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Cuspated Drain (CD) Technology for Landfill Liner Systems: Long-Term Durability and Performance Insights – A Critical Review

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Abstract

The increasing amount of waste being generated in South Africa highlights the need for effective landfill solutions. Currently, landfilling is the most used method for managing solid waste. However, traditional landfill liners face challenges like pressure from gravel contact points and clogging, while cuspated drain (CD) technology offers improved drainage and structural integrity. This critical review examines CDs in landfill liners, focusing on their durability and performance. CDs, made of cuspated high-density polyethylene (HDPE) cores with optional geotextile filters, maintain drainage under compressive loads and are versatile and cost-effective. Despite their advantages, there is limited research on the long-term durability of HDPE CDs compared to traditional HDPE geomembranes (GMBs). This this gap will be addressed by evaluating the performance of HDPE CDs under various conditions and comparing them to HDPE GMBs. The findings will contribute to advancing landfill liner technology and guiding sustainable waste management design decisions.

Keywords: *landfill liner systems, cuspated drain (CD) technology, durability, solid waste management, sustainability.*

1 Introduction

South Africa, a significant contributor to global solid waste generation, ranks as the third-highest producer of municipal solid waste (MSW) in the Sub-Saharan region (International Solid Waste Association (ISWA), 2015; Greencape, 2017; Kubanza & Simatele, 2020). The Department of Fisheries, Forestry, and the Environment (DFFE) reported that waste generation in South Africa escalated from approximately 108 million tonnes in 2012 to 121 million tonnes in 2017, and this is expected to rise significantly by 2030 (Kawai & Tasaki, 2016; The World Bank, 2020; Mor & Ravindra, 2023). This increase, attributed to urbanization, population growth, rural-urban migration, industrial expansion, and improved economic status, underscores the pressing need for effective landfill solutions.

Landfilling remains the predominant method of solid waste management in South Africa, with about 90.1% of waste disposed of in landfills (Nyika et al., 2019; Chen et al., 2020; Nanda & Berruti, 2021). MSW landfills, when properly designed, constructed, and operated, offer an environmentally responsible means of disposing of non-recyclable waste (Barlaz, 2016; Nanda & Berruti, 2021). However, stringent regulations and environmental concerns necessitate the development of robust landfill liner systems to prevent the migration of hazardous substances, especially leachate, into the surrounding soil and groundwater (Idris, Inanc & Hassan, 2004; Nanda & Berruti, 2021; Touze-Foltz, Xie & Stoltz, 2021).

Engineered landfills in South Africa comprise crucial components such as basal liners, side slope liners, and cover/capping liners, alongside features like leachate collection, removal, treatment systems, and leak detection systems (if double liners are employed), all primarily constructed with various geosynthetics forming composite liner systems (Shukla & Yin, 2006; Shukla, 2016). Previously, landfill liner systems used coarse gravel or leachate stones in leachate collection systems to improve drainage and structural integrity. Despite advancements, traditional gravel drainage layers pose challenges such as concentrated pressure due to gravel contact points, stress on GMBs which can lead to stress cracking, and clogging of collection systems (Abdelaal, Rowe & Brachman, 2014; Eldesouky & Brachman, 2018). To address these challenges, cuspated drain (CD) technology, a type of geocomposite drain (GD), emerges as a promising alternative to gravel drainage layers. This review paper aims to critically explore the application of CD technology within landfill liner systems, offering valuable insights into their durability and performance.

2 Landfill Liner Systems in South Africa

The waste management system in South Africa operates within the framework of the waste hierarchy, as outlined in the 1999 National Waste Management Strategy (NWMS) by the Department of Environmental Affairs (2018). This hierarchy prioritizes waste avoidance and reduction, followed by reuse, recycling, recovery, and treatment, with disposal considered a last resort (Nyika et al., 2019, 2021; Nanda & Berruti, 2021). Despite the emphasis on minimizing disposal, landfilling has emerged as the predominant method of solid waste disposal in South Africa, owing to its cost-effectiveness and simplicity (Harvey, Baghri & Reed, 2002; Nyika et al., 2019; Nanda & Berruti, 2021). This preference is evident from statistics indicating that a significant proportion of both general waste (61.4%) and hazardous waste (93.7%) in South Africa is disposed of through landfills (Nyika et al., 2019, 2021; Nanda & Berruti, 2021).

Modern engineered landfills in South Africa se barrier systems consisting of various components to protect the environment. These components include leachate collection layers, geotextile (GTX) or soil protection, geomembrane (GMB) liner, and compacted clay liner (CCL)/geosynthetic clay liner (GCL) with attenuation layers underneath, as can be seen in Figure 1. In some cases, landfills may even have double liner composite systems for added protection (Islam, 2009; Sabir, 2011; Eldesouky, 2018; Adeleke et al., 2021; Muluti et al., 2023). However, coarse gravel as a drainage layer can contribute to clogging of the collection system by chemicals and biological substances (Fleming & Rowe, 2004). To address this challenge and prolong the service life of GMBs, various methods have been proposed, including the use of geotextile (GTX) protection layers between the leachate collection system and the GMB (Brachman & Gudina, 2008a,b; Dickinson & Brachman, 2008; Brachman & Sabir, 2010; Eldesouky & Brachman, 2018, 2023). However, concerns about sustained tensile strains on GMBs have prompted the exploration of alternatives such as cuspated drain (CD) technology, a type of geocomposite drain (GD), as a potential replacement for gravel drainage layers.

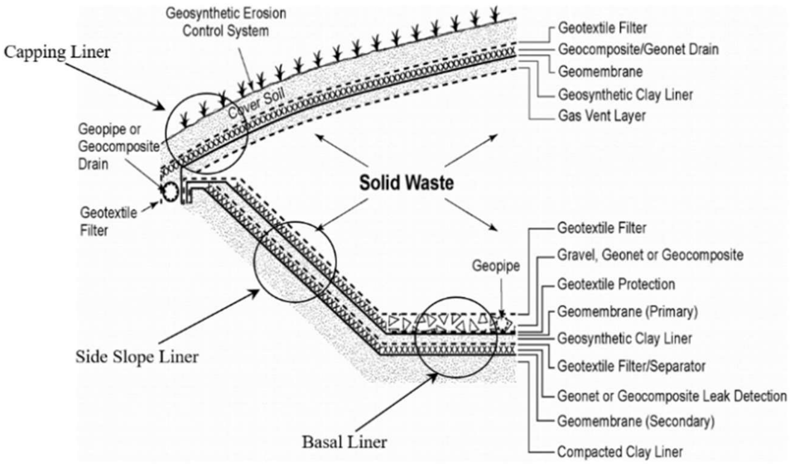

Figure 1: Three main engineering elements of a landfill liner. (after Ng & Ramsey*, 2012*)

3 Understanding Cuspated Drain (CD) Technology

Cuspated drains (CDs) are composed of a single cuspate drainage core with optional geotextile filters laminated on one or both sides, as can be seen in Figure 2 (Othman, 2016; Chao, 2021). This design allows fluids and gases to percolate into the core while providing support to the backfill material. The single cuspated HDPE core creates a high-performance, free-draining void by utilizing the spacing between the cuspates. This unique design offers clear passageways, facilitating flow in all directions (see Figure 2), even in the event of damage or blockage. The core maintains its drainage capacity under various compressive loadings due to its high relative compressive strength and creep resistance properties (Mckean & Inouye, 2001; Yarahmadi, Gratchev & Jeng, 2017a,b).

Cuspated Drains (CDs) are versatile and find diverse applications in various construction scenarios, including capping, cut-off trenches, embankments, gas vents, landfills, mining containments, retaining walls, roadworks, and tunnels. They effectively prevent water penetration and drain excess water, thereby enhancing the stability of structures (ABG Geosynthetics Ltd, 2015). In landfill applications, CDs are integrated into capping/cover, base, and side slope lining systems, serving multiple functions such as drainage, protection, and leak detection (Fowmes, Dixon & Jones, 2007; Nanda & Berruti, 2021). Despite their versatility and potential benefits, previous research has primarily focused on geonets, overlooking the potential advantages of using CDs in landfill applications (Fannin, Choy & Atwater, 1998; Davies & Legge, 2003; Yarahmadi & Gratchev, 2016a,b; Yarahmadi, Gratchev & Jeng, 2017a). CDs are known to facilitate leachate removal and prevent the accumulation of excess moisture. They can also function as a leak detection layer, providing early warnings in case of possible containment system breaches. Furthermore, CDs have been proposed to reduce stress concentrations and distribute loads more evenly, thus protecting GMBs from damage during installation or when encountering uneven surfaces (Nanda & Berruti, 2021). However, questions remain regarding their actual effectiveness in preserving GMB integrity over time.

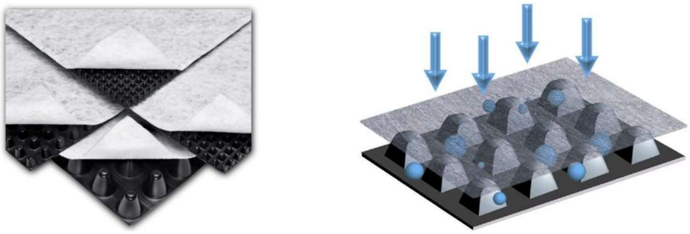

Figure 2: Typical cuspated drains. (ABG Geosynthetics Ltd, 2015)

While CDs effectively facilitate leachate removal and prevent excess moisture accumulation, concerns arise regarding their enduring integrity when exposed to the harsh conditions prevalent in landfill sites. Landfill leachate poses a significant challenge, prompting inquiries into the resilience of CDs against such contaminants. Thus, a thorough examination of their long-term durability is imperative to ensure their effectiveness over time. With this context in mind, it becomes crucial to delve into the intricacies of assessing the long-term durability of CDs, particularly in comparison to traditional HDPE GMBs. This assessment not only complements existing laboratory testing protocols but also instils confidence in the viability of CDs as enduring solutions in landfill liner systems.

4 Long-Term Durability Assessment

Cuspated Drains (CDs) are made by combining a cuspated HDPE drainage core with a polypropylene (PP) geotextile (GTX) in a heat bonding process using polyolefin-based materials (see Figure 2). HDPE materials are known for their strong resistance to a wide range of chemicals. They are commonly used in landfill applications, especially for bottom GMB liners, because they can withstand aggressive leachate components (Rowe & Sangam, 2002; Islam, 2009; Rowe et al., 2010; Lavoie et al., 2020). HDPE GMBs typically consist of approximately 96-97.5% polyethylene resin, 2-3% UV protection (usually carbon black), and 0.5-1.0% other additives like antioxidants and stabilizers (Sangam & Rowe, 2002; Ewais, Rowe & Scheirs, 2014; Lavoie, 2021).

HDPE GMBs can undergo various aging processes, such as UV degradation, extraction degradation, thermal degradation, swelling, biological degradation, and oxidative degradation (Rowe & Sangam, 2002; Lavoie, 2021). These processes can affect properties of the material and reduce its durability. Specifically, oxidation is the most significant degradation mechanism, which can lead to decreased strength and increased brittleness of the GMBs (Hsuan & Koerner, 1998; Hsuan et al., 2008). Durability, in this context, refers to the ability of the GMB material to withstand or resist degradation when exposed to oxidative agents over time. Therefore, to evaluate the effectiveness of using HDPE CDs as a protective layer for GMBs in landfill liners, it is important to comprehensively investigate the durability of HDPE CDs under different conditions. However, before doing so, it is necessary to understand how to evaluate the durability of HDPE GMBs and then apply this concept to assessing the durability of HDPE CDs.

The oxidative degradation of HDPE GMBs involves a complex process influenced by factors such as exposure conditions, exposure medium, and mechanical stresses (Sangam, 2001; Rowe & Sangam, 2002; Jafari, Stark & Rowe, 2014). This degradation can be divided into three stages: antioxidant depletion, induction time to onset of degradation, and time to reach 50% degradation, also known as the half-life (Figure 3) (Hsuan & Koerner, 1998). In the antioxidant depletion stage, the antioxidants in the HDPE GMB gradually deplete, initiating oxidation. This is followed by the induction time, during which oxidation occurs at a slow rate before accelerating and causing noticeable changes in the properties of the material. Finally, the polymer degradation progresses to the point of failure, accompanied by significant alterations in its physical and mechanical properties (Abdelaal & Rowe, 2014; Ewais, Rowe & Scheirs, 2014; Lavoie et al., 2020).

Various testing methods are used to evaluate the oxidative degradation of HDPE GMBs. These include the oxidative induction time (OIT) test, melt flow index (MFI) test, tensile test, stress crack resistance (SCR) test, and puncture strength test (Hsuan & Koerner, 1998; Sangam & Rowe, 2002; Koerner, Wong & Koerner, 2012). The OIT test measures the antioxidative properties of HDPE GMBs by determining the time it takes for oxidation to occur. The MFI test assesses changes in molecular weight caused by oxidative degradation, while the tensile test evaluates changes in mechanical properties due to degradation. The SCR test and puncture strength test provide information on crack resistance and puncture resistance, respectively, which are important for assessing GMB integrity.

The oxidative degradation of HDPE GMBs is influenced by various factors, including material properties, exposure conditions, exposure medium, and mechanical stresses (Sangam, 2001; Jafari, Stark & Rowe, 2014) For example, the chemical structure and thickness of the GMB affect its resistance to oxidation. Exposure to sunlight, heat, and radiation speeds up degradation. Additionally, the presence of transition metals in the exposure medium can enhance oxidation rates. This highlights the importance of considering environmental factors in the design and installation of GMBs. These concepts can also be applied to assessing the durability of HDPE CD to ensure that their durability metrics meet industry standards and guidelines for HDPE GMBs used in landfill liners.

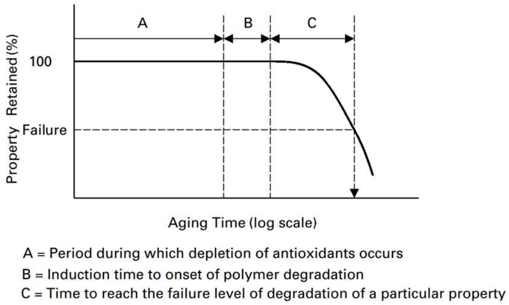

Figure 3: The concept of HDPE oxidative degradation. (modified from Hsuan & Koerner, 1998).

5 Performance Insights of CDs

Traditionally, Class B basal liners in South African landfills consist of a filter GTX directly beneath the waste, followed by a 150 mm stone leachate collection system. This is then underlain by either a 100 mm silt sand protection layer or a GTX of equivalent performance. Below that is a 1.5 mm HDPE GMB placed on top of a 600 mm compacted clay liner (CCL), layered in 4 × 150 mm layers (see Figure 4(a)).

If a geocomposite system with various geosynthetics were to replace this, the 150 mm stone leachate collection system would be replaced by a drainage geocomposite like a CD. The CCL would be replaced by a geosynthetic clay liner (GCL), as shown in Figure 4(b). The CD consists of a cuspated HDPE core with filter textiles on either side. The total thickness of the geocomposite system would be just under 20 mm, which also increases the available landfill volume. The geosynthetic system is easier to install, more cost-effective, and has a lower carbon footprint. In addition, drainage geocomposites allow for faster water flow compared to granular drainage media. For example, a 6 mm thick drainage geocomposite can manage a flow capacity of about 0.13 liters/m/s, equivalent to approximately 0.03 liters/m/s of a 300 mm thick granular stone drainage layer (see Figure 4). This means that the flow capacity of a drainage geocomposite is around 4 times that of drainage gravel due to its open void structure.

ABG Geosynthetics conducted a case study on the development of a new 45 m deep landfill cell at Lean Quarry landfill site in the UK (ABG Geosynthetics Ltd, 2020). The project, carried out by Viridor Waste Management Ltd in collaboration with SLR Consulting, aimed to address the need for additional waste disposal capacity in an environmentally sensitive area under close supervision by the Environment Agency. The main challenge was to design a geosynthetic lining solution that included a composite system (GCL and HDPE membranes), a geocomposite drainage/protection layer, and drainage stone on steep slopes. The design had to ensure UV stability, puncture resistance, and long-term compressive creep resistance under 45 m of waste pressure. ABG Geosynthetics selected a Pozidrain Protector 745 geocomposite drainage layer for its excellent GMB protection, high flow capacity, and ease of installation on steep slopes. This decision resulted in benefits such as excellent GMB protection at 1,200 kPa loading, high flow capacity in both directions, and the replacement of approximately 5 000 m^3 of drainage stones, which led to a more cost-effective design. The design met Environment Agency standards for effective GMB protection and leachate drainage, as well as achieving the required factor of safety for the deep installation.

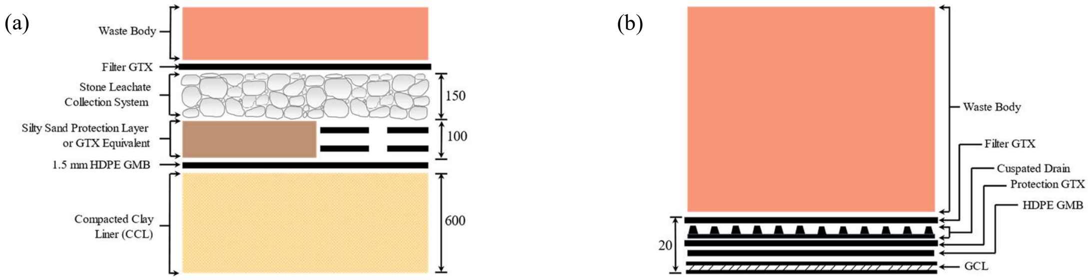

Figure 4: Showing: (a) traditional class B liner system, and (b) geosynthetic liner system.

6 Research Gap and Proposed Approach

Although significant research has been conducted on HDPE geomembranes (GMBs), there remains a noticeable gap in studies specifically focused on HDPE cuspated drains (CDs). This gap underscores the need for further investigation into the performance and durability of CDs in real-world applications, particularly in landfill liner systems. Examining the durability of HDPE CDs in landfill liner applications is crucial, including comparing them to HDPE GMBs to determine if they meet established benchmarks. Design engineers require this information to make informed decisions about the use of CDs. Additionally, there is a scarcity of comprehensive research supporting the practical application of CDs, especially concerning strain and environmental factors impacting HDPE GMBs in landfill liner systems. More data and insights are necessary to validate the suitability and performance of CDs.

Therefore, the proposed study will aim to expand existing knowledge by examining how the unique design and composition of HDPE CDs influence their long-term durability. Specifically, the study will compare the performance of HDPE CDs to conventional HDPE liners under conditions of UV exposure, temperature fluctuations, and mechanical stress. Drawing parallels between this research and previous studies on HDPE GMBs will provide a better understanding of the challenges and opportunities associated with the use of HDPE CDs in real-world applications. Importantly, there has been very little to no research conducted on HDPE CDs, underscoring the significance of our research in filling this gap.

7 Conclusion

In conclusion, this review paper emphasizes the urgent need for effective landfill solutions in South Africa as waste generation continues to rise. Traditional landfill liner systems face challenges that can compromise environmental safety, highlighting the importance of exploring alternative technologies such as Cuspated Drain (CD) technology. CDs offer improved drainage and structural integrity, making them a promising solution for landfill liner systems. However, there is a significant research gap regarding the long-term durability of HDPE CDs, especially when compared to conventional HDPE geomembranes (GMBs). The proposed study aims to address this gap by investigating the performance of HDPE CDs under various environmental conditions and comparing them to HDPE GMBs. By providing insights into the durability and effectiveness of HDPE CDs, this review was aimed at informing design decisions and contribute to the advancement of landfill liner technology for sustainable waste management practices in South Africa and beyond.

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