

Compacted Soil Liners and Covers for Waste Containment: A Review of Soil Type Suitability and Applications

Adamu Umar Chinade^{1,2}; and Gambo Haruna Yunusa¹

¹Department of Civil Engineering, Bayero University, Kano. ²Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi.

Corresponding author: umarchinade@atbu.edu.ng

DOI: <https://doi.org/10.62154/ajesre.2024.016.010400>

Abstract

An effective waste disposal system is essential in preventing the infiltration of leachate into the ground and achieving the sustainable development goal of ensuring access to clean and potable water. Liner is an important component of landfill in waste disposal facilities as it impedes the flow of leachate from the landfill. The choice of liner material depends on factors, such as the type and availability of soil, the site conditions, sustainability, and cost-effectiveness. This paper focuses on different soil types as compacted liners in waste containment facilities. The main purpose of this paper is to present the findings of laboratory investigations and measurements of hydraulic conductivity and other important soil properties extracted from previous literature with the aim of providing a guide in material selection for use as compacted soil liners and covers in waste containment applications. The key results of many laboratory studies previously conducted on soils of different properties, gradation, plasticity, and mineralogy, untreated or stabilized with various additives such as waste materials from industries, agricultural by-products and municipal waste materials are reported. The paper also presents the potential of using biopolymer-treated soils (soils modified by polymers) derived from plants and animals, as potential liner materials.

Keywords: Leachate, Potable Water, Liner, Landfill, Hydraulic Conductivity, Gradation.

Introduction

Proper management of solid waste is a challenge faced by environmental protection agencies in developing countries of the world (Nasara *et al.*, 2023). Landfills, although the least among the waste management options/hierarchy (Wang *et al.*, 2020) play a vital role in the management of solid waste and it prevents the pollution of the environment, soil and water sources provided proper bottom and cover linings are provided (Xin *et al.*, 2016, Umar *et al.*, 2015). The selection of suitable materials for liner and cover is an important aspect of landfill design to minimize the migration of leachate and gases into the surrounding environment (Benson and Daniel, 1990). In order to build a cost-effective landfill, there is a need to use locally available materials as liners and cover (Ojuri *et al.*, 2017). Hamdi and Srasra, (2013) emphasizes the importance of the adequate choice of clay soil for the construction of landfill liners due to the crack potential caused by the desiccation of highly plastic soils.

Clayey soils as traditional lining materials have been widely employed due to their low permeability characteristics and ability to absorb heavy metals from the leachate (Benson *et al.*, 1999, Osinubi *et al.*, 2017; Ramesh and Thyagaraj, 2022). However, with the advancement in technology, various soil types including sands, laterites, lateritic soils, borrow soils, and demolition wastes have been engineered and augmented with additives or used as composites (soil-bentonite, mixed soil) to provide cost-effective and sustainable liner materials (Bacha, 2015).

Bottom and cover liners of landfills are often based on natural materials including clays characterized by approximate hydraulic conductivity coefficient usually below $1\text{E-}9$ m/s (Chinade *et al.*, 2017, Gupt *et al.*, 2022; Hou *et al.*, 2022; Ramesh and Thyagaraj, 2022). This is often supported by unconfined compressive strength (UCS), volumetric shrinkage strain (VSS), and cation exchange capacity (CEC) among other requirements. Various clay types are reported to possess very low hydraulic conductivity (Umar *et al.*, 2016).

For soils to be used as liners in landfills, they should have hydraulic conductivity less than or equal to $1\text{E-}9$ m/s for hazardous and non-hazardous waste while $1\text{E-}7$ m/s or less for inert waste, unconfined compressive strength ≥ 200 kN/m² and volumetric shrinkage strain ≤ 4 % (US EPA, 1989; Özçoban *et al.*, 2022, Tijjani *et al.*, 2021, Osinubi and Nwaiwu, 2006).

Fine-grained soil particles exhibit elevated chemical reactivity at their surface interfaces, characterized by the presence of charged sites. These surface sites can exhibit either negative or positive charges remain neutral, influencing the soil's chemical behavior and interactions. Alkalinity, mineralogical composition, and organic matter content were reported to determine the relative proportion of metal ions attracted to various sites of fine-grained soils (Alhamdan and Reddy, 2006, Nasiru *et al.*, 2016, Saeed *et al.*, 2017, Batari *et al.*, 2017a).

Geosynthetic clay liners and geomembrane have been used as landfill liners. The main reason for using such materials is their low hydraulic conductivity which limits or eliminates the movement of not only the leachate from the bottom of landfills but also the generated gases from the final cap of waste dumps (Shankar and Muthukumar, 2017). However, these materials are prone to accidental puncture and create a potential problem with interface shear between their surfaces.

The problem of inadequate soil type selection can lead to reduced liner and cover performance, increased risk of contamination, and costly repairs or replacements. This review aims to address this problem by examining the suitability of various soil types as compacted liners and covers in waste containment facilities, highlighting the key factors influencing their performance, and providing insights for optimal soil type selection and application.

The objectives of the study are; to investigate the suitability of different soil types as compacted liners in waste containment facilities as well as to evaluate the hydraulic conductivity and other essential soil properties for various soil types and their potential as

liner materials, and finally to explore the effectiveness of using biopolymer-treated soils as alternative liner materials.

Methodology

This study comprehensively reviews existing literature on compacted soil liners and covers in waste containment facilities. The methodology involves the following;

- Literature search: A systematic search of peer-reviewed journals, conference proceedings, and relevant publications was conducted using keywords: 'compacted soil liners,' 'waste containment,' 'hydraulic conductivity,' and 'biopolymer-treated soils.'
- Data collection: Relevant data on soil properties (hydraulic conductivity, unconfined compressive strength, volumetric shrinkage, etc), and performance of compacted soil liners were extracted from the selected literature.
- Data analysis: The collected data were analyzed to identify trends, patterns, and correlations between soil properties and liner performance.
- Biopolymer-treated soils evaluation: A specific focus was given to evaluating the potential of biopolymer-treated soils as liner materials, including their properties, advantages, and limitations.

Literature Review

The literature review approach was chosen to synthesize existing knowledge and identify gaps in current research. The study's population includes various soil types, and the sample size comprises numerous laboratory studies and field applications. Finally, potential limitations include the variability in soil properties, testing conditions, and scalability of results.

Review of previous works on the application of soils of different properties and gradation as a liner in waste containment applications

Bentonite addition to tropical soils is widely recommended because not all tropical soils possess the requisite properties to be considered as a single material for liner in waste containment applications. It has been established that bentonite can reduce hydraulic conductivity and increase the sorption capacity of sandy soils (Morandini and Leite, 2015). The fine particles resulting in the micropores of bentonite and black cotton soil coupled with high surface charges contribute to the low hydraulic conductivity of these soils (Batari, *et al.*, 2017b, Mai-bade *et al.*, 2021). These properties make them good attenuators of landfill leachates (Thankam, 2017, Amadi *et al.*, 2023). The findings also noted the need for more investigation on tropical soils mixed with either bentonite or other low hydraulic conductivity materials for use as compacted landfill liners in the containment of municipal solid waste.

However, several literatures exist regarding the use of tropical soils as liners, among which are; Osinubi and Nwaiwu, (2002), Morandini and Leite (2013), Amadi and Eberemu (2013), Chinade *et al.*, (2017) among others.

Daramola *et al.*, (2024), reviewed different tropical soils for their application as materials for liner in waste containment application. The paper noted the limited availability of suitable clayey soils and the high cost of other conventional materials like geosynthetics which calls for the need to search for alternative locally available soils. Laterites and lateritic soils belong to the category of soils found in tropical and subtropical regions. These soils have been used either alone or stabilized with suitable additives such as cement kiln dust, bentonite, fly ash, and sawdust as liners due to their desirable geotechnical, geological, and geochemical properties based on available literature. The paper concludes that laterites and lateritic soils possess desirable engineering properties coupled with mineralogical compositions which favor lining applications. The author's emphasis and perspective is limited to laterite and lateritic soils which are mostly found in some specific regions.

Yamusa and Ahmad (2018), examined the effect of different fine content (grading) on the laboratory hydraulic conductivity of soils. Soil specimen with 40 % and 50 % fine content were prepared and compacted at -4, -2, 0, +2, +4 of the optimum moisture contents. They reported an increasing maximum dry density as a result of increasing the fine content with a corresponding decrease in optimum moisture content, while the hydraulic conductivity was reported to have decreased with increasing percentage fines. The volumetric shrinkage and unconfined compressive strength also increased with an increase in fine content. They recorded significant improvement in the quality of laterite soil as a result of the alteration in grading ratio. The research recommends that at least laterite soil should contain 50 % fines by weight to be used as material for liner in waste containment applications. Similar findings have been presented by Yamusa *et al.*, (2017) in which laterite was tested at different particle size gradation without any additive as a material for landfill liner. The results show that hydraulic conductivity decreases with higher fine content and therefore concludes that laterite should contain at least 50 % fines in order to be used as a standalone material for landfill liner.

The performance of clays of different plasticity as potential liner materials was investigated by Widomski *et al.*, (2018). In their study, all of the clayey substrates investigated were found to be suitable for application in compacted clay liners for sustainable rural waste landfill. However, emphasis is given to proper monitoring of molding water contents to ensure resistance to swell and shrink potentials of clay, as was observed that low applied molding water contents, dry of optimum, prevented in most cases the reduction of saturated hydraulic conductivity to values lower than 1.0×10^{-9} m/s. The author finally reiterates the importance of using composite soil stabilized with either agricultural or industrial waste materials.

Adeyemo *et al.*, (2022): In a study to investigate the feasibility of using black cotton soil as compacted liner material, cassava peel ash was used to modify black cotton soil (BCS) in

order to achieve minimum specifications for soils to be used as liner in waste containment applications. Proportions of 4 – 24 % by weight of the cassava peel ash were used and compacted using three different compaction energies namely; BSL, WAS, and BSH. The samples were prepared at a molding water content of 2 % dry of the optimum, at Optimum, and at 2 %, and 4 % wet of the OMC i.e. (-2, 0, +2, and +4). The natural soil was classified as A-7-6 (31) and CH based on the AASHTO and USCS classification systems respectively. The study concluded that 16 % by weight of the cassava peel ash modified BCS can be compacted to yield hydraulic conductivity less than or equal to the $1\text{E-}9$ m/s required for compacted clay liner.

Norouzi *et al.*, (2023), considered the use of sand–bentonite mixture as a barrier material in a landfill. The research also established the feasibility of using slag and clinker dust, brick dust, and sewage sludge as potential liner materials. The bentonite was used to act as a filler material between the sand grains. Construction and demolition waste (CD), brick dust, sewage sludge, slag clinker dust, and water treatment waste are widely used in addition to sand–bentonite mixture as materials for landfill liners (Muhammed *et al.*, 2021). It was reported that brick dust can be effectively used as landfill liners and covers because of its pozzolanic properties (Muhammed *et al.*, 2021).

Alla *et al.*, (2017) investigated alternative liner material by blending fly ash, locally available soil, and bentonite. Trial mixes were prepared to test the plasticity characteristics and hydraulic conductivity. The soil-fly ash mixture was (80:20, 70:30, 60:40, 50:50), the soil-bentonite mix was (97:3, 95:5), while the fly ash-bentonite mix was (95:5, 90:10, 85:15), and the combined fly ash-soil-bentonite mix was (85:10:5, 90:5:5) respectively. It was observed that soil-bentonite mix (95:5, 97:3), and fly ash-bentonite mix (85:15) when compacted at OMC and MDD derived from the British standard heavy compaction energy satisfies both the two criteria investigated, i.e plasticity (i.e. Liquid limit, $LL \geq 20\%$ and Plasticity Index, $PI \geq 7\%$) as well as the hydraulic conductivity $\leq 1 \times 10^{-9}$ m/s for material to be employed as a liner and cover in landfills.

Kumar and Kumari (2024) emphasize the economic advantage of a composite mix that comprises locally available soil and industrial waste which satisfies the design parameters of the municipal solid waste (MSW) landfill liner. In the study, the local soil was mixed with bentonite and fly ash in different proportions to evaluate the geotechnical and microstructural properties of the composite such as unconfined compressive strength, X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDAX). The authors observed that soil-bentonite-fly ash mixture in a ratio of 65:15:20 gave the minimum characteristics required for the material to be used as landfill liners in waste containment applications. Also, there was a substantial reduction in hydraulic conductivity (k) in order of 96.04 %. On the other hand, the unconfined compressive strength increased by 209 % after a 28-day curing period.

An experiment with local bentonite stabilized with snail shell ash and granulated blast furnace slag for use as a barrier in waste containment applications was conducted by Fadugba *et al.*, (2024). Specimen containing 15 % snail shell ash (SSA) demonstrated the highest unconfined compressive strength of 272 kN/m² after a 28-day curing period and the lowest hydraulic conductivity of 5.57×10^{-8} cm/s. It was concluded that this material has the potential to be used as a liner in waste containment applications.

Widomski *et al.*, (2018), investigated clays of various particle compositions and plasticity sampled from rural areas as sustainable materials for the construction of landfill liners. The hydraulic conductivity tests were carried out to ascertain their capability to heal/seal after sustained repeated drying and rewetting. The results obtained showed that the clays were found to be suitable as compacted liners for sustainable landfills. The study also showed that clay materials with a high plasticity index (>30 %) allowed very good sealing capabilities but showed high shrinkage potentials. Compaction molding water content dry of the optimum water content does not yield hydraulic conductivity less than or equal to 1E-9 m/s minimum required for liners in waste containment applications.

The potential stabilization of fine grained soil with cement and sawdust ash (SDA) for liner applications was studied by Iliyas *et al.*, (2024). Mix proportions of cement (0–9 %) and SDA (0–10 %) by weight were added to the soil making a total of 24 specimens. Hydraulic conductivity (k), Unconfined compressive strength (UCS), and volumetric shrinkage strain (VSS) tests were carried out. Specimen containing 6% cement and 6% SDA gave the maximum UCS value of 375 kN/m² and minimum k and VSS values of 4.7×10^{-10} m/s and VSS 3.51% respectively when compared with the untreated fine-grained soil, i.e 51 kN/m², 1.7×10^{-8} and 12.8 % respectively. Stabilization using industrial by-products such as SDA is an economical and sustainable soil improvement method for waste containment applications. Shakir and Ali (2019), reported an increasing trend of unconfined compressive strength as a result of an increase in bentonite content in laterite soil. flocculated structure was observed due to a reduction in interparticle repulsive forces caused by the addition of bentonite to the soil leading to a net strength increase. The author concluded that the addition of bentonite increases the liquid limit, plastic limit, and specific gravity while decreasing the maximum dry density and coefficient of permeability of the soil.

Anandha *et al.*, (2021): In an effort to develop a clean, sustainable, and economic alternative liner material for landfills, Guar gum-stabilized soil was tested for hydraulic conductivity. The addition of 2 % guar gum was able to decrease the hydraulic conductivity of poorly graded sand–clay mix by 2.72E5 folds after 120 days of permeation. The additive was able to increase the heavy metal attenuation capacity of the soil. The study also shows that a high dosage of the material produces a material that is resistant to wet and dry cycles (volumetric shrinkage strain).

In a study to assess the suitability of using burrow pit soils collected from southwestern Nigeria as landfill liners, Akinwumi *et al.*, (2021), utilized soil samples collected from six different burrow pits and classified them as MH, CL, MH, CL, CL, CL with the corresponding

percent passing the number 200 sieve size as 62.5, 43.3, 31.5, 41.4, 79.5 and 54.8 % respectively. The liquid limits and plasticity index values of the soils were LL: 65, 38, 57, 61, 46, 40 and PI: 22.9, 12.3, 24.1, 14.4, 19.4 and 12.9 % respectively. The reported hydraulic conductivity values obtained using the falling head permeability test were: $7.911\text{E-}8$, $8.345\text{E-}8$, $8.373\text{E-}8$, $7.676\text{E-}8$, $8.065\text{E-}8$, and $8.539\text{E-}8$ m/s. Based on the reported hydraulic conductivity values which range from $7.676\text{E-}8$ to $8.539\text{E-}8$ m/s, the author recommends the soils to be used for landfill liner to contain inert waste. Modification is needed when the landfill is intended to contain hazardous and non-hazardous waste.

Reddish brown tropical soils of Moniya Ibadan southwestern Nigeria were accessed by Bello (2012) in order to determine the unconfined compressive strength (UCS) which is one of the basic requirements of materials for use as liner in waste containment applications. The soil's major clay mineralogy was found to be kaolinite with some mixtures of smectite, muscovite, halloysite, biotite, quartzite, and aluminum phosphate. A molding water content range of 12.5 to 22.5 % in the preparation of the UCS specimens was used in order to achieve UCS values equal to or greater than the 200 kN/m^2 minimum required for waste containment applications. The results obtained show strength values that were greater than 200 kN/m^2 at a compaction dry unit weight of 16.20 kN/m^3 when WAS and BSH were used.

Omotayo *et al.*, (2023), In an effort aimed at improving the geotechnical properties of lateritic clay using sawdust ash-lime (SDAL) mixture as additives, four compaction energies namely; Reduced British Standard Light (RBSL), British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) were used in the study to prepare the test specimen. The soil was classified as A-7-5 (7) in accordance with the American Association of State Highway and Transportation Officials (AASHTO). The soil has a plasticity index value of 13.7 %. The results show an increase in unconfined compressive strength (UCS) values up to 129.63 kN/m^2 at 6 % SDAL mixture. However, the value of 129.63 kN/m^2 is less than the stipulated regulatory minimum value of UCS for use in waste containment applications. The author recommends further improvement using the SDAL mixture for its suitability in landfill liners.

Morandini and Leite (2015), Reported that tropical soils have the capability to perform efficiently as compacted clay liners for the containment of municipal solid waste. However, bentonites are widely used as an amendment for reducing the hydraulic conductivity of soils and increasing the cation exchange capacity in natural soils.

In research by Morandini and Leite (2015), three tropical soil samples and bentonite proportions (3, 6, 9, and 12 %) by dry weight were characterized and tested for hydraulic conductivity. The soils were classified as Laterite, transitional, and Non-lateritic. It was reported that the bentonite addition considerably reduced the hydraulic conductivity of the soil samples. The findings also show that the addition of 12 % bentonite resulted in hydraulic conductivity reduction of 225.2, 661.5, and 290.0 for the lateritic, transitional, and non-lateritic soils respectively with resulting hydraulic conductivity values of $1.5\text{E-}8$, $1.2\text{E-}9$

and 6.3×10^{-10} cm/s which is less than 1×10^{-7} cm/s regulatory minimum. It was also observed that a greater content of bentonite was required for the lateritic soil to achieve the same hydraulic conductivity values with transitional and non-lateritic soils.

Umar and Elinwa (2020), presents the benefits of using laterite soil with metakaolin (MK) as an additive as liner material in landfill. The laterite used has the following physical properties; Liquid limit of 38%, Plastic limit of 22 %, plasticity index of 16 %, specific gravity of 2.4, and percentage passing number 200 sieve 62. The soil was then classified as A-6 (29) and CL in accordance with the AASHTO and USCS classification systems respectively. The laterite was treated with MK at 0 – 20 % concentration by weight. The result of the investigation shows a decreasing trend in hydraulic conductivity as a result of MK addition to the laterite soil. The addition of only 5 % MK was sufficient in decreasing the permeability to less than 1×10^{-9} m/s minimum required for use in liner for containment of municipal solid waste.

Lateritic clays become the major natural soils for the construction of liners in landfills for waste disposal in many regions of Brazil due to their availability and acceptable geotechnical properties (Boscow *et al.*, 2011).

Chinade *et al.*, (2017), investigated leachate's effect on compacted tropical soil's strength as liner material. The soil was classified as A-6(11) and CL under AASHTO M145-2012 and USCS -ASTM D 2487-2011 classification systems respectively. The specimen was permeated with leachate for a period of up to 120 days prior to testing the unconfined compressive strength. The result obtained shows a decreasing trend of UCS as a result of an increasing permeation period in leachate. The author attributed the strength reduction to an increase in the clay size particles which lowered the frictional resistance between the solid particles at their points of contact. The findings recommend the use of additives to modify tropical soils in order to perform effectively as compacted liners in waste containment applications.

In order to produce a sustainable and eco-friendly geotechnical material, Alqaisi *et al.*, (2020), looked at the potential of recycled waste materials obtained from natural sources as soil stabilizing agents. The product of these has the potential to be utilized in applications such as in subgrade and base courses of road pavement, as compacted liners in waste containment systems, etc. The results of Al-Bakri *et al.*, (2022) suggest that dune sand, collapse soil, and bentonite can be effectively utilized as compacted liners in landfills when stabilized with cement kiln dust (CKD) because of the significant improvement in properties i.e., unconfined compressive strength, collapse behavior, plasticity and hydraulic conductivity when these soils were modified with CKD.

The use of vegetal biomass ashes-based materials for liner production has been investigated by Marchiori *et al.*, (2022), where a decreasing cohesion has been witnessed when vegetal-based biomass ashes (VBA) was used to modify soft soil as a potential liner material at 5, 10, 15 and 20 % addition. The addition of 5% of the residue into the soft soil decreases the permeability values below 1×10^{-9} m/s recommended for liner and cover in

waste containment applications. The findings recommend pozzolanic level and leachability tests as additional tests to further ascertain the material for use in liner applications. Ilman and Balkis (2023), presented the benefits of using biopolymers as an alternative soil stabilizer due to their low carbon footprint and environmentally friendly properties.

Table 1: Summary of studies reviewed

Author/s	Year	Objectives	Testing Program
Daramola <i>et al.</i> ,	2024	Tropical soils as liner material	Review
Fadugba <i>et al.</i> ,	2024	Snail shell ash and granulated blast furnace slag stabilize local bentonite as liner material	UCS and hydraulic conductivity
Rameshand Thyagaraj	2022	Clay – sand mixtures as liner material	Liquid limit, plastic limit, hydraulic conductivity
Aria <i>et al.</i> ,	2023	coarse grain material (Beach sand). mixed with fine grain as liner material	hydraulic conductivity, unconfined compressive strength and shrinkage
Kumar & Kumari	2024	Composite soil as liner material	UCS and hydraulic conductivity
Adeyemo <i>et al.</i>	2022	Black cotton soil/ Cassava peel ash for used as compacted liner material.	Liquid limit, plastic limit, hydraulic conductivity, unconfined compressive strength and shrinkage
Yamusa & Ahmad	2018	laterite soil at different fines content for suitability as landfill liner material	Hydraulic conductivity, UCS, VSS
Özçoban <i>et al.</i> ,	2022	Comparison between sands and clay soils	Hydraulic conductivity
Norouzi <i>et al.</i> ,	2023	Sand/bentonite mixture as compacted liner	Hydraulic conductivity, UCS
Bacha	2015	Laterite mixed black cotton soil for geotechnical applications	Liquid limit, plastic limit, CBR, UCS, hydraulic conductivity
Widomski <i>et al.</i> ,	2018	Different plastic clays as liner materials	hydraulic conductivity
Chinade <i>et al.</i> ,	2017	Laterite soil as liner material	Unconfined compressive strength
Marchiori <i>et al.</i> ,	2022	vegetal biomass ashes-based materials for liner production	Hydraulic conductivity
Al-bakri <i>et al.</i> ,	2022	dune sand, collapse soil, and bentonite	Hydraulic conductivity

Boscow <i>et al.</i> ,	2011	Lateritic clay as liner material	Compaction, Hydraulic conductivity
Umar and Elinwa	2020	Lateritic soil mixed with metakaolin as liner material	Liquid limit, plastic limit, Hydraulic conductivity
Batari, <i>et al.</i> ,	2017a, 2017b	Black cotton soil as geotechnical material	Classification tests, compaction UCS, CBR test.
Morandini and Leite	2015	Tropical soils as potential liner materials	Classification tests, compaction UCS, hydraulic conductivity, VSS
Bello	2012	Reddish brown tropical soil as compacted liner	Classification tests, compaction UCS, hydraulic conductivity,
Alla <i>et al.</i> ,	2017	local soil stabilized with bentonite and fly ash	Plasticity tests and hydraulic conductivity
Akinwumi <i>et al.</i> ,	2021	Burrow pit soils as liner material	Classification tests, compaction UCS, hydraulic conductivity,
Widomski <i>et al.</i> ,	2018	Clays of various particle sizes as liner material	Liquid limit, plastic limit, Hydraulic conductivity
Yamusa and Ahmad	2018	Soils of different fine content as hydraulic barrier material	UCS, VSS, Hydraulic conductivity

Summary of Results Discussed in the Review Section

The review of previous works highlights the potential of various soil types and additives for use as compacted liners in waste containment applications. Bentonite addition to tropical soils is widely recommended to reduce hydraulic conductivity and increase sorption capacity. Laterites and lateritic soils have also been found to possess desirable geotechnical properties, making them suitable for liner applications. The use of biopolymer-treated soils, vegetal biomass ashes, and recycled waste materials as sustainable alternatives for liner production shows promising results.

However, the results also emphasize the need for careful selection and modification of soils to achieve the required hydraulic conductivity and strength properties. The addition of additives such as bentonite, cement kiln dust, and sawdust ash can significantly improve the performance of soils as liners. Nevertheless, the optimal mix proportions and compaction energies need to be determined for each specific soil type and application.

Conclusion

Material selection for use as compacted liners in landfills for waste containment is an important component while planning for the construction of a landfill. This study assessed the suitable application of different types of soils as landfill liner materials. Accessing the findings of many researchers, relative to standard requirements for soils to be used as liners

in landfills shows that different materials ranging from; laterite, lateritic soil, transitional soils, bentonite, black cotton soils, tropical red soils, and so on, have been successfully utilized as compacted liner in waste containment applications. These soil types were either used as standalone materials, graded or modified with various additives such as industrial and agricultural wastes and sometimes mixed with bentonite in certain proportions in order to improve their long-term performance as compacted liners. Consequently, it can be deduced that geometric mean hydraulic conductivity less than or equal to $1\text{E-}9$ m/s can be achieved with different soil types provided the liquid limit ≥ 20 %, plasticity index ≥ 7 , percent clay ($< 2 \mu\text{m}$) ≥ 15 %, percent fines (less than No. 200 sieve size) $\geq 30 - 50$ % and the soil classified as CL in the unified soil classification system.

However, the review focused primarily on existing literature, and further experimental research is needed to validate the findings. The study did not consider the impact of climate, leachate composition, and soil degradation on the long-term performance of compacted liners.

Actionable Recommendations

- **Soil Selection and Testing:** Conduct thorough soil tests to determine the suitability of local soils for use as compacted liners, considering factors such as liquid limit, plasticity index, clay content, and fines content.
- **Additive Selection and Application:** Explore the use of sustainable and eco-friendly additives, such as biopolymers, to improve soil performance as liners, and develop guidelines for additive selection and application.
- **Compaction and Construction:** Develop and implement optimal compaction methods and construction techniques to achieve the required hydraulic conductivity and strength properties of compacted liners.
- **Quality Control and Monitoring:** Establish quality control measures and monitoring programs to ensure the long-term performance and integrity of compacted liners in waste containment applications.
- **Regulatory Framework and Guidelines:** Develop and update regulatory frameworks and guidelines to incorporate the use of compacted liners in waste containment applications, considering factors such as soil type, additive selection, and compaction methods.
- **Further Research and Development:** Conduct further research to address the limitations of this study, including the impact of climate, leachate composition, and soil degradation on the long-term performance of compacted liners.

Acknowledgements

The authors wish to express their sincere gratitude to Bayero University, Kano and Abubakar Tafawa Balewa University, Bauchi for their invaluable support and contributions

to this study. Their assistance was instrumental in facilitating the research and is greatly appreciated.

Conflict of Interest

The authors declare no conflict of interest.

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