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Role of Clay Liners in Municipal Solid Waste Landfills: A Review

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Abstract

Rapid population growth has significantly increased the generation of municipal solid waste (MSW) in urban and suburban regions. Disposal of MSW in landfills without proper liner systems may lead to leachate migration and subsequent contamination of groundwater and surrounding soils. The use of liner systems at the base of landfills is therefore essential to minimize leachate percolation and protect the environment. Geosynthetic clay liners (GCLs) and compacted clay liners (CCLs) are commonly used as barrier materials in modern landfill systems. GCLs generally consist of a bentonite layer encapsulated between geotextiles and bonded through needle punching or stitching techniques, whereas CCLs are prepared using compacted natural soils mixed with bentonite or other additives to achieve the required hydraulic conductivity, strength, and durability characteristics. CCLs are comparatively economical and possess good contaminant attenuation capacity, while GCLs provide very low hydraulic conductivity and ease of installation. However, CCLs require greater thickness compared to GCLs for effective performance. The hydraulic conductivity of CCLs is strongly influenced by moisture content and compaction conditions during construction. Since natural clay resources are limited and non-renewable, locally available soils are often modified using bentonite and other stabilizing materials to satisfy liner design criteria. This review summarizes the design requirements of clay liners and discusses the geotechnical characteristics of various liner materials, including clay–bentonite, dune sand–bentonite, fly ash–bentonite, rice husk ash–soil, and quarry dust–bentonite mixtures. This review critically evaluates the role of clay liners in controlling leachate migration from MSW landfills.

Keywords: Municipal solid waste landfill, compacted clay liners, geosynthetic clay liners, hydraulic conductivity, bentonite, geotechnical properties

INTRODUCTION

Over the last few decades, population growth and urbanization have substantially increased the generation of municipal solid waste (MSW) worldwide [1]. According to Kaza et al. (2018), approximately 2.01 billion tonnes of municipal solid waste were generated globally in 2016, and this quantity is expected to increase to 3.40 billion tonnes by 2050 if current waste generation and management practices continue. Among the available waste disposal techniques, sanitary landfilling remains one of the most commonly adopted methods because of its economic feasibility, particularly in developing countries [2]. However, improper landfill management and leachate migration can result in severe contamination of groundwater and surrounding soils. Therefore, effective liner systems are essential to minimize the movement of contaminants from landfill sites into the environment.

Clay barriers have received considerable attention in environmental and geotechnical engineering because of their ability to control leachate migration and reduce groundwater

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pollution [1]. According to Nath et al. (2023), landfill liners act as protective barriers that restrict the downward movement of leachate and harmful contaminants into underlying aquifers and nearby water bodies [3]. Compacted clay liners (CCLs) are widely used because of their low hydraulic conductivity, satisfactory swelling behaviour, and adequate shear strength. However, locally available soils may not always satisfy the required liner specifications, necessitating the use of additives such as bentonite to improve engineering properties. Bentonite enhances the cohesion and sealing capacity of soils and significantly reduces hydraulic conductivity. Garg et al. (2020) reported that the permeability of compacted clay liners should generally be less than or equal to 1.0×10^{-7} cm/s to effectively control contaminant transport. In addition to natural clay liners, sand–bentonite mixtures and other amended soils are also used as engineered barriers in landfill systems [4].

Geosynthetic clay liners (GCLs) have emerged as an effective alternative to conventional compacted clay liners. GCLs generally consist of a thin layer of sodium or calcium bentonite enclosed between geotextiles or bonded with geomembranes. Compared with CCLs, GCLs offer several advantages, including low hydraulic conductivity, improved mechanical performance, ease of installation, and reduced construction thickness [5]. By exchanging the bulk of the compacted clay for a thin coating of pure sodium bentonite, GCLs provide an effective alternative to compacted clay liners [6]. Some recent studies have shown that compacted clay liners are still preferred as natural materials [7]; however, saving natural resources should also be taken into consideration. More than about 1 billion m^2 of GCL has been used worldwide up to now, saving about 1 million tons of natural clay. In other words, by using a needle punched GCL instead of 0.5 m thick CCL, there is no need to excavate about 1 billion tons of natural clay [8]. Earthen liners have been widely used to contain waste materials in landfill [9]. Considering the environmental impact of municipal solid waste disposal, this review focuses on the role of clay liners in controlling leachate migration and protecting groundwater systems. The paper also discusses the design requirements of compacted clay liners and summarizes the geotechnical characteristics of different soil–bentonite and industrial waste-based liner materials.

TYPES OF CLAY LINERS USED IN MSW LANDFILLS

According to Al-Soudany et al. (2024) [1], modern landfill systems generally employ two major categories of liners: synthetic liners, commonly manufactured from high-density polyethylene (HDPE), and natural liners, which are primarily composed of compacted clay materials. Compacted clay barriers have been widely used for controlling the migration of toxic leachates from landfill sites. To ensure effective containment performance, the liner material should generally possess a hydraulic conductivity less than or equal to 1.0×10^{-9} m/s and an unconfined compressive strength of at least 200 kPa. Because of their low cost, ease of construction, and contaminant attenuation capacity, CCLs are extensively used in landfill liner systems.

CCLs are generally preferred where suitable natural soils are locally available. These liners provide low permeability and good contaminant adsorption characteristics; however, excessive swelling, shrinkage, and desiccation cracking may adversely affect their long-term stability and performance. In contrast, GCLs exhibit very low hydraulic conductivity and can be installed rapidly under field conditions. GCLs also demonstrate good resistance against environmental degradation such as freeze–thaw and wet–dry cycles. Typically, GCLs consist of a thin layer of sodium or calcium bentonite sandwiched between geotextile layers or bonded with geomembranes. The bentonite used in GCLs is generally available in granular or powdered form. In landfill applications, CCLs commonly require a thickness of approximately 0.75–1.0 m [9], whereas the thickness of GCLs generally ranges from 5 mm to 12 mm [10].

Geosynthetic Clay Liners

GCLs are factory-manufactured hydraulic barrier systems consisting of a thin layer of bentonite clay placed between geotextiles and/or geomembranes. These components are bonded together using needling, stitching, or chemical adhesives. The internal shear strength of GCLs is influenced by several factors, including the properties of bentonite, the arrangement of needle-punched or stitched fibres penetrating through the liner thickness, and the type of adhesive used to bind the bentonite to the geotextile layers [11].

According to Kong et al. (2017), bentonite used in GCLs exhibits extremely low hydraulic conductivity and high swelling potential, making GCLs highly effective as hydraulic barriers in landfill systems. Hydraulic conductivity is considered one of the most important parameters governing the performance of GCLs [5]. The swelling and creep behaviour of bentonite helps to maintain low permeability and enhances the sealing performance of the liner. Typically, the hydraulic conductivity of bentonite to water ranges between 2×10^{-12} m/s and 2×10^{-10} m/s, and it generally decreases with increasing confining pressure. In addition, the method used to bond the GCL components significantly affects the self-healing behaviour of the liner. Needle-punched GCLs generally exhibit better self-healing characteristics and internal stability compared to stitch-bonded GCLs.

Compacted Clay Liners

CCLs are commonly constructed using natural clayey soils, although mixtures of soil and bentonite are also widely used to improve liner performance. These liners are generally placed in successive compacted lifts, each having a compacted thickness of about 150 mm. Depending on the landfill configuration, the compacted layers may be laid horizontally or parallel to side slopes. The hydraulic conductivity of compacted clay liners is strongly influenced by factors such as moisture content, method of compaction, and compactive effort. Low hydraulic conductivity is generally achieved when the soil is compacted slightly wet of optimum moisture content using high kneading-type compactive energy. The water content of the soil at the time of compaction is the single most important factor that affects hydraulic conductivity of compacted soil liners. Soft, wet pieces of clay are much easier to remold into a homogenous, low hydraulic conductivity mass than dry, hard pieces. Kneading the soil during compaction with a high level of compactive energy also helps to remold clods and to eliminate large pore spaces [12].

According to Parastar et al. (2017) [8] and Al-Soudany et al. (2024) [1], natural clay soil is an ideal liner material due to its high sorption capacity, long-term structural stability, and low permeability. Building a landfill liner to fulfil the anti-seepage criteria and pollutant-blocking capabilities always consumes a substantial quantity of clay minerals. Although clay minerals are natural resources that do not regenerate, they are considered non-renewable. The primary benefits by making use of clays as liners include clays, where they are accessible locally, either on or adjacent to the dumping site, are the most cost-effective method for providing landfill containment; because of the microscopic particle size of their constituent particles, clays have a very low permeability, cause insufficient seepage rates for the fluids in landfills; thick clay barriers are often more resistant to being damaged than their synthetic equivalents, which are thinner; due to the broad distribution of clays around the globe, it is guaranteed that materials with poor permeability will be found near most waste disposal locations; clay minerals are the end-product of geological weathering, which may take thousands of years and can last hundreds of thousands of years. Because of this, clay minerals are essentially inert and usually do not undergo substantial chemical interaction with leachate.

As per Mohamedzein et al. (2016), the usage of clays will not be economically viable in areas where they are not readily accessible near dump sites. However, sands or coarse silts may be used with synthetic' clays, such as bentonite, to generate a barrier with low permeabilities comparable to natural clays. Bentonite is a generic word that may refer to either calcium montmorillonite or sodium montmorillonite [13].

DESIGN REQUIREMENTS FOR COMPACTED CLAY LINERS

Indian Guidelines for Landfill Liner Materials

In India, the Central Pollution Control Board (CPCB) and the Ministry of Urban Development have recommended specific geotechnical criteria for landfill liner materials used in municipal solid waste disposal facilities. According to these guidelines, liner materials should possess a plasticity index in the range of 7–10%, liquid limit between 25% and 30%, hydraulic conductivity less than or equal to 1.0×10^{-9} m/s, and a minimum unconfined compressive strength of 200 kPa [14, 15]. These criteria are intended to ensure adequate strength, low permeability, and long-term stability of compacted clay liners.

Criteria reported by Daniel (1993)

Daniel (1993) reported that the hydraulic conductivity of compacted clay liners should not exceed 1×10^{-7} cm/s to minimize leachate migration through landfill barriers. To achieve this level of hydraulic performance, the liner material should contain approximately 30–50% fines and exhibit a plasticity index ranging from 7% to 10%. The percentage of gravel in the soil should generally remain within 20–50%, while the maximum particle size should range between 25 mm and 50 mm. In this context, fines refer to the fraction of soil passing through the 0.075 mm sieve, whereas gravel corresponds to the material retained on the 4.75 mm sieve [12].

Requirements given by O'Sullivan and Quigley (2002)

O'Sullivan and Quigley (2002) suggested general design requirements for compacted clay liners used in landfill engineering. According to their recommendations, the hydraulic conductivity of the liner should be equal to or less than 1.0×10^{-9} m/s, with a minimum liner thickness of 1 m. The liner material should contain at least 10% clay and more than 30% fines (clay and silt fraction). In addition, the plasticity index should range between 10% and 65%, while the liquid limit should remain below 90%. The maximum allowable particle size in the liner material was recommended as 75 mm [16].

Requirements based on BS 1377:1990 and U.K. Environment Agency (2009)

The U.K. Environment Agency (2009), based on BS 1377:1990 test specifications, recommended several minimum requirements for compacted clay liners used in landfill applications [17]. The characteristic permeability of laboratory-tested samples should be less than or equal to 5×10^{-10} m/s, while the remoulded undrained shear strength should typically be greater than or equal to 50 kN/m². The plasticity index of the liner material should range between 10% and 65%, and the liquid limit should not exceed 90%. The percentage of fines passing the 0.063 mm sieve should be at least 20%, including a minimum clay fraction (particle size < 2 μm) of 8%. Furthermore, the gravel content (> 5 mm size fraction) should not exceed 30%. The maximum particle size should generally remain within two-thirds of the compacted layer thickness, typically around 125 mm, to avoid the formation of larger lumps that could adversely affect liner integrity [17, 18]

GEOTECHNICAL CHARACTERISTICS OF CLAY LINER MATERIALS

When suitable natural clay materials are not available near landfill sites, locally available soils can be modified using commercial bentonite to achieve the required hydraulic conductivity for landfill liners. Even a small percentage of sodium bentonite can significantly reduce the permeability of soil mixtures by several orders of magnitude. There are no specific material requirements for soils that are to be blended with bentonite. Any material can be made to have a hydraulic conductivity $\leq 1 \times 10^{-9}$ m/s; the only issue is how much bentonite is needed. Soils with a broad range of grain sizes usually require a relatively small amount of bentonite (≤ 6% on a dry-weight basis). Uniform-sized soils, such as a dune sand, usually require more bentonite (up to 10 to 15%) [12]. Kumar and Kumari (2023) emphasized that hydraulic conductivity, plasticity index, and fines content are the most important parameters governing the suitability of clay materials for landfill liner applications [19].

Tripathi and Roy (2025) investigated the suitability of soils collected from areas surrounding Lucknow City, India, for use as compacted clay liners in municipal solid waste landfills. Soil samples obtained from three different locations were evaluated for permeability and expansivity characteristics. None of the natural soils independently satisfied the required permeability criteria for liner applications. One of the soils exhibited high expansivity based on free swell ratio measurements. To improve its engineering properties, bentonite was added in proportions of 0%, 10%, 20%, 30%, and 40%, and the mixtures were tested for maximum dry density, optimum moisture content, hydraulic conductivity, and free swell ratio. The study reported that the soil mixed with 40% bentonite fulfilled the required permeability criteria and exhibited the highest swelling characteristics [20].

Nath et al. (2023) examined the applicability of bentonite-modified local clay soil for landfill liner construction by blending bentonite in proportions of 5%, 10%, 15%, and 20%. The prepared mixtures were evaluated for compaction characteristics, consistency limits, hydraulic conductivity, free swell index, unconfined compressive strength, and Ph [3]. The results indicated that the addition of 10% bentonite produced satisfactory liner properties, with hydraulic conductivity values lower than 1×10^{-7} cm/s and unconfined compressive strength exceeding 200 kPa. The study concluded that bentonite amendment significantly improved the engineering behaviour of local soils by reducing permeability and enhancing strength characteristics.

Mohamedzein et al. (2016) investigated the performance of dune sand–bentonite mixtures for landfill liner applications by incorporating bentonite contents ranging from 5% to 20%. The mixtures were evaluated in terms of hydraulic conductivity, swelling potential, shrinkage behavior, compressibility, and shear strength. The study observed that hydraulic conductivity decreased substantially with increasing bentonite content, while the rate of reduction became less pronounced beyond 15% bentonite addition. Acceptable permeability values ($< 1 \times 10^{-7}$ cm/s) were achieved when the bentonite content exceeded 10%. However, swelling pressure and shrinkage characteristics increased considerably at higher bentonite contents, particularly above 15%. The mixtures also exhibited acceptable compressibility behaviour and adequate shear strength for liner applications [13].

Akayuli et al. (2013) evaluated the suitability of Ghanaian black cotton soil for use as clay liners in tailings dam construction. Laboratory investigations demonstrated that the soil satisfied several important liner requirements, including hydraulic conductivity (10^{-10} m/s), plasticity index (62.12%), liquid limit (91.72%), percentage of fines (81.30%), and cation exchange capacity. Although the liquid limit slightly exceeded the values recommended by the U.K. Environment Agency (2009), the authors considered the variation insignificant and concluded that the soil remained suitable for liner applications. The geotechnical characterization of the liner materials was carried out using standardized laboratory procedures in accordance with BS 1377-1:1990 methods for soils used in civil engineering applications [17, 18, 21].

Wasil (2020) studied the influence of bentonite addition on the engineering properties of fly ash intended for landfill sealing layers. The study revealed that the hydraulic conductivity of fly ash mixtures could be reduced to values less than or equal to 1.0×10^{-9} m/s with the addition of 15% bentonite, thereby satisfying the permeability requirements for compacted liners and cover systems. Bentonite addition also resulted in a reduction in optimum moisture content and an increase in maximum dry density. Furthermore, the specific surface area of the fly ash mixtures increased with increasing bentonite content [22].

Garg et al. (2020) investigated fly ash–bentonite composite mixtures for landfill liner applications by critically evaluating their unconfined compressive strength and hydraulic conductivity characteristics. Based on the experimental findings, a mixture containing 70% fly ash and 30% bentonite was identified as the optimum composition, satisfying both strength requirements (> 200 kPa) and permeability criteria ($\leq 1 \times 10^{-7}$ cm/s) for compacted clay liners [4].

Arathy and Sai (2017) carried out laboratory studies on kaolinite soil blended with rice husk ash in proportions as 0%, 3%, 6%, 9%, 12% and 15% by dry weight of soil. The mixtures were tested for compaction characteristics, Atterberg limits, unconfined compressive strength, and hydraulic conductivity to identify a suitable liner composition [14]. The study indicated that the addition of 9% rice husk ash produced acceptable liner properties. In addition, they also evaluated the effect of pore fluid prepared using calcium chloride and acetic acid with varying concentration 0.25, 0.5, 1, 2 molarity (M) in the optimum mix (9%) of liner material. With the addition of pore fluids to the optimum rice husk ash and kaolinite mix, it was observed that liquid limit and plasticity index increased whereas plastic limit decreased as the dielectric constant of pore fluid decreased. Shrinkage limit and unconfined compressive strength (UCS) increased with the addition of pore fluids up to 0.5 M concentration.

Giridhar and Dharani (2018) examined the suitability of clayey soil blended with bentonite and quarry dust for landfill liner applications. Bentonite was added in proportions of 3%, 6%, 9%, 12%, and 15%, while quarry dust was maintained at a constant 10% content in all mixtures. The prepared samples were evaluated for liquid limit, shrinkage limit, optimum moisture content, maximum dry density, unconfined compressive strength, permeability, and free swell index. The study reported the lowest hydraulic conductivity value of 0.583×10^{-10} mm/s for the mixture containing 15% bentonite and 10% quarry dust, indicating its suitability as a liner material for landfill systems [23].

CONCLUSIONS

- Clay liners play an important role in controlling leachate migration and protecting groundwater and surrounding soils in municipal solid waste landfills. CCLs and GCLs are widely used because of their low hydraulic conductivity and contaminant attenuation capacity. GCLs offer advantages such as reduced thickness, ease of installation, self-healing ability, and conservation of natural clay resources, whereas CCLs remain economical and widely applicable where suitable soils are locally available.
- The reviewed studies indicate that the engineering performance of liner materials can be significantly improved by mixing local soils with bentonite and other additives such as fly ash, rice husk ash, and quarry dust. The required bentonite content depends mainly on the mineralogical composition and geotechnical properties of the soil. Several soil–bentonite mixtures investigated by different researchers satisfied the recommended permeability and strength criteria for landfill liners. Overall, the use of modified local soils and industrial by-products can provide sustainable and cost-effective alternatives for landfill liner construction.

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