13,07

Table 3.2 First stage emissions in tCO2e/hectare final cover barrier - source - Prof. Andrea Dominijanni (Research Project, BENTONIC BARRIERS FOR PFAS CONTROL IN THE SUBSOIL)

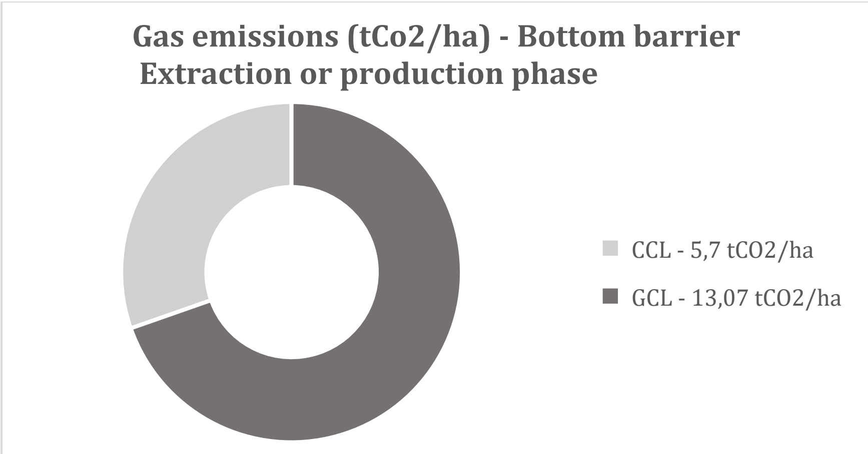

Figure 3.9 Gas emission (tCO2/hectare) - Bottom barrier, extraction or production phase

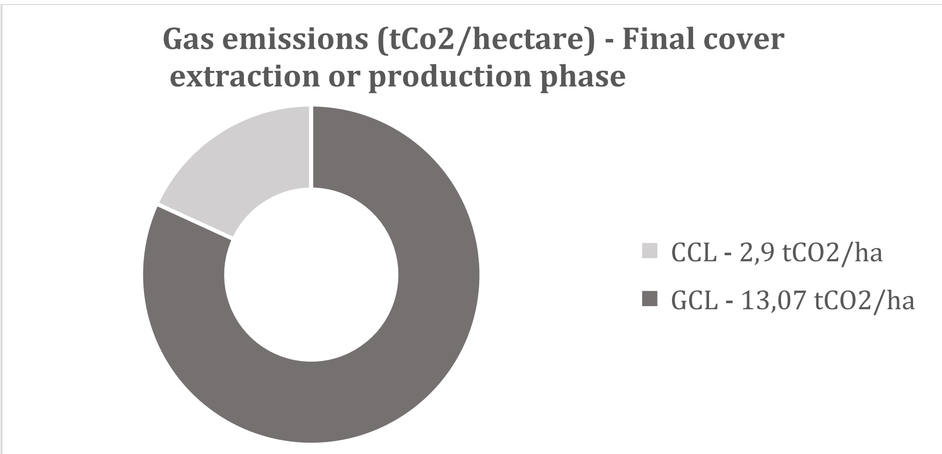

Figure 3.10 Gas emission (tCO2/hectare) - final cover barrier, extraction or production phase

The graphs are designed to illustrate the comparative analysis conducted by Professor Dominijanni in his research project, which examined the emissions generated during the raw material extraction and in-plant production phases of GCLs and CCLs.

The data demonstrate that, despite the significantly lower mass of material involved in this phase for GCLs, they emit a greater quantity of greenhouse gases in tonnes per hectare than CCLs. In the case of background barriers, this accounts for as much as 70% of total emissions, with 2.29 times more tonnes of CO_2 emitted. For end-coverages, this figure rises to 80% of total emissions, with a delta of 4.51 times higher.

These values are entirely predictable, as this stage of the life cycle is the most wasteful in terms of greenhouse gas emissions for bentonite geocomposites, which are produced in the plant. The following statement will be elucidated through the presentation of the remaining life cycle stages that have been subjected to analysis.

3.1.2 Emissions in the transport phase

T-emissions considered during the transport phase to the landfill site, calculated using the equation (Raja et al. 2015):

$$T = \frac{2 \cdot \beta \cdot N}{\alpha}$$

They consider both the outward journey with loaded vehicles and the return journey to the material loading point.

β represents the CO2 emission per litre of fuel assumed as 2.6 kgCO2/L (source DEFRA 2013), α is the fuel consumption of the means of transport considered for the phase, assumed as 3.33 km/L, N on the other hand represents the number of means required to complete the operation, considering the maximum amount of transportable material per means to be 20 tonnes.

The results presented below are per unit of distance travelled, from the extraction site for clay or the production plant for GCL, to the landfill site.

Materiali	N	T
	(L/ettaro)	(tCO2e/ettaro x km)
CCL	950	1,4983
GCL	2,97	0,005

Table 3.3 Transportation phase emissions in tCO2e/hectare bottom barrier - source - Prof. Andrea Dominijanni (Bentonite barriers for the control of pfas underground)

Materiali	N	T
	(L/ettaro)	(tCO2e/ettaro x km)
CCL	475	0,742
GCL	2,97	0,005

Table 3.4 Transportation phase emissions in tCO2e/hectare final cover barrier - source - Prof. Andrea Dominijanni (Bentonite barriers for the control of pfas underground)

In the present case, we may assume a distance of 20 km from the clay extraction site and a distance of the same value from the GCL production plant. The data presented herewith relate to the emission levels during the transport phase to the construction site, and include both the quantity inherent to the background barrier and the quantity inherent to the final cover.

Distanza sito	Materiali	T copertura	T barriera	T tot
(km)		(tCO2e/ettaro)	(tCO2e/ettaro x km)	(tCO2e/ettaro x km)
20	CCL	14,84	29,97	44,81
	GCL	0,10	0,10	0,20

Table 3.5 Transportation phase, total emissions in tCO2e/hectare x km

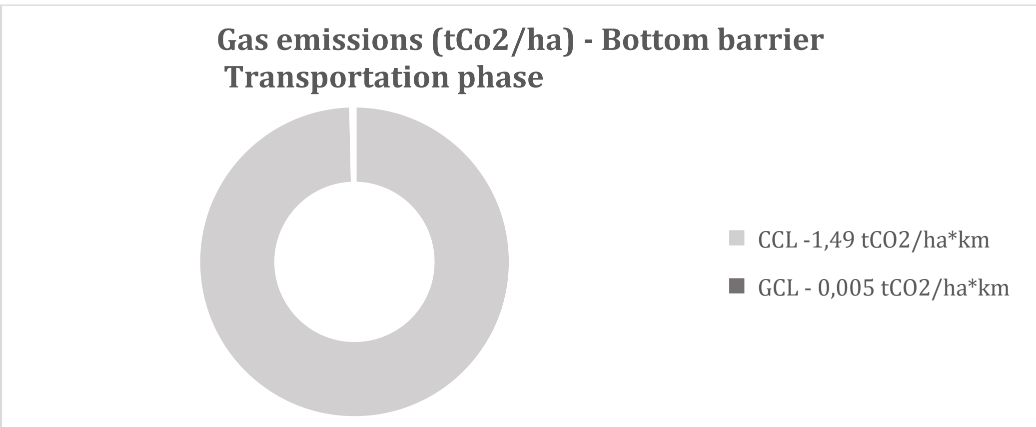

Figure 3.11 Total gas emission (tCO2/hectare) - Bottom barrier, transportation phase

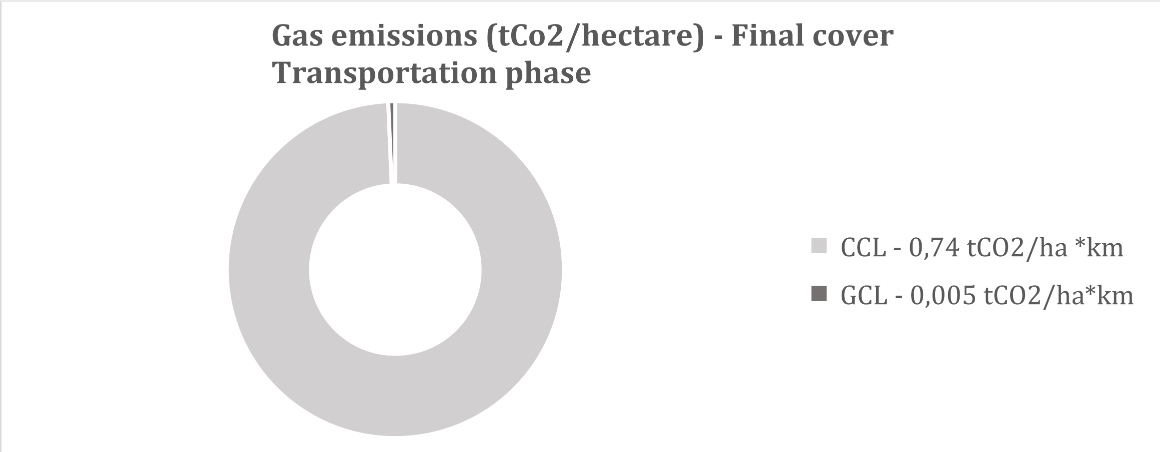

Figure 3.12 Total gas emission (tCO2/hectare) - Final cover, transportation phase

The comparison illustrated in the graphs above is designed to highlight the category with the greatest impact on CO_2 emissions during the various stages of the life cycle of the two design solutions under examination, namely transport.

The pie charts employed to illustrate the proportions in relation to the whole demonstrate a striking imbalance between the two materials, with the emissions on the CCL side exceeding 99% of the total weight of tCO_2 per hectare per kilometre in both cases (final cover and background barrier).

The discrepancy between the two calculations demonstrates a significant increase in the number of heavy goods vehicles (HGVs) utilised for the transportation of clay materials for CCLs, with an estimated 298-fold rise, and a notable 148-fold increase for the transportation of materials for final covers.

3.1.3 Emissions during the construction of the bottom barrier and the final cover

As elucidated in the research project report, "Bentonite Barriers for the Control of PFAS in the Subsurface," authored by Professor Andrea Dominijanni, the calculation of CO2 equivalent emissions per unit area of the barrier, denoted by C, can be developed by assuming that the installation of the bentonite geocomposite generates negligible greenhouse gas emissions compared to those resulting from the operations required for the construction of a compacted clay barrier (Raja et al., 2014). This calculation is exclusive to the construction phase of the site.

Figure 3.13 Subgrade preparation and clay spreading - Source 3-K-VON-MAUBEUGE-Naue

It can be seen that for the design solution with GCL, C=0 is assumed. In contrast, for the design solution with CCL, the calculation of emissions requires additional assumptions to be made regarding the duration of clay spreading and compaction operations, the type of machinery used, and the fuel consumption of such machinery.

Figure 3.14 GCL Installation phase - Source 3-K-VON-MAUBEUGE-Naue

Specifically, the calculation of emissions at this stage for CCLs was performed according to the following equation:

$$C = \frac{n_{strati} \cdot n_{passaggi} \cdot \beta \cdot \zeta}{P}$$

Where ζ represents the hourly fuel consumption, the number of layers and the number of passes respectively indicate the number of layers and the number of passes for each layer during the compacted clay barrier phase, for the material spreading phase both are assumed to be 1, P is the hourly productivity of the machinery used.

Figure 3.15 Watering, Sheep-foot compacting, levelling, smooth compacting (typical for two layers) - Source 3-K-VON-MAUBEUGE-Naue

The C-consumption results obtained from the *C* calculation are summarised in the table below, P-values and ζ given by Athanassopoulos & Vamos (2011) and Koerner (2016) are used for spreading and compaction of materials.

Fasi di lavorazione CCL	P	ζ	n.strati	n.pass	C
	(ettari/h)	(L/h)	-	-	(tCO2e/ettaro)
spargimento	0,025	25,7	1	1	2,673
compattazione	0,1	16	4	8	13,312
					15,985

Table 3.6 Construction phase emissions in tCO2e/hectare bottom barrier, CCLs - source - Prof. Andrea Dominijanni (Bentonite barriers for the control of pfas in the subsurface)

Fasi di lavorazione CCL	P	ζ	n.strati	n.pass	C
	(ettari/h)	(L/h)	-	-	(tCO2e/ettaro)
spargimento	0,025	25,7	1	1	2,673
compattazione	0,1	16	2	8	6,6656
					9,329

Table 3.7 Construction phase emissions in tCO2e/hectare final cover barrier, CCLs - source - Prof. Andrea Dominijanni (bentonite barriers for the control of pfas underground)

3.2 CUMULATIVE ENERGY DEMAND (CED)

Cumulative Energy Demand (CED) is an indicator that assesses the energy and, thus, environmental impact of a product throughout its life cycle.

It permits the quantification of the total energy consumed during the phases of a cycle, as previously described in detail, including production, transportation and the construction of mineral barriers.

In the case of barrier and cover systems in waste landfills, a comparison is made between the CED of the two barriers considered in the design solutions: that with Geosynthetic Clay Liners (GCL) and that with Compacted Clay Liner (CCL). (C. Martin, "Life Cycle Assessment of Geosynthetic Clay Liners").

The previously calculated carbon footprint can be combined with the concept of CED, which expresses the amount of energy required by the product life cycle.

The conversion is contingent upon the quantity of CO_2 emitted in the generation of the energy utilized in each production process.

The Cumulative Energy Demand (CED) and the carbon dioxide (CO_2) emissions, expressed in tonnes of CO_2 (tCO_2), are two distinct parameters employed in analyses to evaluate their environmental impact.

In order to establish a relationship between CED and the CO_2 emissions calculated above, it is necessary to know the specific emission factors at the different stages of the process.

$$CED(MJ) = \frac{Emissioni\ di\ CO_2(kg)}{Fattore\ di\ emissioni\ medio(\frac{kgCO_2}{MJ})}$$

It is feasible to quantify the CED associated with the various stages of the process under examination.

As reported by J. Keller in "Impact of Transportation on Cumulative Energy in Construction" and M. Russo in "Construction Machinery Energy Demand and Emission

Factors," the average emission factor varies depending on the energy mix considered in the process or system analysed. The following examples illustrate this point:

- Coal: ~0.094 kg CO2/MJ;
- National gas: ~0.056 kg CO2/MJ;
- Diesel: ~0.074 kg CO2/MJ;
- Hydro, wind, solar energy: ~0.0 kg CO2/MJ (but indirect emissions related to plant production and maintenance could be considered, which are neglected for the case study).

Analysing the scenario, it is possible to assume for each stage of the product life cycle:

<u>Extraction or production phase</u>

Different energy mixes for different industrial processes:

- 50% electricity from natural gas (in-plant production process for GCLs) - emission factor 0.056 kg CO2/MJ;
- 50% electricity from renewables (in-plant production process for GCLs) - emission factor 0.0 kg CO2/MJ;

- 100 per cent diesel (as the main fuel powering the vehicles involved in clay extraction processes) - emission factor 0.074 kg CO2/MJ.

Transport phase

Energy mix considered equal, considering the same means of transport for both design solutions, with a diesel emission factor of 0.074 kg CO_2/MJ.

Construction phase

Energy mix deemed comparable, considering the same means of constructing the barrier layers for both design solutions, with a diesel emission factor of 0.074 kg CO_2/MJ.

(M. Russo, 'Construction Machinery Energy Demand and Emission Factors,') (*H. Lee, K. Park, 'Diesel Use in Construction: Emissions and Energy Consumption,')*

3.2.1 Raw material extraction or production phase

The initial phase of the life cycle under examination is the extraction of the raw materials necessary for the manufacture of GCL and CCL.

This phase is particularly costly, as illustrated in the graphs above, particularly for GCL, which requires complex industrial processes for the production of synthetic, polymer-based materials.

At this stage, the equivalent CO2 emissions related to the extraction of raw materials for GCLs are 13.07 tCO2 for the background barrier and an equivalent 13.07 tCO2 for the hedge, for a total of 26.14 tCO2 emitted. Based on the considerations made in the previous paragraph, this is divided equally at 50% considering production using electricity derived from natural gas (with an emission factor of 0.056 kg CO2/MJ) and 50% considering production using electricity derived from renewable sources (with an emission factor of 0.0 kg CO2/MJ).

The CED for this phase is equal to:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ produzione\ GCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{13{,}07\ tCO_2\ x\ 1000}{0{,}056\ (\frac{kgCO_2}{MJ})} \sim 233\ GJ$$

For a total of 233 GJ.

For the CCL, emissions are significantly lower, with 5.7 tCO2 for the bottom barrier and 2.9 tCO2 for the cover, respectively.

The corresponding CED values are, for the background barrier:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ Estrazione\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{5{,}7\ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 80\ GJ$$

While for coverage you have:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ Estrazione\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{2{,}9\ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 40\ GJ$$

For a total of 120 GJ.

3.2.2 Transport Phase to Site

The transportation of materials to the construction site represents a further critical stage in the determination of the CED.

The primary application of diesel is in heavy trucks and handling equipment, which frequently result in considerable emissions. CCL, due to its greater weight and the enormously larger volume of clay to be transported (approximately 300 times larger than that of GCL), has significantly higher emissions than bentonite geocomposites.

When a distance of 20 km is considered from the landfill site, the transport emissions for the GCL are found to be 0.1 tCO_2 for both the cover and the bottom barrier layer, resulting in a relatively low CED equivalent to:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ trasporto\ GCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{2\ x\ 0{,}1\ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 2{,}7\ GJ$$

While the CCL, records transport phase emissions of 29.66 tCO2 for the bottom barrier and 14.84 tCO2 for the cover.

The corresponding CED values for transport are for the background barrier:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ trasporto\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{29{,}66\ \ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 400\ GJ$$

While for the cover:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ trasporto\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{14{,}84\ \ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 200\ GJ$$

For a total of GJ 600.

3.2.3 Bottom barrier System Construction Phase

The construction of any project system, is a phase in which the difference between the two barriers is evident.

GCL requires a minimal amount of energy for installation, as it is a pre-assembled, lightweight and easy-to-install material.

This is reflected in emissions set at 0 tCO2, and thus:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ costruzione\ GCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} \sim 0\ GJ$$

In contrast, the CCL requires the use of heavy machinery to compact the clay, with emissions of 15.98 tCO2 for the bottom barrier and 9.32 tCO2 for the cover.

The corresponding CED values are for the background barrier:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ costruzione\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{15{,}98\ \ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 215\ GJ$$

While for the cover:

$$CED(GJ) = \frac{Emissioni\ di\ CO_2(kg)\ costruzione\ CCL}{Fattore\ di\ emissioni\ diesel\ (\frac{kgCO_2}{MJ})} = \frac{9{,}32\ \ tCO_2\ x\ 1000}{0{,}074\ (\frac{kgCO_2}{MJ})} \sim 126\ GJ$$

For a total of 341 GJ.

The total Cumulative Energy Demand (CED) quantities for the two different design solutions are shown below:

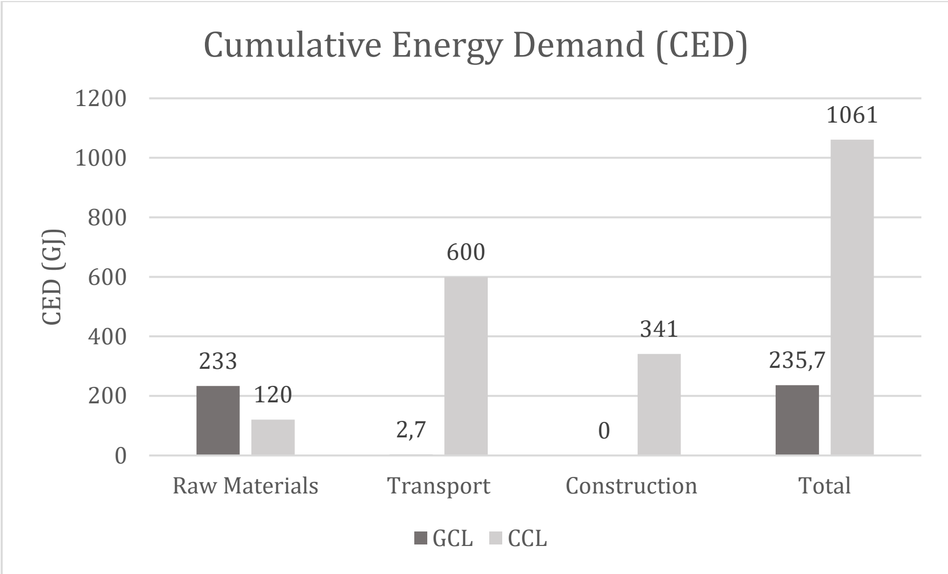

Figure 3.16 Comparison Cumulative energy demand CED (GJ) - GCL & CCL

A summation of the CED value for each phase reveals that the GCL exhibits a markedly lower energy demand in comparison to the CCLs, with a discrepancy of approximately one-third.

As evidenced by the results and as previously presented in the calculation of CO_2 emissions at the various stages of the process, the CCL exhibits a higher cumulative energy demand, primarily due to the transportation and construction phases.

The results obtained and widely discussed indicate that the use of GCLs can lead to a significant reduction in energy consumption and CO_2 emissions, which in turn can result in a lower overall environmental impact.

The subsequent analysis reveals that the energy demand over the life cycle of CCLs is approximately 4,5 times higher than that of GCLs. This discrepancy can be attributed to the significant difference in material usage and the potential for green energy utilisation in the production of bentonite geocomposites.

3.3 DIFFUSIVE GAS FLOW THROUGH THE COVER

3.3.1 Calculation of gas emissions through coverage

In this part, we tend to quantify and calculate gas fluxes through landfill cover systems, focusing mainly on the two gases most commonly present and contained in municipal solid waste from landfills (*Babikova 2015*)

- carbon dioxide (CO_2)
- methane (CH_4)

which account for 40-60% and 45-60% of the gas in the landfill respectively.

In order to evaluate the diffusive behaviour of gases through the coverings, it is necessary to determine the effective diffusion coefficient, as fully explained in the previous paragraphs. This coefficient takes into account material properties such as porosity and degree of saturation, as well as the thickness of the two barriers, which have been isolated from the rest of the barrier package in accordance with the relevant regulations. This approach allows us to emphasise their performance independently of the rest of the layers. In particular, a GCL thickness of 0.01 m was assumed, while a compacted clay thickness (CCL) of 0.5 m was used.

The porosity of geocomposites is assumed to be 75% (defined as the ratio of the volume of voids to the total volume), while that of compacted clays is assumed to be 40% (also defined as the ratio of the volume of voids to the total volume).

The landfill was assumed to have a surface area of one hectare (10,000 m^2).

The data were processed and presented in the following tables, which illustrate the profiles of gas concentration and flow as a function of the different roof system configurations and materials used.

The flow data are expressed in mol/(m^2 s) to facilitate comparison, with the units converted to tonnes per day.

CH4				
	Deff (m2/s)	F(mol/m2s)	F(g/m2s)	F(t/day)
CCL	1,61E-06	9,67E-05	1,60E-03	1,3
GCL	3,56E-08	1,07E-04	1,70E-03	1,5

Table 3.8 Flow of emissions through the roof considering methane (CH4)

CO2				
	Deff (m2/s)	F(mol/m2s)	F(g/m2s)	F(t/day)
CCL	1,17E-06	2,58E-05	1,14E-03	1
GCL	2,59E-08	2,85E-05	1,30E-03	1,1

Table 3.9 Emissions flow through coverage considering carbon dioxide (CO2)

The results demonstrate fluxes of a higher order in comparison to the assumed design setup, given that the design solutions analysed differ solely in the selection of the mineral layer, which comprises either GCL or CCL.

Therefore, the discrepancy in the evaluation of the environmental impact, and consequently in this case the gas emission from the final cover, between the two solutions is attributed to the distinct characteristics of the bentonite geocomposite barrier and the compacted clay barrier.

In this regard, all elements common to both design solutions were excluded, with consideration limited to the bentonite geocomposite ($s_{gcl} = 0.01m$) and compacted clay ($s_{ccl} = 0.5m$), and a landfill surface area of one hectare.

The tables present trends and provide a basis for the environmental assessment and equipotentiality of geocomposite overburden barriers, demonstrating their efficacy in limiting gas migration.

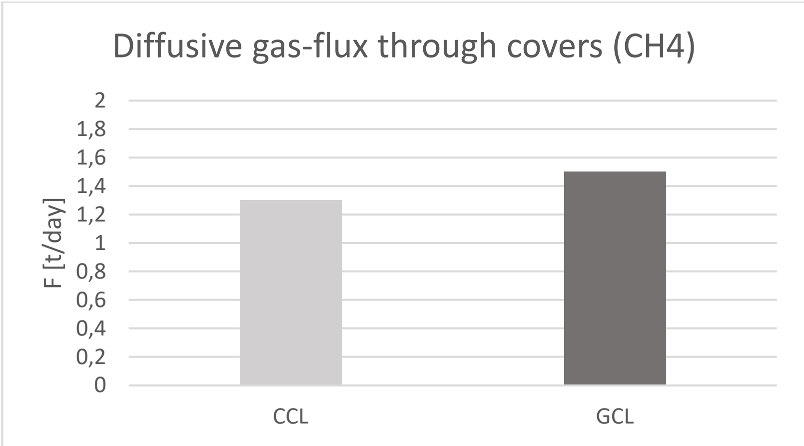

Figure 3.17 Comparison between diffusive gas-flux through covers (CH4)

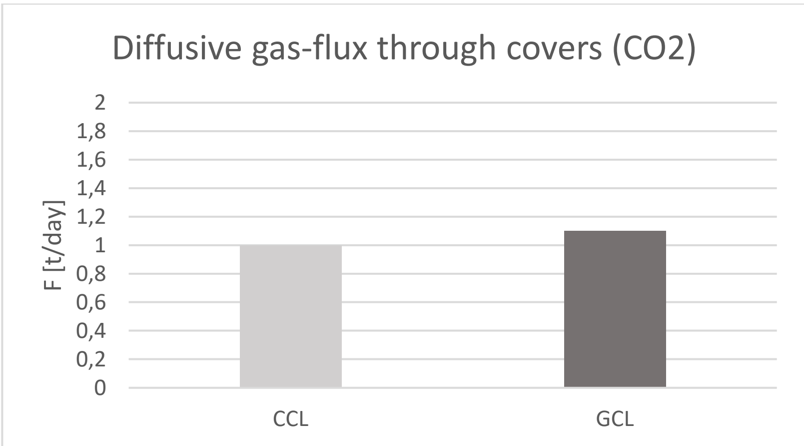

Figure 3.18 Comparison between diffusive gas-flux through covers (CO2)

It can be observed that the behaviour of the two barriers in terms of gas diffusion through the cover is comparable, with a slightly higher emission from the GCL barrier design solutions in the case of diffusive flow, when such flow is considered.

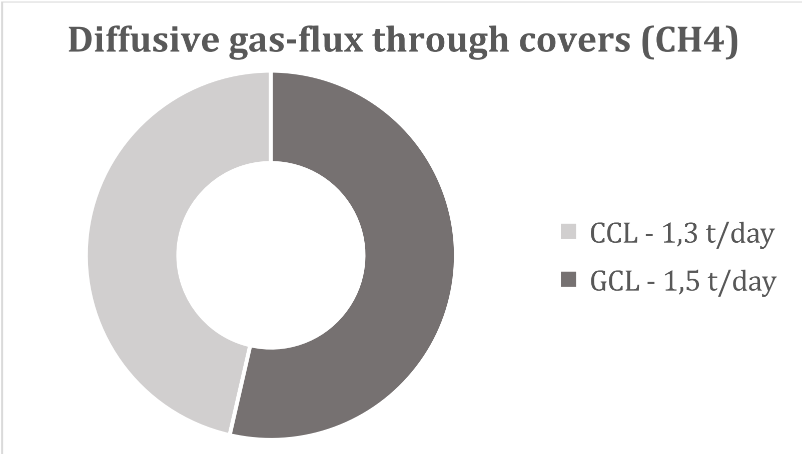

Figure 3.19 Diffusive gas-flux through covers (CH4) - comparison between GCL vs CCL

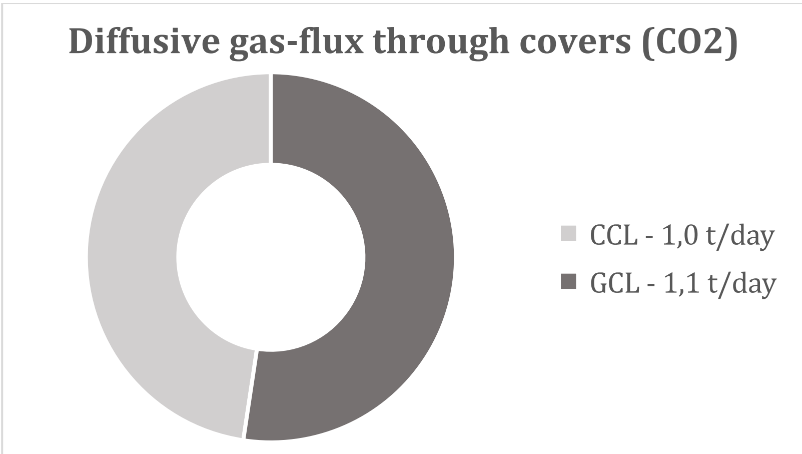

Figure 3.20 Diffusive gas-flux through covers (CH4) - comparison between GCL vs CCL

In particular, the emission of methane gas was observed to be approximately 15 per cent higher in the bentonite geocomposite solutions, while for carbon dioxide the difference was a delta of 10 per cent.

These variations, while significant, are relatively minor when viewed in the context of the greater design depth of CCLs compared to GCLs.

The behaviour of GCLs is therefore competitive and potentially advantageous in terms of sustainability and installation costs, despite the fact that they exhibit a slightly higher gas spread than CCLs, for the design configuration under consideration.

Nevertheless, this discrepancy may be deemed acceptable when weighed against other advantages, such as the simplicity of installation, the reduction in material requirements, and the diminished overall environmental impact of GCL. As illustrated below, GCL offers considerable benefits from both a design and an environmental standpoint.

3.4 Comparison of emissions between gcl and ccl

The construction of landfills necessitates the implementation of a composite lining system to mitigate the migration of harmful gases produced within the landfill into the subsoil.

The analysis was conducted through a comprehensive sustainability assessment of two technically equivalent composite barrier systems for controlled waste landfills. The assessment employed both traditional design solutions and more innovative design solutions with bentonite geocomposites.

The data obtained from the analysis, which compared the carbon footprint of the two methods of waste landfill cover and barrier, revealed that the most relevant component between the two design solutions is transport. This is due to the fact that transport weighs heavily in the total CO2 emission count for CCLs, whereas it is practically zero for GCLs. The latter is estimated to require around 950 lorry loads of 20 tonnes each for clay transport, in comparison to approximately 3 lorry loads for bentonite geocomposites.

The findings of the study indicate that the utilisation of a mineral barrier comprising bentonite geocomposite (GCL) represents a more sustainable approach, while simultaneously proving to be more effective in mitigating the migration of gaseous contaminants.

Despite the significantly reduced design thickness, approximately 50 times less than that of compacted clay layers (CCL), this type of barrier offers comparable performance in terms of its ability to limit the flow of contaminants. The superior sustainability of GCL can be attributed to two key factors: firstly, the reduction in material required, and secondly, the smaller ecological footprint associated with its production, transport and installation in comparison to clay layers.

Furthermore, the composite structure and high density of bentonite in GCL result in high resistance to gas diffusion, which is a crucial characteristic for waste landfills. This prevents internally generated gaseous contaminants from migrating to the outside, thereby maintaining greater protection of the surrounding environment.

The utilisation of bentonite geocomposite not only markedly diminishes the resource consumption and environmental impact of the roofing system, but also provides an efficacious barrier against the migration of contaminants, thereby conferring a technically and environmentally beneficial choice.

The preceding paragraphs present the results of the study, which are illustrated in the tables below.

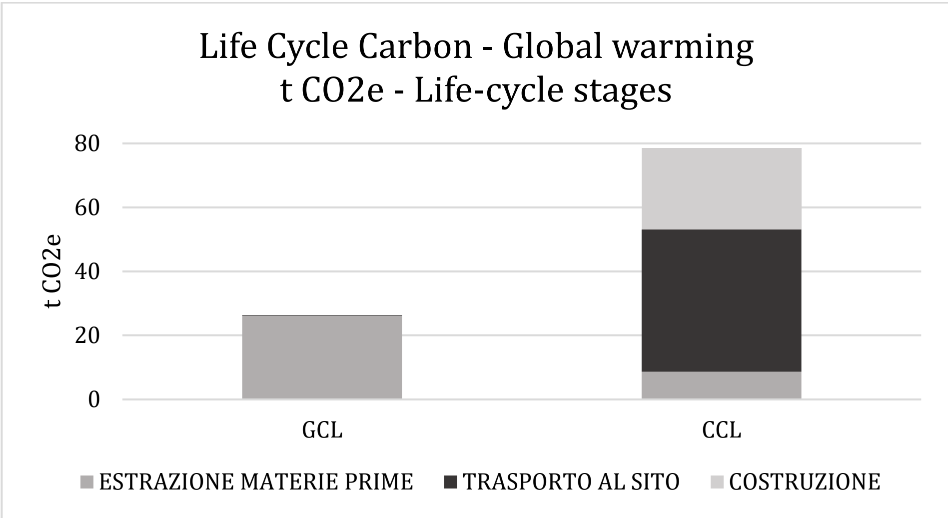

Figure 3.21 Life Cycle Carbon - Global warming (t CO_2 e) Life-cycle stages

The environmental sustainability of the two design solutions can be quantified through life cycle analysis, which enables the assessment of the environmental impacts associated with the different phases of the products' life cycle, from raw material extraction and production to transport and installation.

In the initial stage of raw material extraction, GCLs, which are primarily composed of bentonite clay and geosynthetic materials, exhibit the highest rate of tCO2 consumption and a considerable quantity of emissions associated with this phase, accounting for approximately 26% of the total emissions. This is in contrast to CCLs, where the emissions remain below 10%.

As previously discussed in depth, the transportation of materials for both the GCLs and the CCLs represents a significant portion of the overall life cycle. In particular, the transportation of clay from the extraction mines to the construction site is a notable contributor to the environmental impact. This process involves the use of approximately 300 times more trucks for the transportation of clay materials for the construction of CCLs than for the transportation of bentonite geocomposites.

The installation of GCLs necessitates the preparation of the ground, the unrolling of the GCLs and the covering with other construction materials. This phase entails the utilisation of machinery and human labour. At this stage, the energy used during installation, together with potential emissions from machinery, represents a minor component of the overall life-cycle impact in comparison to production and transport. Consequently, it is considered to be completely negligible. Conversely, the calculation for the design solution with CCL represents over a third of the total amount of CO_2 emitted throughout the entire life cycle.

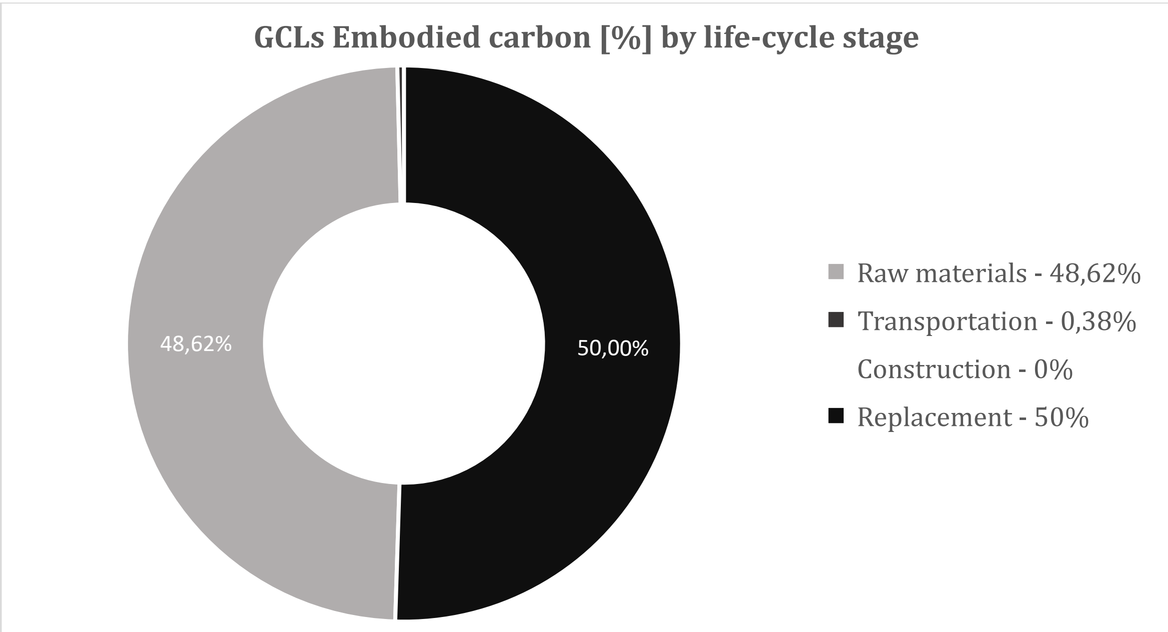

Figure 3.22 Embodied carbon (%) by life-cycle stage - CCL

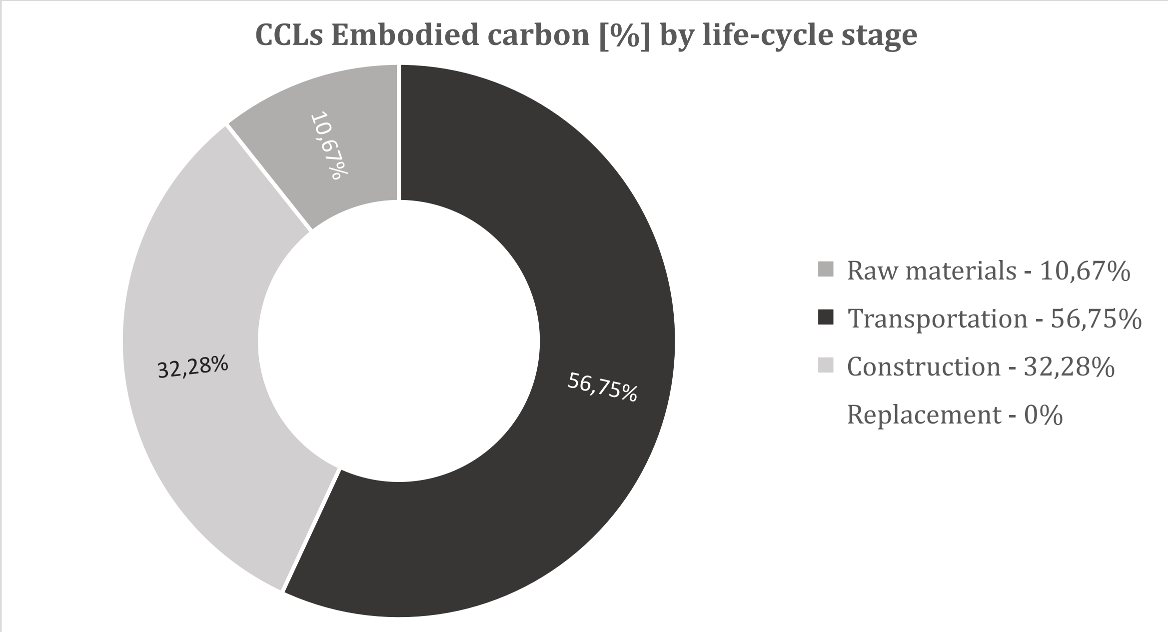

Figure 3.23 Embodied carbon (%) by life-cycle stage - CCL

The pie charts illustrate the percentage distribution of contributions to emissions or life cycle-related environmental impacts of the products under analysis, with CCL above and GCL below.

The categories shown are consistent with those presented in the preceding bar graph and are divided into three sections: the impact due to the production (or extraction) of the materials, including the processing of the raw materials and the transportation of the materials from the production (or extraction) site to the installation site; the impact due to the installation process; and the impact due to the replacement phase, which is included in the graph concerning GCL. The latter was deliberately considered in this graph because it represents the largest contribution, 50%, attributed to GCL replacement, as analysed in Kuo Tian's study from Huazhong University of Science and Technology for International Geosynthetics Society.

This indicates that the process of replacing the bentonite geocomposite has been identified as the most impactful factor, as the lifespan and frequency with which the GCL must be replaced has a significant environmental impact compared to the competing compacted clay layer.

The term 'replacement' is used to describe the costs and emissions associated with the removal, disposal and replacement of the GCL throughout the system's life cycle.

Upon reaching the end of their useful life, GCLs may be left on-site or removed. If they are left on-site, their environmental impact is minimal, as they remain part of the closed landfill system. However, if they have to be removed, they generally end up in the disposal phase, and their geosynthetic components are not biodegradable. Conversely, the recycling of GCL components is currently constrained. However, given that bentonite is a natural material, it does not present a significant long-term environmental risk. Nevertheless, its extraction may have contributed to initial environmental impacts, as previously indicated.

The assessment of carbon footprints is dependent on the specific location of the project site in question, as well as the distances between this site, the source of clay, and the GCL production plant. Additionally, the solution under consideration plays a significant role in determining the overall carbon footprint.

In light of the findings, we intend to pursue a more in-depth investigation, with a particular focus on quantifying the potential landfill area that could be constructed by equating the CO_2 emissions between the two design solutions. In light of the aforementioned data, it can be posited that:

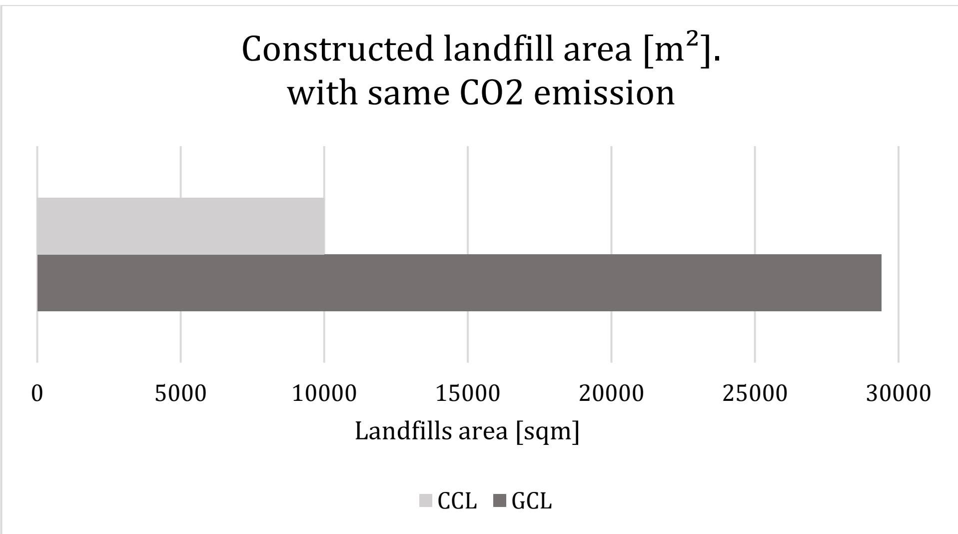

Figure 3.24 Constructed landfill area in m², with same CO2 emisison

In particular, having previously quantified the tCO_2 emitted during the different life-cycle stages of the two products, it appears that during the construction of as much as 2.94 hectares of landfill site using bentonite geocomposites (GCL), the CO_2 emissions recorded during the construction of a single hectare of landfill site using compacted clay (CCl) are reached.

This figure serves to underscore the imbalance in terms of greenhouse gas emissions by calculating the new quantities of CO_2 generated by the construction of 2.94 hectares of landfill and comparing the different cases.

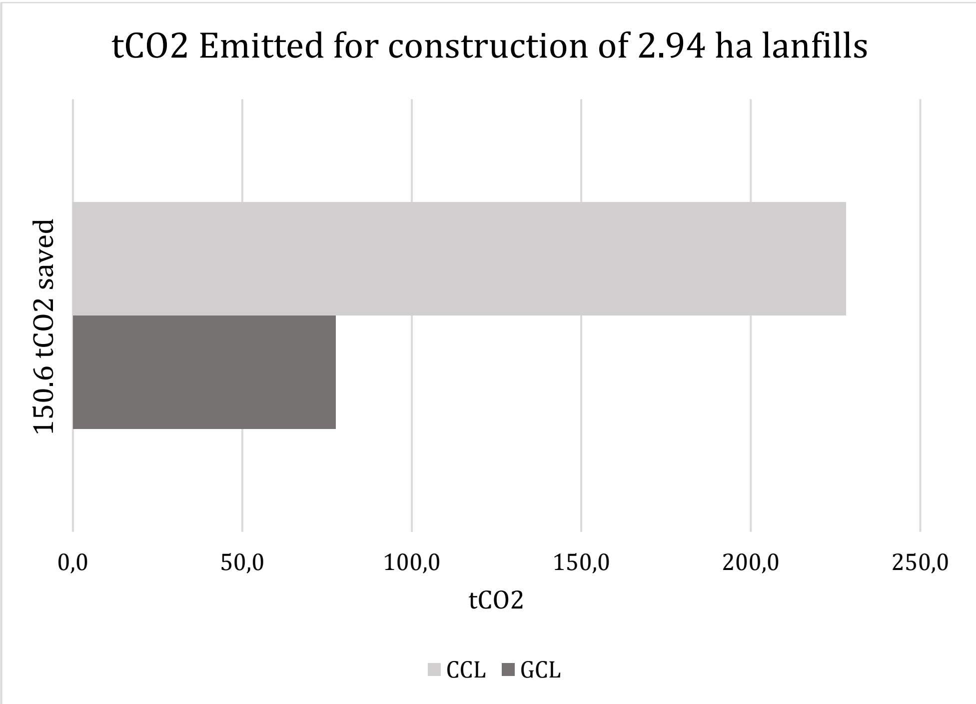

Figure 3.25 tCO2 amission, constructing 2.94 ha landfill - GCLs vs CCLs

In light of the nearly threefold expansion in surface area, the greenhouse gas emissions are currently estimated at this juncture. The findings illustrate that up to 150.6 tonnes of CO_2 can be conserved by constructing an equivalent landfill area, solely through the strategic alternation of design specifications, namely the incorporation of a CCL barrier on one side and a GCL barrier on the other.

4 EFFICIENCY OF THE BOTTOM BARRIER LAYER

The efficiency of the bottom barrier layer, comprising a bentonite geocomposite (GCL), hinges on its capacity to impede the migration of liquid contaminants. This represents an advanced and high-performance solution for waste confinement in landfills and sites with potential environmental contamination.

GCLs comprise a thin layer of bentonite, typically sodium bentonite, combined with reinforcing geotextiles that provide structural integrity and durability. This combination renders them particularly effective in limiting the percolation of contaminants to the underlying aquifer (Bouazza et al., 2006). In conditions of partial saturation, bentonite clay exhibits a swelling phenomenon, increasing in volume and forming a matrix with low hydraulic permeability (even lower than 10^{-10} m/s). This reduces the diffusion of contaminants (Koerner & Daniel, 1997), rendering GCLs comparable, if not superior, in performance to traditional compacted clay layers (CCLs). However, the latter are typically much thicker and require significant amounts of material storage for construction and assembly.

Furthermore, the chemical resistance of GCLs has been demonstrated in studies. The exchange of cations with contaminants in leachates by sodium bentonite contributes to an enhanced chemical resistance compared to CCLs, particularly in the presence of complex or aggressive contaminants (Rowe et al., 2004).

It is important to note that the long-term efficiency of GCLs may be affected by exposure to high concentrations of monovalent cations, which have the potential to reduce the swelling capacity of the bentonite and, consequently, its impermeability. This phenomenon underscores the necessity for site-specific assessments to guarantee that environmental and chemical conditions do not diminish the efficacy of the barrier.

In terms of applicability and sustainability, GCLs have additional advantages. They are easier to install than CCLs, require less space and have a reduced environmental impact, as their thickness is considerably less (approximately 1 cm compared to 50-100 cm for CCLs). Furthermore, this difference in thickness does not compromise the effectiveness of containment, as evidenced by the following study, discussed in more detail in the following paragraphs, and by comparative studies that show a similar containment capacity for liquid and gaseous contaminants (Bouazza, 2002).

The following section will present an analysis of contaminant flow through the bottom barrier layers, which consist of two different design solutions.

- GCL + AL
- CCL+AL

The AL attenuation layer placed at a standard thickness of 3 metres reduces the migration of contaminants and improves the overall functionality of the barrier system by increasing the hydraulic gradient.

4.1 CONTAMINANT FLOW ANALYSIS AND COMPARISON

Moving on to the two design solutions studied, consisting of bentonite geocomposites or compact clay layers with, in both cases, an attenuation layer as shown in the figure:

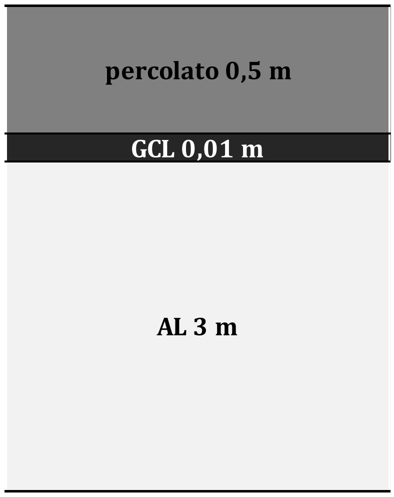

Figure 4.1 Stratigraphy analysed, bottom barrier with GCL

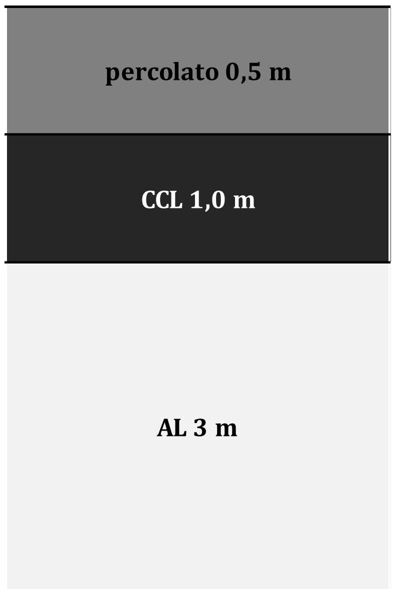

Figure 4.2 Stratigraphy analysed, bottom barrier with CCL

The volumetric flow of solution q and the mass flow of dissolved contaminant in solution J are analysed considering a two-layer system in the presence of semi-permeable membrane behaviour by the bentonite geocomposite.

The layout of the stratigraphy studied is depicted in the figures above, and is discussed in more detail below:

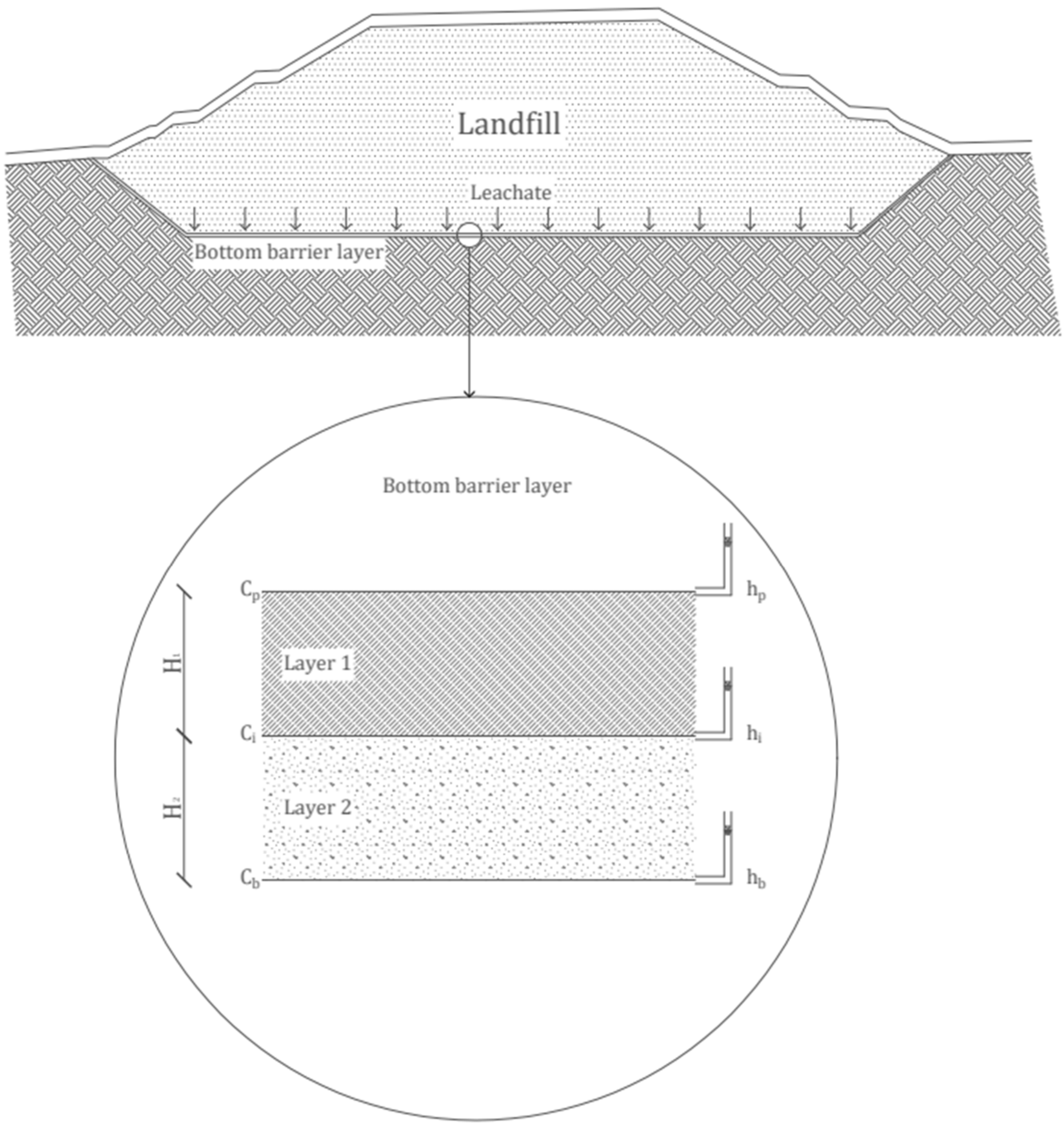

Figure 4.3 Landfill section and bottom barrier particular

The following table specifies the variables that come into play in the calculations:

	ω	k	n	τ
	(-)	(m/s)	(-)	(-)
1) GCL	variable	1,0E-11	0,75	0,3
2) AL	0	1,0E-07	0,4	0,25

Table 4.1 Data analysis case with GCL

	ω	k	n	τ
	(-)	(m/s)	(-)	(-)
1) CCL	0	1,0E-09	0,4	0,2
2) AL	0	1,0E-07	0,4	0,25

Table 4.2 Data analysis case with CCL

The reflection coefficient, designated as ω, represents the capacity of a semi-permeable membrane to impede the permeation of solutes while simultaneously facilitating the permeation of the solvent (water).

The value of ω varies between 0 and 1. The two extremes indicate, respectively, that the membrane does not exhibit semi-permeable membrane behaviour and that the membrane acts as a perfect barrier for solutes, completely retaining salts dissolved in the solvent and only allowing water to pass through.

A parametric analysis will be presented subsequently, which will demonstrate the variation of the contaminant mass flux passing through the barrier as a function of the variation of the reflection coefficient ω between 0 and 50 per cent.This will indicate moderate, but optimal, membrane behaviour.

The hydraulic conductivity, k, is typically lower in GCLs than in CCLs, with a ratio of approximately two orders of magnitude. It is generally set equal to 10^{-11} or 10^{-9}.

The term n indicates porosity and is generally higher in bentonite geocomposites (75 per cent) compared to 40 per cent in CCLs.

This characteristic ensures that, despite the higher initial porosity, the GCL remains highly effective in blocking the flow of water and contaminants.

In contrast, in CCLs, the clay is highly compacted with the objective of reducing porosity, which in turn reduces the number of voids in the material and, consequently, its permeability. The increased porosity enables the bentonite within the GCL to rapidly absorb water and expand, thereby closing the voids and reducing permeability.

This behaviour is particularly advantageous in the case of micro-cracks or small defects in the GCL, which can be sealed automatically when the bentonite expands.

The matrix tortuosity, defined as the ratio of the effective path length that a solute particle will have to face to migrate out of the membrane over a direct linear distance between two points, is generally higher in GCLs (in the following study placed 10% higher than the relative tortuosity of CCLs) due to the fine structure of bentonite and the expansion behaviour of the material.

Shown in the figure representing the Landfill section and bottom barrier in particular, we have three different concentrations considering precisely the bistrate configuration for analysis, c_p, representing the concentration at the interface between leachate and GCL (or CCL), c_i, representing the concentration at the interface between the GCL (or CCL) layer and the AL attenuation layer (unknown in the problem), and c_b, the concentration at the exit of the barrier layers, towards the underlying aquifer.

The latter is set equal to 0($c_b = 0\ mol/m^3$) thus assuming a perfect flushing situation.

The piezometric heights are set equal to:

- $h_p = 0{,}5\ m$piezometric height of landfill leachate;
- h_i piezometric height at the interface, the unknown of the problem;
- $h_b = 0$.

The volume flow equation q for the first layer can be rewritten as:

$$q_1 = k_1 \frac{H_1 + h_p - h_i}{H_1} - (\nu_c + \nu_a) RT \frac{k_1}{\gamma_w} \omega_1 \frac{c_{p-} c_i}{H_1}$$

Similarly for the second layer, we have:

$$q_2 = k_2 \frac{H_2 + h_i - h_b}{H_2} - (\nu_c + \nu_a) RT \frac{k_2}{\gamma_w} \omega_2 \frac{c_{i-}c_b}{H_2}$$

The contaminant flux J_s [mol/(m2·s)] relative to the first thickness is given by:

$$J_1 = (1 - \omega_1) q_1 \frac{c_p \exp\left(\frac{q_1 H_1}{n_1 D_1^*}\right) - c_i}{\exp\left(\frac{q_1 H_1}{n_1 D_1^*}\right) - 1}$$

With $D_1^* = D_0 \cdot \tau_{m1}$

Similarly, for the second layer you have:

$$J_2 = (1 - \omega_2) q_2 \frac{c_p \exp\left(\frac{q_2 H_2}{n_2 D_2^*}\right) - c_b}{\exp\left(\frac{q_2 H_2}{n_2 D_2^*}\right) - 1}$$

With $D_2^* = D_0 \cdot \tau_{m2}$

In the equations just shown, we have:

- ν_c, ν_a representing the stoichiometric coefficients of the cation and anion of the salts considered, which will be specified below;
- $R$the universal gas coefficient of 8.314 N m $mol^{-1}K^{-1}$, T;
- $T$the absolute temperature in Kelvin, which is 298.15 K;
- $\gamma_w$the weight per unit volume of water, which is 10000 (N/m3);
- $D_0$the diffusion coefficient in free solution of the solute (contaminant) considered and specified below.

A review of the literature on leachate from waste landfills, including its formation and the composition and concentration of chemical species present (Leachate and biogas production in controlled landfills: analysis with mathematical and physical models – Katerina Babikova, 2018), reveals that chlorine is the chemical species most frequently present and with the most important volumes within landfill leachate. Furthermore, it is identified as the most dangerous. Consequently, studies were conducted with regard to salts formed from chlorine as an anionic species.

- Ammonium chloride NH_4Cl;
- Magnesium chloride $MgCl_2$;
- Potassium chloride KCl;
- Calcium chloride $CaCl_2$;
- Sodium chloride $NaCl$.

The respective effective diffusion coefficients, calculated according to the previously stated theory of Yuan-Hui Li, Sandra Gregory are shown below:

EFFECTIVE DIFFUSION COEFFICIENT

	$D_{0,cat}$	$D_{0,anion}$	ν_c	ν_a	D_0
NH4Cl	1,98E-09	2,03E-09	1	1	2,00E-09
MgCl2	7,05E-10	2,03E-09	1	2	1,25E-09
KCl	1,96E-09	2,03E-09	1	1	1,99E-09
CaCl2	7,93E-10	2,03E-09	1	2	1,34E-09
NaCl	1,33E-09	2,03E-09	1	1	1,61E-09

Table 4.3 Effective diffusion coefficient of target chemical species

At this point, as mentioned earlier, the unknowns of the system are the concentration of the solute c_i at the interface and the piezometric height $h_i$which will be obtained by imposing the condition of continuity of the flows in the bistrate system.

The two equations of the algebraic system with two unknowns will be precisely:

I. $q_1 = q_2$

II. $J_1 = J_2$

Implementing the iterative calculation using Excel, the initial unknowns and above all the solution volume flow were derived q_2 and in a completely preliminary manner the mass in tonnes per year of solute passing through the barrier to the outside of the barrier layer of the landfill J_2.

For which, one has:

CCLs	c_i	h_i	q_1	q_2	J_1	J_2
	(mol/m^3)	(m)	(m/s)	(m/s)	(mol/(m^2·s))	(mol/(m^2·s))
NH4Cl	84,16	-2,87	4,37E-09	4,37E-09	3,68E-07	3,68E-07
MgCl2	47,32	-2,87	4,37E-09	4,37E-09	2,07E-07	2,07E-07
KCl	63,94	-2,87	4,37E-09	4,37E-09	2,79E-07	2,79E-07
CaCl2	56,41	-2,87	4,37E-09	4,37E-09	2,46E-07	2,46E-07
NaCl	112,83	-2,87	4,37E-09	4,37E-09	4,93E-07	4,93E-07

Table 4.4 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (CCLs)

NH4Cl	GCLs					
	c_i	h_i	q_1	q_2	J_1	J_2
ω_1 (-)	(mol/m^3)	(m)	(m/s)	(m/s)	(mol/(m^2·s))	(mol/(m^2·s))
0	84,16	-2,90	3,41E-09	3,41E-09	2,87E-07	2,87E-07
0,1	83,49	-2,90	3,38E-09	3,38E-09	2,82E-07	2,82E-07
0,2	82,71	-2,90	3,27E-09	3,27E-09	2,70E-07	2,70E-07
0,22	82,55	-2,90	3,24E-09	3,24E-09	2,67E-07	2,67E-07
0,25	82,29	-2,90	3,18E-09	3,18E-09	2,62E-07	2,62E-07
0,28	82,03	-2,91	3,12E-09	3,12E-09	2,56E-07	2,56E-07
0,3	81,85	-2,91	3,07E-09	3,07E-09	2,52E-07	2,52E-07
0,32	81,67	-2,91	3,02E-09	3,02E-09	2,47E-07	2,47E-07
0,33	81,58	-2,91	3,00E-09	3,00E-09	2,45E-07	2,45E-07
0,4	80,93	-2,92	2,79E-09	2,79E-09	2,25E-07	2,25E-07
0,5	80,00	-2,93	2,41E-09	2,41E-09	1,93E-07	1,93E-07

Table 4.5 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (GCLs)

MgCl2	GCLs					
	c_i	h_i	q_1	q_2	J_1	J_2
ω_1 (-)	(mol/m^3)	(m)	(m/s)	(m/s)	(mol/(m^2·s))	(mol/(m^2·s))
0	47,32	-2,90	3,41E-09	3,41E-09	1,61E-07	1,61E-07
0,1	46,73	-2,90	3,37E-09	3,37E-09	1,57E-07	1,57E-07
0,2	46,07	-2,90	3,23E-09	3,23E-09	1,49E-07	1,49E-07
0,22	45,93	-2,90	3,19E-09	3,19E-09	1,46E-07	1,46E-07
0,25	45,72	-2,91	3,12E-09	3,12E-09	1,43E-07	1,43E-07
0,28	45,50	-2,91	3,04E-09	3,04E-09	1,38E-07	1,38E-07
0,3	45,36	-2,91	2,98E-09	2,98E-09	1,35E-07	1,35E-07
0,32	45,22	-2,91	2,92E-09	2,92E-09	1,32E-07	1,32E-07
0,33	45,15	-2,91	2,89E-09	2,89E-09	1,30E-07	1,30E-07
0,4	44,65	-2,92	2,64E-09	2,64E-09	1,18E-07	1,18E-07
0,5	43,99	-2,93	2,21E-09	2,21E-09	9,71E-08	9,71E-08

Table 4.6 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (GCLs)

KCl	GCLs					
	c_i	h_i	q_1	q_2	J_1	J_2
ω_1 (-)	(mol/m^3)	(m)	(m/s)	(m/s)	(mol/(m^2·s))	(mol/(m^2·s))
0	63,94	-2,90	3,41E-09	3,41E-09	2,18E-07	2,18E-07
0,1	63,43	-2,90	3,38E-09	3,38E-09	2,15E-07	2,15E-07
0,2	62,83	-2,90	3,30E-09	3,30E-09	2,07E-07	2,07E-07
0,22	62,70	-2,90	3,28E-09	3,28E-09	2,05E-07	2,05E-07
0,25	62,49	-2,90	3,23E-09	3,23E-09	2,02E-07	2,02E-07
0,28	62,28	-2,90	3,18E-09	3,18E-09	1,98E-07	1,98E-07
0,3	62,14	-2,91	3,15E-09	3,15E-09	1,96E-07	1,96E-07
0,32	61,99	-2,91	3,11E-09	3,11E-09	1,93E-07	1,93E-07
0,33	61,91	-2,91	3,09E-09	3,09E-09	1,91E-07	1,91E-07
0,4	61,37	-2,91	2,91E-09	2,91E-09	1,79E-07	1,79E-07
0,5	60,54	-2,92	2,59E-09	2,59E-09	1,57E-07	1,57E-07

Table 4.7 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (GCLs)

CaCl	GCLs					
	c_i	h_i	q_1	q_2	J_1	J_2
ω_1 (-)	(mol/m^3)	(m)	(m/s)	(m/s)	(mol/(m^2·s))	(mol/(m^2·s))
0	56,41	-2,90	3,41E-09	3,41E-09	1,92E-07	1,92E-07
0,1	55,75	-2,90	3,36E-09	3,36E-09	1,87E-07	1,87E-07
0,2	55,02	-2,90	3,21E-09	3,21E-09	1,76E-07	1,76E-07
0,22	54,86	-2,91	3,16E-09	3,16E-09	1,73E-07	1,73E-07
0,25	54,63	-2,91	3,09E-09	3,09E-09	1,69E-07	1,69E-07
0,28	54,40	-2,91	3,00E-09	3,00E-09	1,63E-07	1,63E-07
0,3	54,24	-2,91	2,94E-09	2,94E-09	1,59E-07	1,59E-07
0,32	54,09	-2,91	2,87E-09	2,87E-09	1,55E-07	1,55E-07
0,33	54,01	-2,91	2,84E-09	2,84E-09	1,53E-07	1,53E-07
0,4	53,49	-2,92	2,57E-09	2,57E-09	1,37E-07	1,37E-07
0,5	52,82	-2,94	2,11E-09	2,11E-09	1,12E-07	1,12E-07

Table 4.8 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (GCLs)

NaCl	GCLs					
	c_i	h_i	q_1	q_2	J_1	J_2
ω_1 (-)	(mol/m^3)	(m)	(m/s)	(m/s)	($mol/(m^2 \cdot s)$)	($mol/(m^2 \cdot s)$)
0	112,83	-2,90	3,41E-09	3,41E-09	3,84E-07	3,84E-07
0,1	111,73	-2,90	3,35E-09	3,35E-09	3,75E-07	3,75E-07
0,2	110,50	-2,90	3,18E-09	3,18E-09	3,52E-07	3,52E-07
0,22	110,25	-2,91	3,13E-09	3,13E-09	3,46E-07	3,46E-07
0,25	109,87	-2,91	3,05E-09	3,05E-09	3,35E-07	3,35E-07
0,28	109,49	-2,91	2,96E-09	2,96E-09	3,24E-07	3,24E-07
0,3	109,24	-2,91	2,89E-09	2,89E-09	3,16E-07	3,16E-07
0,32	108,99	-2,92	2,82E-09	2,82E-09	3,07E-07	3,07E-07
0,33	108,86	-2,92	2,78E-09	2,78E-09	3,02E-07	3,02E-07
0,4	108,04	-2,93	2,49E-09	2,49E-09	2,69E-07	2,69E-07
0,5	107,03	-2,94	2,01E-09	2,01E-09	2,15E-07	2,15E-07

Table 4.9 Contaminant flux J (mol/(m2·s)) computation, passing through bottom barrier (GCLs)

Flows J_2, in $mol/(m^2 \cdot s)$, are largely stationary at values in the order of 10^{-7}, registering significantly higher quantities for the case of the barrier layer in CCL.

The bentonite geocomposite flow trend J_2, in $mol/(m^2 \cdot s)$, tends to decrease with the increase of the omega reflection coefficient, as is easily desirable, as the membrane behaviour of the GCL is gradually increased and the mitigation of the contaminant flux is gradually reduced, up to the order of 10^{-8}, for some salts considered with an osmotic chemical efficiency coefficient of 0.5.

The parametric analysis, by allowing the value of the reflection coefficient ω_1 relative to the GCL layer, between 0 and 0.5 allows us to understand the influence that chemical-osmotic efficiency has on the proper functioning of the barrier acting as a semi-permeable membrane in the case of geocomposites.

The calculated results are condensed below, expressing the J flux in tonnes per year for GCLs:

Contaminant flow through bottom layer - GCLs

	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(t/year)	(t/year)	(t/year)	(t/year)	(t/year)
0	4,84	4,84	5,12	6,73	7,09
0,1	4,75	4,72	5,04	6,56	6,91
0,2	4,56	4,46	4,88	6,17	6,48
0,22	4,51	4,40	4,83	6,07	6,37
0,25	4,42	4,28	4,75	5,90	6,18
0,28	4,32	4,15	4,66	5,71	5,97
0,3	4,24	4,06	4,60	5,58	5,82
0,32	4,17	3,97	4,53	5,44	5,66
0,33	4,12	3,92	4,49	5,36	5,57
0,4	3,80	3,54	4,20	4,80	4,95
0,5	3,25	2,92	3,69	3,91	3,97

Table 4.10 Contaminant flux J (t/year) computation, passing through bottom barrier (GCLs)

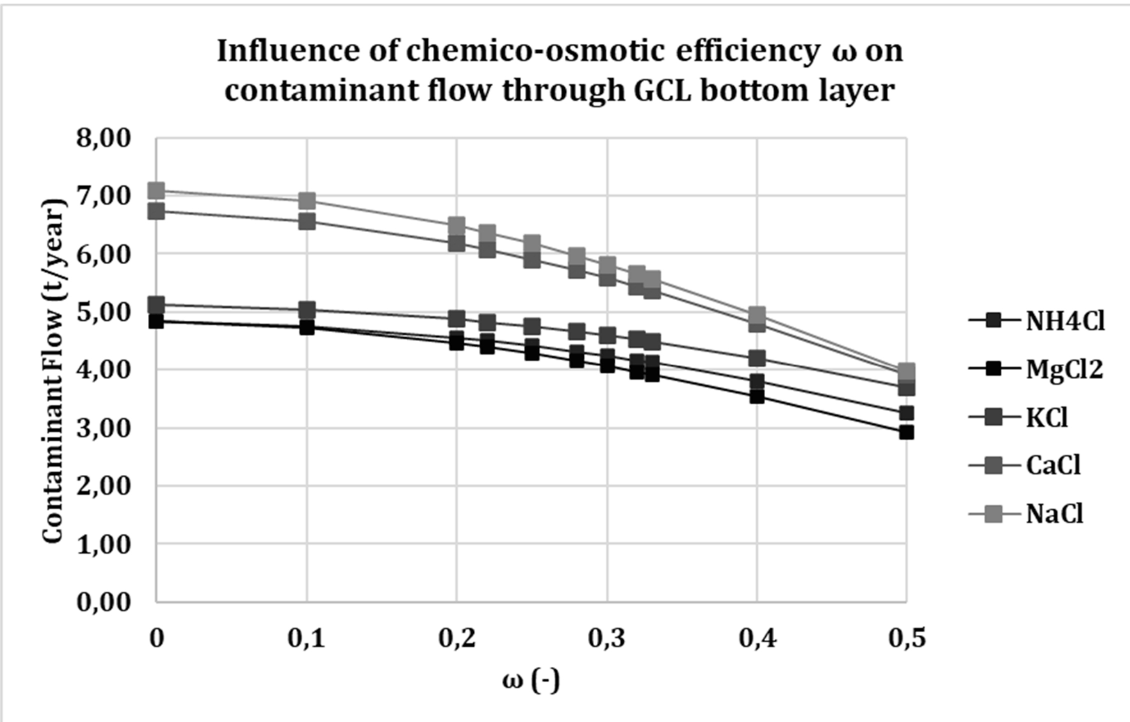

Figure 4.4 Influence of chemico-osmotic efficiency ω on contaminant flow through GCL bottom layer

The graph above illustrates that when the GCL layer functions as a semi-permeable membrane (ω=0.5), the contaminant flux past the barrier layer is reduced by approximately one-third compared to a less significant membrane behaviour, which would occur for much lower values of ω.

A further environmental comparison, of mass release of contaminant outside the landfill, tends even more towards bentonite geocomposites if the contaminant flux values obtained for CCLs (with a ω value of 0, characteristic of compacted clay layers, not assuming semi-permeable membrane behaviour) are combined.

Contaminant flow through bottom layer - CCLs

	NH4Cl	**MgCl2**	**KCl**	**CaCl2**	**NaCl**
ω_1 (-)	(t/year)	(t/year)	(t/year)	(t/year)	(t/year)
0	6,20	6,21	6,57	8,63	9,08

Table 4.11 Contaminant flux J (t/year) computation, passing through bottom barrier (CCLs)

Comparing the obtained contaminant fluxes crossing the two different bottom barriers with GCL and with CCL, it can be stated that the contaminant fluxes crossing the layers composed of bentonite geosynthetics, represent only 52.4% when considering NH4Cl, even lower and more precisely 47% when analysing MgCl2, 56.1% of KCl, 45.3% CaCl2 and closing with 43.7% of NaCl.

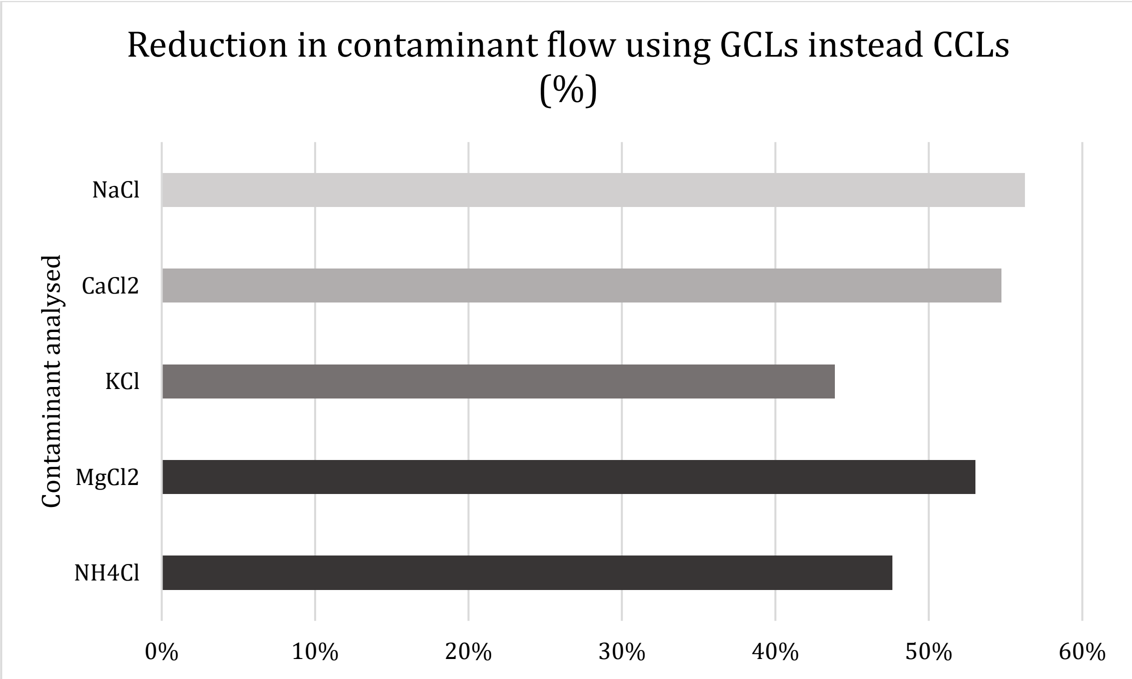

Figure 4.5 Reduction in contaminant flow using GCLs instead CCLs (%)

The graph illustrates the percentage reduction in contaminant flux when Geosynthetic Clay Liners (GCL) are employed in lieu of Compacted Clay Liners (CCL), with consideration given to the various contaminants analysed: NaCl, $CaCl_2$, KCl, $MgCl_2$ and NH_4Cl. The graph illustrates the remarkable efficacy of bentonite geocomposites in mitigating contaminant fluxes. The reduction in contaminant fluxes when using GCLs instead of CCLs is consistently approximately 50%, with the greatest reduction observed for NaCl and $CaCl_2$ (approximately 55%). The overall analysis indicates that GCLs outperform CCLs in retaining contaminants, with the effectiveness varying depending on the type of ion analysed.

This variability can be attributed to several factors, including ionic interactions (ions with a higher charge (such as Mg^{2+}) tend to interact more strongly with bentonite, thereby improving the barrier's effectiveness), ionic size (smaller ions may have greater mobility through the porous structure, which affects the degree of confinement), and bentonite behaviour (the swelling capacity of bentonite in GCLs creates a low-permeability structure that restricts the flow of contaminants, a phenomenon that is less pronounced in CCLs).

4.1.1 Water pollution potential (WPP)

The study continues with the calculation of the concentration of contaminant that, once in the aquifer below the landfill, exceeds the planar extension of the landfill itself (l=100 m). This is done until it reaches sensitive points close to the waste landfill site, such as inhabited areas and crops, which represent an environmental hazard as well as a health hazard for the living beings in these areas.

Subsequently, the concentrations identified will be evaluated in comparison with the regulatory limit values set forth in Legislative Decree 31/2001, which implements Directive 98/83/EC on the quality of water intended for human consumption. This provides a benchmark for assessing the potential risk of groundwater contamination, assuming that the water is intended for human consumption.

Once the contaminant flow, J_s, has been calculated through the barrier by performing a mass balance just below the landfill considered in the project, the concentration of contaminant flowing into the aquifer can be derived.

In particular, with reference to the diagram in the figure, we have:

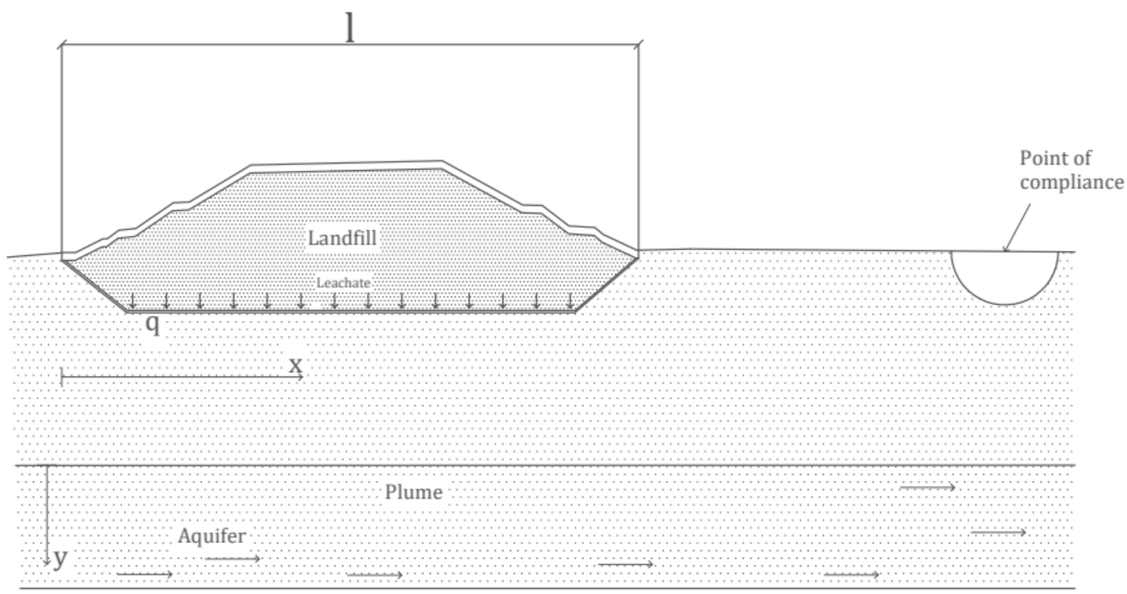

Figure 4.6 Landfill section and aquifer particular

In this regard, we have an extension l equal to 100 m of the considered analysis landfill, a height of the underlying aquifer equal to H=10 m considering an average thin aquifer with a height equal to 1/10 of the extension (*source Dominijanni, Manassero - Environmental Geotechnics 2019*), a flow rate q_x [L/T] relative to the aquifer equal to $1 \cdot 10^{-6}$ m/s (=31.6 m/year) *(source Dominijanni, Manassero - Environmental Geotechnics 2019*), proceeding as described, it will be possible to derive the concentration downstream of the landfill.

The initial assumptions take into account that at x=0 (i.e. exactly from the initial point of the landfill extension), the aquifer will be free of contaminant. Furthermore, the flow rate q_x below the landfill, will be kept constant along x despite the fact that the contribution through the barrier and into the aquifer is not 0.

The mass balance results:

$$J_s \cdot l = q_x \cdot c_{(x=l)} \cdot H$$

Where c $\left[{}^{mol}/_{m^3}\right]$ will be the concentration at the outlet of the unknown landfill extension:

$$c_{(x=l)} = \frac{J_s \cdot l}{q_x \cdot H} = \left[{}^{mol}/_{m^3}\right]$$

At this point, having derived the concentrations flowing downstream of the landfill, for the contaminants considered above, which are shown below:

	Concentration at the landfill outflow [mol/m3]				
GCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)
0	2,87	1,61	2,18	1,92	3,84
0,1	2,82	1,57	2,15	1,87	3,75
0,2	2,70	1,49	2,07	1,76	3,52
0,22	2,67	1,46	2,05	1,73	3,46
0,25	2,62	1,43	2,02	1,69	3,35
0,28	2,56	1,38	1,98	1,63	3,24
0,3	2,52	1,35	1,96	1,59	3,16
0,32	2,47	1,32	1,93	1,55	3,07
0,33	2,45	1,30	1,91	1,53	3,02
0,4	2,25	1,18	1,79	1,37	2,69
0,5	1,93	0,97	1,57	1,12	2,15

Table 4.12 Table 4.13 Concentration at landfill outflow -GCLs

	Concentration at the landfill outflow				
CCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)
0	3,68	2,07	2,79	2,46	4,93

Table 4.14 Concentration at landfill outflow -CCLs

The mass of contaminant was calculated J_s crossing the section and thus reaching the areas considered sensitive, (with the variable chemical-osmotic coefficient for GCLs) first in mol per day;

Mass of contaminant crossing the section (and therefore reaching sensitive areas) per day

GCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(mol)	(mol)	(mol)	(mol)	(mol)
0	247,79	139,32	188,26	166,09	332,21
0,1	243,50	135,89	185,40	161,88	323,86
0,2	233,59	128,46	179,16	152,43	303,95
0,22	230,87	126,47	177,45	149,90	298,56
0,25	226,30	123,19	174,59	145,71	289,63
0,28	221,15	119,54	171,34	141,06	279,74
0,3	217,39	116,92	168,97	137,73	272,64
0,32	213,37	114,15	166,41	134,21	265,16
0,33	211,27	112,72	165,07	132,39	261,29
0,4	194,78	101,74	154,44	118,55	232,09
0,5	166,39	83,90	135,51	96,44	186,15

Mass of contaminant crossing the section (and therefore reaching sensitive areas) per day

CCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(mol)	(mol)	(mol)	(mol)	(mol)
0	317,95	178,85	241,06	212,54	425,95

Table 4.15 Mass of contaminant crossing the section (mol por day)

To conclude in grams per day:

Mass of contaminant crossing the section (and therefore reaching sensitive areas) per day

GCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(g)	(g)	(g)	(g)	(g)
0	13,25	13,27	14,03	18,43	19,41
0,1	13,02	12,94	13,82	17,97	18,93
0,2	12,49	12,23	13,36	16,92	17,76
0,22	12,35	12,04	13,23	16,64	17,45
0,25	12,10	11,73	13,02	16,17	16,93
0,28	11,83	11,38	12,77	15,66	16,35
0,3	11,63	11,13	12,60	15,28	15,93
0,32	11,41	10,87	12,41	14,89	15,50
0,33	11,30	10,73	12,31	14,69	15,27
0,4	10,42	9,69	11,51	13,16	13,56
0,5	8,90	7,99	10,10	10,70	10,88

Mass of contaminant crossing the section (and therefore reaching sensitive areas) per day

CCLs	NH4Cl	MgCl2	KCl	CaCl2	NaCl
ω_1 (-)	(g)	(g)	(g)	(g)	(g)
0	17,01	17,03	17,97	23,59	24,89

Table 4.16 Mass of contaminant crossing the section (g por day)

It can be observed that, while a moderate chemical-osmotic efficiency can be considered for the geocomposite bottom barrier layer, with ω=0.5 (semi-permeable membrane behaviour of moderate GCLs), the concentration values flowing downstream of the landfill (i.e. beyond the site extension assumed to be l=100 m) demonstrate a ratio that is indicative of GCLs in terms of environmental impact and risk.

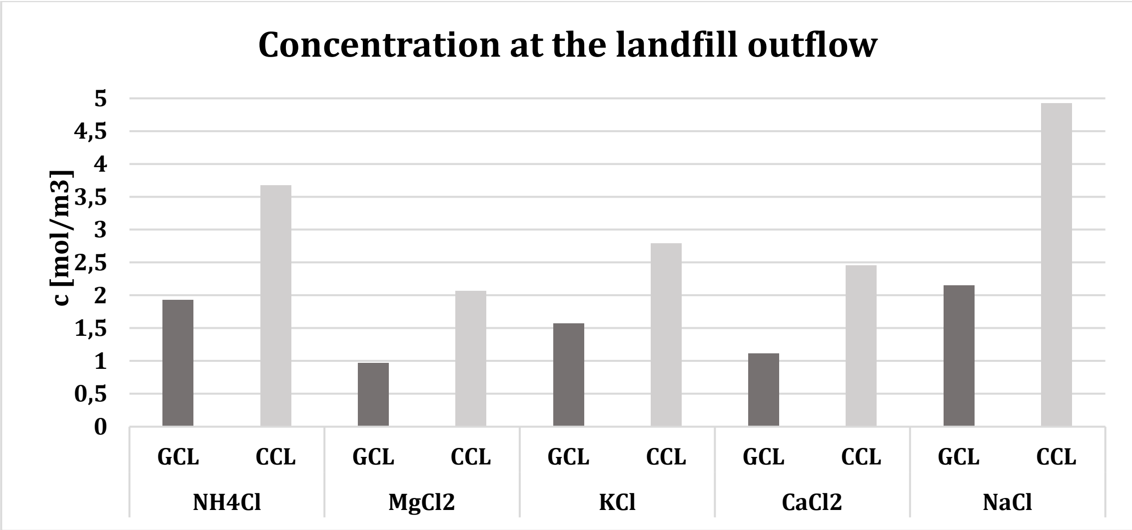

Figure 4.7 Concentration at the landfill outflow

The concentrations obtained will, in fact, be proportional to the masses of contaminant arriving downstream from the landfill. This represents a potential danger to inhabited areas, crops and, more generally, to the aquifers flowing below the waste dumps.

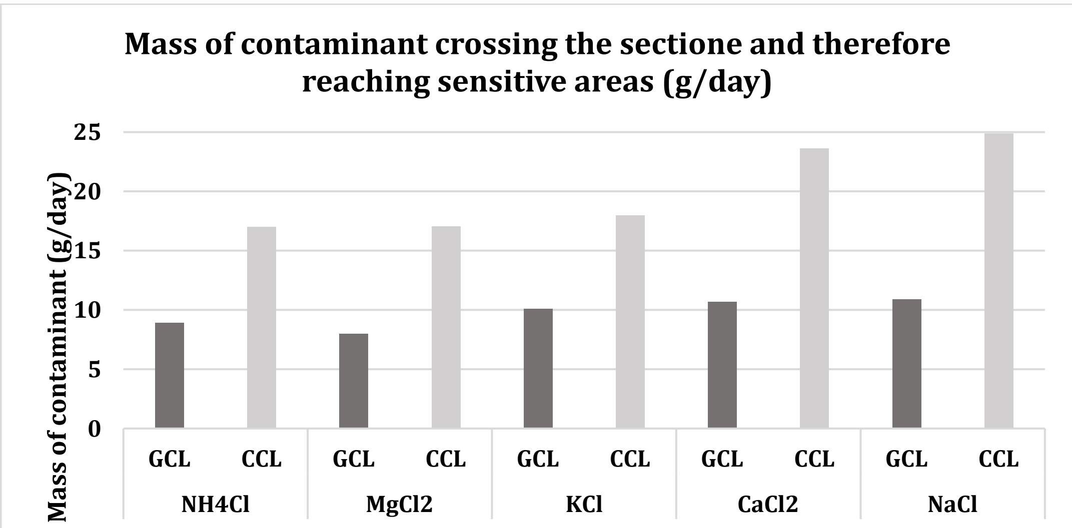

Figure 4.8 Mass of contaminant crossing the sectione and therefore reaching sensitive areas (g/day)

Resuming previously calculated concentrations:

	NH4Cl	MgCl2	KCl	CaCl2	NaCl
	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)	(mol/m3)
GCLs	1,93	0,97	1,57	1,12	2,15
CCLs	3,68	2,07	2,79	2,46	4,93

Table 4.17 Concentration of contaminant at landfill outflow

A comparison of the pollution potential impacted by different design choices is to be made with GCLs rather than CCLs.

The analysis considers the polluting potential of chloride ions Cl^- from the different salts (NH_4Cl, $MgCl_2$, KCl, $CaCl_2$ and NaCl) in aquifers. A comparison is made between the maximum concentration values set by the regulations of Legislative Decree 31/2001, which implements Directive 98/83/EC on the quality of water intended for human consumption, and the limit concentration of 250 mg/L for chlorides Cl^-in water intended for human consumption have a limit concentration of 250 mg/L.

The data will be presented in the form of percentages, with a comparison of the chloride concentration obtained in the aquifer with the regulatory limits:

$$Water\ Pollution\ Potential = \frac{Cl^- Concentration\ (\frac{mg}{L})}{Limit\ Concentration\ (\frac{mg}{L})}$$

For the concentrations obtained, we have:

	[Cl-] Concentration (mg/L) GCL	[Cl-] Concentration (mg/L) CCL	WPP(%) GCL	WPP(%) CCL	Limit [Cl-] concentration (mg/L)
NH4Cl	68,42	130,46	27,4%	52,2%	250
MgCl2	68,27	146,79	27,3%	58,7%	
KCl	55,67	98,92	22,3%	39,6%	
CaCl2	79,82	174,26	31,9%	69,7%	
NaCl	76,22	174,73	30,5%	69,9%	

Table 4.18 Potential pollution of water intended for human consumption (%)

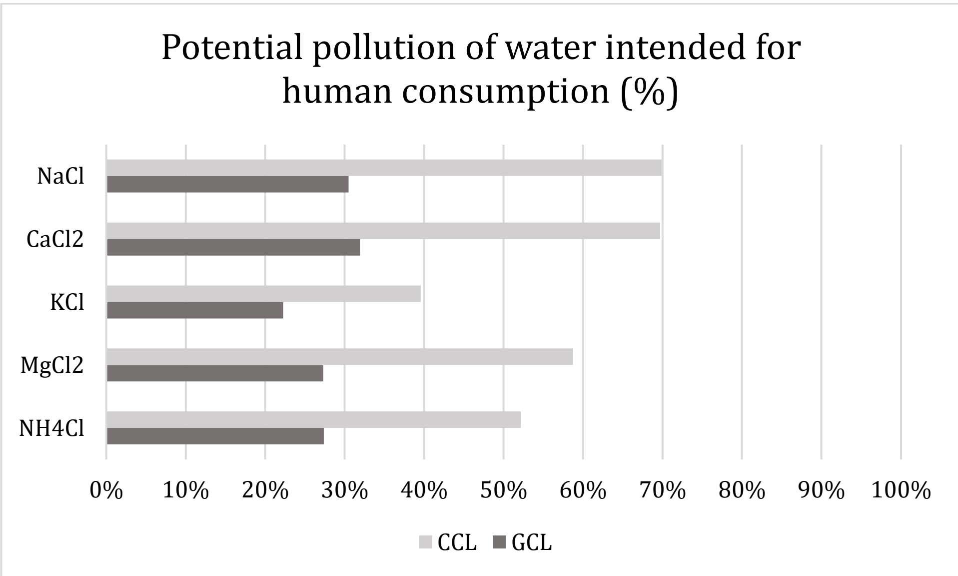

Figure 4.9 Potential pollution of water intended for human consumption (%)

The analysis demonstrates that the concentration of chloride ions associated with salt is markedly lower than the regulatory threshold of 250 mg/L for both barrier types. However, the pollutant potential is observed to be higher for CCL barriers than for GCL barriers.

This result indicates that under identical conditions and initial salt concentrations, CCLs release a greater quantity of pollutant ions than GCLs, exhibiting a higher pollutant potential.

CONCLUSIONS

This study focuses on the environmental assessment of bentonite geocomposites, a more recent and technologically advanced design solution compared to more traditional methods made of compacted clay (CCLs). The objective was to compare the effectiveness of the two types of barriers in reducing the flow of contaminants, both in the liquid and gas phase, and to identify the advantages and limitations of each depending on the operating conditions.

The analysis of the transport of contaminants in the liquid phase demonstrated that both the GCL and CCL barriers are capable of providing effective protection against the mitigation of the spread of contaminated liquids. However, significant differences were observed in terms of permeability in relation to the expected design thickness and the potential pollutant represented.

CCLs, composed of compacted clay, demonstrate a higher permeability than GCLs, which consist of layers of sodium bentonite sandwiched between geotextiles and exhibit comparable performance despite the use of very thin design thicknesses.

The permeability of CCLs varies between the order of 10^{-9} and 10^{-10} m/s, while GCLs offer a much more effective barrier layer, with permeabilities of the order of 10^{-10} 10^{-12}m/s.

This discrepancy can be attributed to the swelling properties of bentonite in contact with water or when properly hydrated, which results in the formation of an impermeable gel that markedly enhances performance.

This phenomenon is elucidated in Chapters 3 and 4, wherein the behaviour of GCL barriers is examined as a function of proper hydration.

With regard to the transport of gas-phase contaminants, both types of barriers exhibited comparable behaviour, with gas permeability being markedly sensitive to the water content of the barrier.

The presence of bentonite in GCLs results in a significant reduction in gas permeability as the degree of hydration increases, as mentioned.

This characteristic enables bentonite geocomposites to function as effective barriers for the containment of biogas and other noxious gases produced by the decomposition of waste in landfills.

Conversely, CCLs may be less effective in confining gases if not maintained under optimal saturation conditions, as gases tend to migrate more easily through open pores in a material that is not fully saturated.

A principal objective of this study was to evaluate the comparative performance of GCLs as an alternative to more conventional CCL techniques. This involved an examination of their behaviour in terms of contaminant flux in solution, as well as an analysis of the carbon footprint associated with different life cycle stages.

From a technical standpoint, GCLs offer superior performance in terms of permeability and adaptability to various operating scenarios, particularly in the presence of highly saturated conditions or liquid contaminants. This is largely attributed to the semi-permeable membrane behaviour of bentonite, which is discussed in greater detail in Chapter 4.

In terms of installation, bentonite geocomposites are demonstrably more cost-effective, requiring less time and fewer resources than CCLs.

The reduced operational complexity associated with GCLs also serves to reduce the risk of human error during installation, which is a crucial factor in ensuring the long-term integrity of the barrier.

An evaluation of the environmental impact of the two design solutions studied in terms of sustainability and carbon footprint reveals that geosynthetics offer a significant advantage in terms of environmental sustainability. This is due to the less impactful production and transport of geosynthetics in terms of CO_2 emissions, which is a consequence of their in-depth performance in mitigating the flow of contaminants in both liquid and gaseous solutions.

Furthermore, the transportation of compacted clay necessitates the use of a considerably larger quantity of material, which in turn results in an elevated level of CO_2 emissions.

The findings of this study present promising avenues for future research in environmental engineering, particularly with regard to the utilisation of GCLs as the primary means of constructing impermeable barriers in landfill sites and other waste management facilities.

The thesis was developed by focusing on a comparison of the environmental impact and equivalence of the two design solutions studied, employing a series of simplifications in the hypotheses.

Consequently, it does not aim to provide definitive predictions regarding actual behaviour or the quantification of contaminant leakage from the landfill.

Instead, it recommends that further verifications be carried out by adapting the proposed procedures with new methods and models.

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