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DESIGN OF LANDFILLS AND THE UTILIZATION OF WASTES AS SUSTAINABLE LINER MATERIALS: A MINI-REVIEW

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ABSTRACT

Modern landfills, designed to minimize environmental and health risks, play a crucial role in solid waste disposal. Poorly managed municipal solid waste facilities have severe environmental consequences, prompting intervention and remediation. Landfill construction is not enough; regular maintenance is essential to prevent harm. Landfills' historical evolution reflects societal needs, technological advancements, and environmental awareness. The 20th century saw engineered landfills with practices like compaction, daily covering, and leachate collection. Despite progress in recycling and incineration, landfills remain dominant, posing challenges like methane emissions, leachate contamination, and land use. Research emphasizes integrating landfills with recycling, composting, and waste-to-energy technologies for a sustainable future. Engineered landfills are advantageous over dumpsites, in terms of groundwater and air protection, odor control, energy generation, and job creation. Seismic analysis of landfills addresses deformation and seismic reactivity, emphasizing proper liner construction to reduce seismic impact. Leachate, a potential environmental hazard, requires careful management with effective liners to prevent groundwater and soil pollution. Various materials, including fly ash, paper mill sludge, waste foundry sand, recycled concrete aggregate, rice husk ash, and plastic waste, are reviewed for landfill liners. Research shows these materials can offer effective barriers, reducing environmental impact and promoting sustainability. Future studies should continue exploring alternative materials, considering factors like strength, hydraulic conductivity, and environmental protection.

1. INTRODUCTION

Modern landfills are sophisticated containment systems meant to reduce health and environmental hazards (Hughes et al., 2005). Li et al. (2017) stated that due to their ease of use and low construction costs, landfills are significant systems for discarding solid wastes. Employed in the context of municipal waste management, this system facilitates its ultimate disposal, and it was designed and built with minimal environmental impact in mind. In the early 1990s, the landfill design concept favoured absolute containment and isolation. Subsequent aftercare and renewal of barriers is necessary where waste is non-degradable and hazardous. The fundamental tenet of all contemporary landfills is that waste products which would not eventually become stable or inactive will be considered as "Stored," not "Disposed" (Rani & Chandra, 2017).

The effect of poorly managed municipal solid waste (MSW) facilities on the environment cannot be overemphasized. A case was studied by Tamunobereton-ari et al. (2012) in Port-Harcourt, Nigeria. Canvassing techniques were utilized to gather the necessary data, and the results revealed that the operators of these facilities did not adhere to operational norms. The overall environment around the facilities had deteriorated in appearance and was severely polluted. Since groundwater near the landfills was potentially contaminated, government agencies took swift action. They closely monitored the landfill operators' efforts to follow regulations. This included assessing safe operation limits, closure procedures, and long-term environmental impacts. The focus was on ensuring the safety of the surrounding area for as long as the landfill remains in use and even after closure. Landfills are significant contributors to global methane emissions, a potent greenhouse gas with 28 times the warming potential of CO_2 over a 100-year period (IPCC, 2021). Also, leachate leakage from unlined landfills can contaminate groundwater sources, posing health risks to nearby communities (Renou et al., 2008). These factors can become a severe issue overtime. Hence, the provisioning of landfills should not only stop at its construction but should also encompass proper design and regular maintenance so that it does not

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cause more harm than good. To mitigate these environmental concerns, the focus of landfill design has shifted towards sustainability, aiming to minimize environmental impact throughout the landfill's lifecycle (Parameswari et al., 2021).

Landfills, though often associated with modern life, have a historical background. Their evolution reflects changing societal needs, technological advancements, and growing awareness of environmental impacts.

Some of the earliest evidence of landfills dates back to 3000 BC in Knossos, Crete, where large pits were dug to dispose of refuse. Similar practices were observed in ancient Athens around 500 BC, with the first known waste regulations requiring residents to dump refuse outside city limits (Commercial Zone Products, 2023). During this period, waste management primarily consisted of dumping refuse in pits, ditches, or open areas, often leading to environmental and public health concerns (Rihn, 2021).

The 20th century witnessed a shift towards engineered landfills designed to minimize environmental impact. Compaction, daily covering with soil, and leachate collection became standard practices. With increasing waste generation and limited land availability, landfills face challenges in terms of capacity and environmental impact. Concerns regarding methane emissions, leachate contamination, and land use are driving research into alternative waste management solutions (Rihn, 2021). Significant advancements have been seen in the previous three decades. Separation, re-use, and recycling operations have been effectively adopted in several nations, with the goal of extending the life of landfills. Despite progress toward recycling and incineration in numerous nations, landfilling is a dominating waste disposal technique and will continue to be so in the near and long term (Galvão et al., 2008).

However, the future of landfills likely lies in their integration with other waste management strategies like recycling, composting, and waste-to-energy technologies. Minimizing waste generation and promoting resource recovery are crucial steps towards a more sustainable future (Wikipedia Contributors, 2023).

Solomon and Poulose (2018) proposed three major landfill types:

- Municipal solid waste landfill (MSWLF); able to hold residential waste. A MSWLF might take additional non-hazardous wastes, like incinerators with integrated reprocessing mechanisms. To reclaim the material, filters are utilised.
- Construction and Demolition Landfills (C&D); collects construction and demolition waste, which consists customarily of excavated debris, roadwork resources, demolition waste, construction/renovation waste, and site clearing rubbish. Industrial solid wastes and hazardous materials are not dumped in C&D landfills unless they are approved to receive such waste and meet certain conditions.
- Industrial Landfills; accept certain industrial effluents. Industrial waste can be summed up as solid waste collected through production or industrial procedures. It also contains byproducts of production. Mining and oil and gas industry waste are not considered to be industrial waste. Landfills for industrial wastes are frequently mono-fills connected to a particular site or company.

In Figure 1, its standard features are showcased.

With respect to a study carried out by Ireaja et al. (2018), the precedence engineered landfills have over dumpsites are outlined.

- It does not contaminate the groundwater and air;
- It keeps odours and unsightliness at bay;
- It is a helpful energy source, similar to methane gas;
- It monitors fly breeding, rat and vermin infestation, and bird clustering for airplanes;
- It provides jobs for low-skilled workers, who are widespread in developing countries;

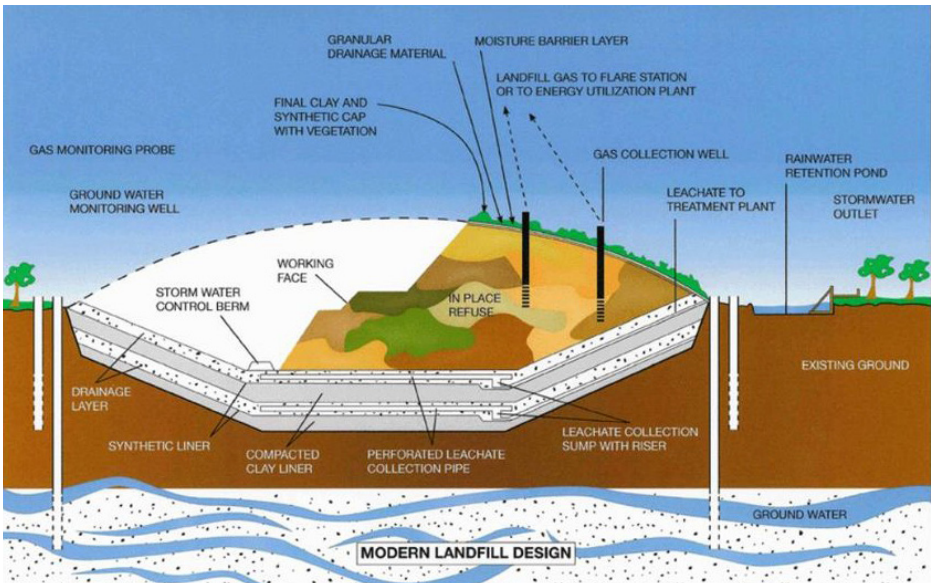

FIGURE 1: Common elements of contemporary landfill architecture (CSIR, 2000).

- It is a large business for investors;
- It is advantageous in waste management.

Furthermore, during the rainy season, public waste dumps encourages breeding for rats, rodents and other disease-carrying organisms, while polyethylene terephthalate (PET) bottles and other items that are not biodegradable from these garbage dumps choke waterways. This can lead to epidemics like lassa fever, which is caused by rodents living in an unhealthy environment, as is the case in Nigeria right now (Ukwaba et al., 2018). Hence, the need for engineered landfills with effective liner systems that are locally suitable and sustainable. To this end, different materials, especially wastes, have been employed within the protective layers of liner systems. This is with the purpose of reducing the skyrocketing degree of environmental wastes and also develop satisfactory landfill technologies. The utilization of certain waste materials in the construction of liners is a promising avenue, which potentially offers a dual benefit of waste management and improved environmental performance (Rubinos & Spagnoli, 2018). Therefore, this mini-review explores the potential of utilizing waste materials in landfill liner construction, contributing to the advancement of sustainable waste management practices. Utilizing wastes as landfill liner materials can contribute to Sustainable Development Goal (SDG) 12: Responsible Consumption and Production (United Nations, 2015), in some ways. Traditional landfill liners often rely on mined resources like clay and specific types of gravel. By finding ways to use treated waste products as replacements, we can conserve natural resources. Furthermore, landfills are taking up valuable space, and finding alternative uses for some waste streams helps reduce the overall amount needing disposal. This translates to less land being used for landfills and potentially even diverting some waste from landfills altogether.

2. SEISMIC ANALYSIS OF LANDFILLS AND LANDFILL LEACHATES

A key factor in the complex dynamic soil-structure interaction challenges including seismic response and earthquake-induced landfill movement is the geosynthetic interface. Feng et al. (2018) analyzed landfill deformation and seismic reactivity while rationally taking into account the liner contact influence. The work conducted adopted a softening-displacement variational elastic plastic constituent structure was created and tested using empirical values from nonlinear shear tests and shaking table validation to illustrate the dynamic friction behaviour of the geosynthetic clay liner interaction under a wide range of functional stress conditions. The shifting displacement and dynamical reactions along the geosynthetic clay liner link are addressed using a two-dimensional in nature time-domain dynamical finite element calculations of a prevalent above-the-ground landfill. These studies include the newly proposed dynamic interfacial framework, as shown in Figure 2. There are frequently large discrepancies when the nonlinear elasto-plasticity and deformations characteristics of the geosynthetic interface are ignored. The study's findings indicated that the characteristics of the geosynthetic interface have a significant impact on the seismic response and long-term displacement of above-ground landfill. Therefore, careful consideration should be given to the liner layer's design in order to limit the response and deformation brought on by earthquakes.. The dynamic behaviour of the geosynthetic interface should be carefully taken into account when assessing the seismic stability of MSW landfills with potential slippage along the liner interface. Furthermore, when employing simplified dynamic analytic methods for landfill assessment or seismic design, great caution is needed.

When water passes through the landfill, it gathers in the refuse and other water-soluble materials, creating leachate. Water from runoff or even waste itself could be the source of this substance. Risks to the health of people and the surroundings are presented by the landfill's leachate, which has the potential to pollute both groundwater and soil (Onyelowe et al., 2021). Depending on a range of factors, leachate can have distinct constituents. The leachate typically contains humic acid and organic compounds, whereas inorganic components include natrium, cadmium, ammonium, iron, and calcium. For the sake of not deteriorating the environment, especially degrading the soil and groundwater, the leachate from the landfill ought not to spill out. A liner that acts as a leachate barrier must be provisioned in the landfill with the goal of safeguarding against harm to the soil and groundwater supplies (Budihardjo et al., 2019).

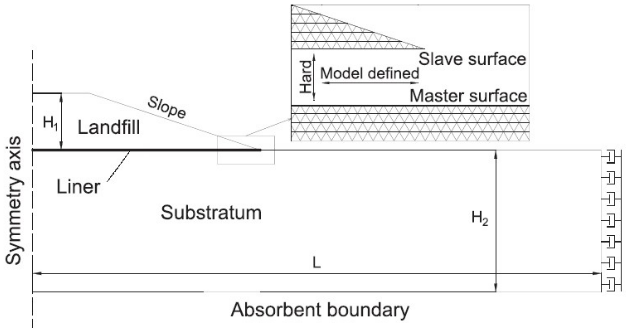

FIGURE 2: Finite element model of a typical above ground landfill (Feng et al., 2018).

3. LANDFILL LINER

Patil et al. (2009) expounded engineered landfill liners as multilayered systems consisting of a hydraulic barrier layer as an important component. This layer's intent is to lessen water percolation through the cover system by restricting water directly and indirectly facilitating drainage or water storage in the underlying layers. Because communities rely on groundwater for drinking water due to increased pollution of the available sources of surface water, effective landfill liner systems are critical in preserving groundwater from leachate contamination and controlling the release of methane and other gases to prevent buildup and potential explosions. Designed landfill's liner system works as a leachate barrier, preventing pollutants from being transported to the pollution-prone surroundings. As a result, one of the most important design issues in a landfill is the liner system (Olaoye et al., 2019).

3.1 Municipal solid waste landfill liners

Du et al. (2009) examined the effectiveness of two Chinese MSW landfill bottom liner system types. The standard landfill bottom liners for municipal solid waste (MSW) were mandated by the Chinese government. Nevertheless, very little study has been done to assess the effectiveness of the typical MSW landfill bottom liners that the Chinese government recommends. The maximum leachate head, the leakage rate, the peak concentration of the intended contaminant in the aquifer beneath the assumed landfill, and the total mass per unit area of the target contaminant released into the aquifer were the criteria used in this study to assess the performance of the two kinds of Chinese MSW landfill bottom liner frameworks – Type 1 and Type 2. In Type 1, a natural clay deposit with a thickness larger than 2 m and a hydraulic conductivity less than 10^{-9} m/s were used as a containment barrier. In Type 2, a composite liner system is used. The thicknesses of the high-density polyethylene (HDPE) geomembrane liner (GM) and compacted clay liner (CCL) are greater than 1.5 mm and 1 m, respectively. Also, the hydraulic conductivity of CCL was less than 10^{-9} m/s. It is also notable that the drainage gravels' grain size surrounding the leachate collection pipes is not a requirement for the Chinese standard. After an evaluation and comparison of the Chinese and German standard MSW landfill bottom liner systems' performance was conducted, it was discovered that the German standard being more strictly prescribed has a maximum leachate head requirement of less than 0.3 m on the liners, and a grain size of the drainage gravels ranging from 16 mm-32 mm around the leachate collection pipes. It is discovered that the Chinese landfill liner systems' estimated maximum leachate head was considerably greater than the German system's. When it comes to reducing the negative effects of landfills on groundwater quality, the Chinese standard landfill liner Type 2 performed almost exactly like the German standard landfill liner in terms of leakage rate, peak concentration, and maximum total mass per unit area in the target contaminant aquifer. In contrast, the Chinese standard landfill liner Type 1 performed less well in this regard. Material differences, leachate head, overall design, etc., are factors that can influence the performance of MSW landfill bottom liners, thus they must be paid attention to.

Engineering professionals have to take into account the hazardous waste conveyance techniques of advection, diffusion, mechanical dispersion, and adsorption when defining the time necessary for breakthrough of MSW landfill liners, as suggested by Shu et al. (2019). In MSW landfills, geomembranes and compacted clay liners are occasionally adopted as bottom liners to reduce the pollution of groundwater from leachate generated by landfill migration. Leachate seepage, nevertheless, has the potential to contaminate the environment by traversing the bottom liner and carrying pollutants. In order to design a landfill, it is necessary to ascertain the bottom liner's breakout time. This advances future design of these liner systems to be more effective when these outcomes are determined. Also, regulators and landfill developers should pay closer attention to how long each part of the landfill system will last. This will help prevent environmental issues down the line (Rowe et al., 2023).

3.2 Performance of clay liners

Experimental research was carried out by Aldaeef and Rayhani (2015) to estimate how cycles of heat on a daily basis interfere with CCLs' hydraulic efficacy in a simulation resembling a landfill. After being subjected to ambient condition and dehydration cycles, several soil samples were tested for hydraulic conductivity. 30 heat cycles increased CCL hydraulic conductivity by an order of magnitude for low plasticity-index soil materials (PI = 9.5%). Medium (PI = 25%) and high (PI = 37.2%) plasticity materials did not exhibit significant variations in its ability to transmit fluids (hydraulic conductivity) because of the ability to remediate itself. Even after 60 temperature cycles, a barrier covering kept the CCL's hydraulic conductivity constant while reducing the impact of the thermal day-to-day cycles. The low plastic hydrological characteristic of CCLs is greatly altered by wet-dry phases. On the other hand, as demonstrated in Figures 3 and Figure 4, the hydraulic performance of CCLs of medium and high plasticity remained uninterrupted during the course of the test sessions. The report highlighted the requirement for a geomembrane or temporary soil barrier to defend the CCL from atmospheric endangerment.

However, it may not always be the case that high plasticity CCLs would remain unaffected by wet-dry cycles. Melchior et al. (2010) tested the in-situ performance of landfill cover systems in Germany for a span of 18 years. Results from this study indicated that the clay barrier system can indeed be at risk of crack formations due to desiccation and ion exchange. No "self-healing" of the barriers was observed as there was a successive decline in the efficiency of the geosynthetic clay liner system during the first years, having annual leakage rates of 90-220 mm/year which was about 50% of the water that percolates through the soil cover and reaches the drainage layer above the barriers. On the other hand, the composite layer having welded geomembrane performed better during the test period, having an average leakage rate of 2mm/year. It was also noted that the cover thickness is a vital determinant of these outcomes.

If compacted clay liners, which are frequently employed as barrier frameworks for landfills, undergo exposure to the atmosphere for a long time before covering layers are placed on top of them, their hydraulic conductivity may adversely be affected. Considering the presence and absence of geotextile cover, Safari et al. (2014) investigated the fluctuation of the fracture intensity factor in three compacted clay liners while subjected to a yearly cycle of atmospheric conditions. It was found that the desiccation crack severity may be considerably diminished by the geotextile cover placed over the compacted earth. The important finding was that, in every instance, soil layers covered with geotextiles seemed to have kept moisture at the conclusion of

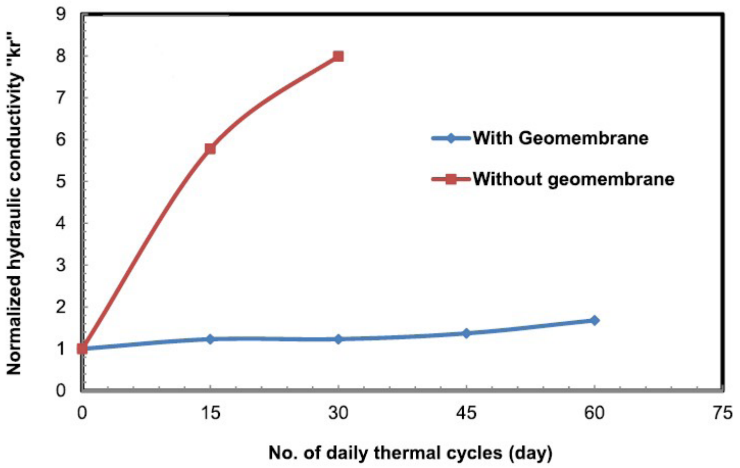

FIGURE 3: Halton clay hydraulic capabilities in the presence and absence of a geomembrane (Aldaeef & Rayhani, 2015).

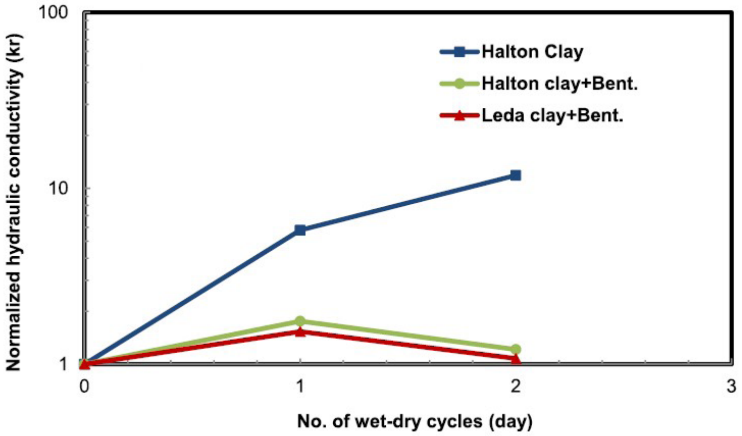

FIGURE 4: Wet-dry cycle influences CCL hydraulic effectiveness (Aldaeef & Rayhani, 2015).

the trial, in contrast to significantly drier soil surfaces that were directly exposed to air conditions. This could be one of the causes of the notable impact of geotextile cover on lowering cracking magnitude, combined with the possibility that white geotextile safeguarded the soil surface colder than the surface-exposed topsoil. However, it is important to note that CCL materials tend to shrink significantly when they dry out. This shrinkage can cause cracks to form within the material leading to an increase in hydraulic conductivity. In this case, geotextiles may not be strong enough to restrain the shrinkage forces causing the desiccation cracks (Melchior et al. 2010). This further leads to the conclusion that two criteria determine the continued efficacy of clay barrier coverings; appropriate barrier layer construction to ensure that the field-scale hydraulic conductivity criterion is satisfied and maintaining the protective layer over time to keep minimal hydraulic conductivity levels (Albright et al., 2006). Due to its thickness, CCL has a higher dampening potential than geosynthetic clay liners (GCL) and is maximally inert to any permeating substances that come into touch with it. GCLs have become prevalent due to ease of fabrication and significantly less air space usage (Daniel, 1993; Vishnupriya & Rajagopalan, 2022). Research continues to advance to study and understand the performance of clay liners, incorporated with different materials, under different environmental conditions.

4. UTILIZING WASTE FOR GOOD: EXPLORING ALTERNATIVE LANDFILL LINER MATERIALS

In landfills, waste is encapsulated by a liner system at the bottom and a cover system at the top (Solomon & Poulose, 2018). The bottom liner system, which is installed at the base of the containment structure prevents leachate from seeping into the ground and contaminating groundwater. It is characterized by low permeability, consisting of a multi-layered system, often including compacted clay, geomembranes to minimize leakage. On the other hand, the cover liner system protects the landfill from above and manages gas emissions. It is placed on top of the waste materials in a containment structure, reducing infiltration of rainwater, minimizing leachate generation and controls the release of methane and other gases to prevent buildup and potential explosions. Both systems work in tandem to minimize the environmental impact of landfills and protect surrounding ecosystems. Over the years, different materials have been explored for use within the protective layers of these liner systems. This is in a bid to reduce the ever-growing number of environmental wastes and also develop locally suitable landfill technologies. Some of these materials are predominantly wastes, like fly ash (FA) and rice husk ash (RHA). Alone, they pose no economic value (Ikpe et al., 2020), but have protective potential when utilized within the layers of liner systems. This is given that the reduce, reuse, and recycle operation has applied recent technological developments and improved comprehension of materials, adding financial and commercial worth to discarded matter while also mitigating the negative environmental implications of uncontrolled waste (Igbinomwanhia, 2012; Ikpe et al., 2019). Research have been performed to assess the practicality of using these waste products in landfill liner systems.

4.1 Fly ash (FA)

When coal is burned in power plants, fly ash is created as a byproduct. It is frequently handled like waste and must be discarded the same way as waste from municipalities. Power plant FA make up a large amount of industrial wastes, produced in millions of tons each year (Yadav et al., 2023). Consequently, a great deal of research has been conducted, especially with regard to the viability of using FA as an engineering component (Mollamahmutoglu & Yilmaz, 2001), in an effort to reduce this alarming growth of this waste generated.

A research investigation on the hydraulic performance of FA-Bentonite mixtures in landfill isolation facilities was conducted by Budihardjo et al. (2021). The combination of FA and 25% bentonite, according to the outcomes had the least amount of permeability and satisfied the requirements for CCLs, with hydraulic conductivity (k) values up to 1×10^{-9} m/s. The combination of bentonite and FA reinforced the cohesion links between molecules and boosted stability. The conclusion that followed was that the permeability coefficient of mixed soils could be effectively decreased by combining FA, which was being utilized as a landfill material, with other materials like bentonite. In general, this combination provides substantial strength in compression, lesser hydraulic conductivity, a degree of adaptability, and reduced crack susceptibility (Amina & Ravi, 2017). FA has been applied to blends of cement as well. The 90% FA + 10% cement mixture's hydraulic conductivity was determined to be less than 1×10^{-9} m/s, meeting the requirements for a landfill lining material (Mishra & Ravindra, 2015). Furthermore, FA that had been passed through a 0.075 mm sieve (No. 200) with up to 10% rubber and bentonite included looked to be a good material for making a liner since it fulfilled the most crucial requirement—hydraulic conductivity (Cokca & Yilmaz, 2004). FA is well recognized for its pozzolanic behaviours, which, when cured, triggers it to solidify and get stronger over time (Garg et al., 2020). As a result, the curing time causes the hydraulic conductivity to decrease, thus, improving the stability of the landfill. Furthermore, FA can typically be developed in various ratios with other materials to achieve the acceptable hydraulic conductivity and strength threshold.

4.2 Paper mill sludge (PMS)

Paper mill sludge (PMS) is produced when wastewater is treated in the paper-making process. Techniques for handling and disposing of it raise significant worries. It can be rid of as waste or turned into valuable products, transforming it into a substance with extra worth (Likon et al., 2009). Using it as a material for landfill liners is one option of utilizing it so as to reduce its nuisance to the ecosystem, as approximately 400 million wet tons of PMS are generated globally every year (Faubert et al., 2016).

After evaluating the geotechnical features involved in using PMS as a bottom liner and landfill cover, Balkaya (2019) came to the conclusion that the material's geotechnical qualities make it an appealing replacement for compacted clay in landfills that house MSW. According to Kuokkanen et al. (2008), PMS has appropriate hydraulic conductivity, making it ideal for use as a barrier at the sides and base of toxic waste landfills as well as in the constructed layers of the landfill covering architecture. The combination of PMS and sepiolite has also been investigated. Their aggregation yields an effective void filler which in turn reduces void ratio and hydraulic conductivity, making them suitable for landfill liner design (Thomas & Thomas, 2019). This is also an effective way of ridding the environment of paper mill sludge.

4.3 Waste Foundry sand (WFS)

WFS is the sand that has been used repeatedly in the foundry until it is exhausted and can no longer be utilized to create moulds. It is typically a blend of fine homogeneous sand, bentonite, and other components. Millions of tons of these sands are dumped as waste from foundries each year, which poses a significant disposal issue (Ochepo, 2020, Ahmad et al., 2022). Additionally, studies have been conducted to assess WFS as a potential substitute barrier component in constructed landfills.

In a laboratory investigation conducted by Abichou et al. (2000), foundry green sands were found to meet the hydraulic conductivity demand of less than 1×10^{-9} m/s. WFS has also been incorporated with rice husk ash and fly ash to yield stronger materials with reduced hydraulic conductivity. More cementing gel is produced by this mixture, increasing the amount of bonding in the material's matrix (Ochepo, 2020; Cherian & Abraham, 2020), making it suitable as landfill liners.

4.4 Recycled concrete aggregate (RCA)

The amount of waste generated during building and demolition has increased recently, which is having a negative impact on the ecosystem. The majority of waste produced during construction and demolition (C&D) is still aggregate, accounting for 85% of all waste produced. (Tam et al., 2018). In the building sector, utilizing waste materials like recycled aggregate can have positive effects on the environment and the economy (Wagih et al., 2013). One of such applications is in the design of landfill liners. Vathani and Logeshwari (2023) carried out a study on leachate repellency in landfills using Recycled Coarse Aggregate (RCA) enhanced with paper pulp and adsorbent. The results here also displayed promising characteristics. This caters for strength of the liner material and also effective disposal of wastes (Xu et al., 2023).

4.5 Waste wood ash (WWA)

Wood ash consists of organic and inorganic residues formed as a result of burning wood and wood products. When wood is burned, an average of 6-10% of its weight is turned into ash (Siddique, 2012). Globally, the production of woody biomass is approximately 4600 million tons per year, out of which 60% is used for energy production, 20% is used for industrial purposes, and the remaining 20% is the primary production loss that decomposes in the field (Tripathi et al., 2019). Ash from wood is a pozzolanic admixture. An alumina and silica-rich substance known as a pozzolana has barely any cementitious effect by itself, but when it splits finely and combined with moisture at room temperature, it reacts chemically with calcium hydroxide to produce compounds having cementitious attributes. In wood-fired power plants, paper mills, and other wood-burning establishments, wood ash is produced as a byproduct of burning. In the future, there will be a greater use of wood in the production of energy since it is an environmentally beneficial and renewable resource. The quantity of wood ash generated will rise consequently. This calls for the need to device new ways to reduce this increasing amount of WWA occurring in the ecosystem (Ghorpade, 2012; Martínez-García et al., 2022). One of such ways is in the application as landfill liner materials.

Oluremi et al. (2019) looked at the use of WWA as a liner in landfill building on lateritic soil. The results of this study indicate that WWA, with a content of 4%, is an appropriate material for landfill liners since it meets the requirements for both unconfined compressive strength (UCS) of 200 kN/m^2 and hydraulic conductivity threshold of 1×10^{-9} m/s when coupled with laterite. This is essential for waste confinement operations and will reduce contamination and the detrimental impacts of disposing of wood waste on the ecosystem.

4.6 Rice husk ash (RHA)

Ash from burning rice husk—the outer layer that encircles the rice—in a controlled setting is known as RHA. Around 20 million tons of RHA are produced per year according to Market Data Forecast, 2023. 85-90% of it is made up of amorphous silica. It is known that RHA is a potent pozzolan. When used as a soil stabilizer/admixture in soil stabilization as well as a substitute for cement in concrete mixes, it has had favourable outcomes (Ochepo, 2020). One of its more current uses is as a material for landfill liners.

Onyelowe et al. (2021) examined RHA for its possibility for use as a liner material. It displayed good qualities as a micro-pore filler within soil matrices, which affirms it as an excellent "green" building materials which strengthen the landfill clay liner's leachate barrier for environmentally friendly construction. According to findings, RHA with a pozzolanic chemical-based modulus of 81.47% can be used in place of cement in the design of landfills and containment facilities that are less toxic and effective. This will protect the soil, subsurface water, and surrounding environment from carbon emissions and wastewater harm (Onyelowe et al., 2022).

4.7 Bagasse ash (BA)

Bagasse, the leftover material from sugarcane after the juice has been obtained, is often burned in sugar mill incinerators to create steam and power. It then turns into black fiber and ash. There continued to be a lot of bagasse disposals in open spaces, triggering environmental problems. When inhaled in significant quantities, BA causes respiratory diseases because it ferments and decomposes in the open atmosphere. Based on findings by Shahbandeh (2024), Brazil, India, China and Thailand produce 724.43, 439.42, 103.38, and 92.1 million metric tons of sugar cane respectively. These numbers continue to skyrocket, leaving disposal issues for wastes from sugar cane. This gives birth to the need to utilize these wastes especially in the field of engineering. Using BA is essential to lowering the quantity of waste in the natural world. Investigations have been implemented on the practical application of BA, particularly in building, as a substitute material and to address ecological concerns (Kartika et al., 2022). In the aspect of its use as a landfill liner material, BA has proved effective in its application. In waste confinement facilities (covers and liners), laterite modified by a concentration of as much as 12% BA can function as an efficient hydraulic barrier, with the best results occurring at 8% administration, according to Eberemu (2013). A hydraulic conductivity of 1×10^{-9} m/s and a UCS of more than 200 kN/m^2 were obtained from these BA ingredients. BA decreases the permeability of soil, which indicates that it can prevent leaching out of contaminants and can further prevent contamination of ground water (Jishnu & Mohini, 2020). These findings assist in addressing some of the environmental issues caused by bagasse that comes from the sugar industry and provide an affordable method of disposal in addition to advocating for the use of an alternate landfill lining component.

4.8 Coconut fiber (CF)

The most well-known fibrous byproduct of coconut farming is coconut fibre. At least 30 million tons of coconuts are produced worldwide yearly, and they are widely available in tropical countries' coastal regions (Gaspar et al., 2020). According to Panyakaew and Fotios (2011), the coconut husk has a high lignin and phenolic content and is made up of 70% pith and 30% fibre. Coconut fiber's high lignin content makes it incredibly elastic, strong, and decay-resistant. Danso (2017) found that the fibres from coconut husks were more resilient than the fibres from oil palm bark, with a mean diameter of 400 μm and a mean length of 103 mm. Given that waste materials and fibers from nature are affordable, readily available locally, and ecologically friendly, their use to improve the state of soil is advantageous (Kaushik & Singh, 2021). To this effect, the geotechnical properties of coconut fiber, otherwise known as coir, has been looked into for its use as a geotechnical material in soils and landfill liners. Puspita et al. (2023) evaluated coconut fiber and FA-composites for utilization in landfill retention layering. The results here showed that coconut fiber additions would yield considerable and workable results in terms of strength and hydraulic conductivity. This solves the issue of coir disposal, while providing a sustainable and locally accessible liner technology.

4.9 Cassava peel ash (CPA)

Research on the effects of agricultural solid wastes from cassava on the engineering qualities of soil has been undertaken (Tiza and Iorver, 2016). This agricultural waste ash has recently been investigated as a potential barrier material, with CPA demonstrating favorable outputs. CPA-treated black cotton soil was studied by Adeyemo et al. (2022) as a potential material for hydraulic barriers in MSW containment facilities. CPA passing through 0.075mm sieve was utilized. The findings indicated that black cotton soil with a 16 % CPA concentration successfully meets the design standards needed to be applied as a liner or cover in MSW plants after it produced a UCS value more than 200 kN/m^2 and a hydraulic conductivity lesser than 1 × 10^{-9} m/s. Approximately 40 million metric tons of cassava peels are being generated annually in Sub-Saharan Africa (IITA, 2022). This alarming number can be catered for via utilization of the ash from this waste as a landfill liner material.

4.10 Plastic waste (PW)

Numerous types of solid wastes are generated as a consequence of population growth, fast urbanization, manufacturing operations, and evolving living expenses (Reddy et al. 2020; Kaza et al. 2018) especially plastic wastes. One of the most significant problems the world is currently experiencing is plastic waste, which has far-reaching effects. It can damage ecosystems, cause harm to wildlife, especially marine species, and impair human health. It can be found fouling everything from the highest mountains to the deepest ocean trenches. The issue of plastic waste has been more acute in recent times due to the steady increase in the consumption of this multipurpose material. Since the turn of the century, the amount of plastics produced worldwide has doubled, reaching about 400 million metric tons annually. Plastic items typically last 10 years, but depending on their composition and disposal method, they can take up to 500 years to degrade (Alves, 2024). Since plastic degrades at a slower rate, reducing plastic has become a major concern. Considering there is little recycling or repurposing of this waste in an eco-friendly manner, a significant portion of it ends up as garbage in landfills or oceans. PW-recycling is a more productive technique than landfilling and incineration. Therefore, it has been determined that using PW in geotechnical and civil engineering applications has the greatest potential for large-scale consumption, which can also aid in reducing disposal problems (Reddy et al., 2022). Abd-Aziz et al. (2019) carried out a series of shear strength tests on the application of PW as a liner material and concluded that it possesses considerable shear strength needed for engineering application. This simultaneously caters for the disposal of the increasing number of PW being generated while also proffering an alternative liner material that is sustainable.

4.11 Waste Tire Textile Fibers (WTTFs)

Globally, an estimated one billion End-of-Life tires (ELTs) are discarded yearly, and this waste flow is growing dynamically (Golawska, 2024). The increasing number of tires and automobiles on the market means that disposing of WTTFs is very harmful to the ecosystem. This is because burning them releases harmful gases into the atmosphere and takes up a lot of important landfill space. Since tires burn quickly, release dangerous fumes, and tend to contaminate groundwater and soil, burning them is not an ideal environmental practice (Gheni et al., 2019). Additionally, it is not advised to bury End-of-Life Tires (ELTs) in landfills since they take up a lot of useful space, hold water, provide a home for rodents as well as insects to reproduce, and pose a significant risk of fire (Abbaspour et al., 2019; Thomas and Gupta, 2016). Research has been done on the reuse of waste products generated during the ELT recycling process in the field of civil engineering, even in its use as landfill liner materials.

Narani et al. (2020) studied the use of WTTFs as a landfill liner material and concluded that it is feasible to employ WTTF-expansive soil combinations specifically for municipal solid waste landfills as coverings and impermeable liners. This allows for the improvement of the liner without placing an undue financial burden on the projects, while also addressing the increasing environmental hazard posed by WTTFs.

5. IMPLICATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

It is not a surprise that researchers are actively scouting and testing out new approaches and technologies that can be employed for landfill liner design and construction, especially waste materials. This is because as globalization increases, so does the generation of wastes (Akinwumi et al., 2019). To this effect, there is an increasing need to devise new means to dispose of these waste substances. Their incorporation in the design of landfill liners poses to be one of such sustainable disposal methods on the long run, as research has shown that they are useful, eco-friendly, and cost effective in their application as composite liner materials.

The drive for sustainability in construction has been advancing over the years. Diverse research has been carried out and is still being carried out, with respect to finding ways in which construction can be carried out with the aim of protecting the ecosystem in the most effective ways. One of such area of construction is in the design of landfills and landfill liners, where various assessments have been carried out on potential landfill liner materials that can be incorporated in landfill design, especially the waste materials discussed thus far. However, more research and analysis can be carried out on other waste materials that are locally suitable for construction purposes, with the desire to determine their potential as effective landfill liner materials. Some of these wastes that can be looked into are textile wastes (TW), reclaimed asphalt pavement (RAP), gypsum waste (GW), groundnut shell ash (GSA), coffee husk ash (CHA), eggshell powder (EP), etc. These materials have been employed for the stabilization of soil for construction purposes and also as concrete admixtures (Oyebisi et al., 2020; Bamigboye et al., 2021), in a bid to discover sustainable alternatives to drive environmentally sustainability (Ofuyatan et al., 2020). They infuse strength gain within the soil matrix due to their pozzolanic nature, which is as a result of the complete chemical process of hydration and cation exchange, leading to the formation of calcium silicate hydrates and calcium aluminate hydrates. These compounds then fill the soil voids, resulting in an improvement in their inter-particle cohesion and microstructural integrity (Edeh et al., 2012; Sathiparan et al., 2023; Dezfouli, 2020.). This same principle must be put in mind during future research and advances carried out in aspects of the design of innovative landfill liner materials so as to aid the discovery of alternative materials that are suitable in strength, hydraulic conductivity and also environmental protection.

6. CONCLUSIONS

The design and utilization of sustainable liner materials in landfill construction plays a crucial role in mitigating environmental and health hazards associated with improper waste disposal. Modern landfills have evolved over centuries, reflecting societal needs, technological advancements, and a growing awareness of environmental impacts. The 20th century witnessed a shift towards engineered landfills, incorporating practices such as compaction, daily covering, and leachate collection to minimize environmental impact.

Seismic analysis of landfills and the management of landfill leachates are essential aspects of landfill design, requiring careful consideration. Proper liner systems are crucial for preventing leachate contamination and controlling gas emissions, especially methane. The choice of landfill liner materials significantly influences the effectiveness of containment systems.

Research has explored various landfill liner materials, including fly ash, paper mill sludge, waste foundry sand, recycled concrete aggregate, waste wood ash, rice husk ash, bagasse ash, coconut fiber, cassava peel ash, plastic waste, and waste tire textile fibers. These materials have demonstrated potential in meeting design parameters for hydraulic conductivity and strength, making them viable options for sustainable landfill construction. The incorporation of these waste materials not only addresses the challenges of waste disposal but also contributes to environmentally friendly construction practices.

While the current research highlights the promising performance of these materials, there is a need for continued exploration of other locally suitable waste materials, such as textile wastes, reclaimed asphalt pavement, gypsum waste, groundnut shell ash, coffee husk ash, eggshell powder, among others. Future studies should focus on assessing the potential of these materials as effective landfill liner components, considering their strength, hydraulic conductivity, and environmental protection attributes. In striving for sustainability in landfill design, ongoing research efforts will contribute to the development of innovative and eco-friendly solutions for waste containment and environmental conservation.

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