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Waste valorisation in landfill barriers: Opportunities and challenges

Valorisation des déchets en tant que barrières d'étanchéité de décharge: Opportunités et défis

F. Chihi*, G. Varga
Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering, Budapest University of Technology and Economics, Budapest, Hungary

**chihi.feten@emk.bme.hu*

ABSTRACT: Landfill barriers play a fundamental role in environmental protection, mitigating the migration of contaminants into the surrounding environment. This review provides an in-depth analysis of the potential of diverse waste types as substitutes or amendments for conventional landfill liners and covers. Outlined from extensive literature, the study highlights the dual advantage of waste utilization in landfill barriers: conservation of natural resources and waste recycling enhancement. While certain waste products have shown promise due to their improved geotechnical and mechanical characteristics, concerns about the leaching of hazardous contaminants remain paramount. This review evaluates the optimal use of waste in landfill barriers. It emphasizes the necessity of comprehensive chemical and bioassay evaluations to accurately predict long-term leaching behavior and environmental compatibility. Research indicates the prospective utility of waste-derived materials in landfill barrier applications, aligned with environmental sustainability objectives. However, this approach mandates a heightened emphasis on safety, necessitating comprehensive, site-specific evaluations.

RÉSUMÉ: Les barrières d'étanchéité de décharge jouent un rôle fondamental dans la protection de l'environnement, en atténuant la migration des contaminants dans l'environnement environnant. Cette revue fournit une analyse approfondie du potentiel de divers types de déchets en tant que substituts ou amendements pour les revêtements et couvertures de décharge conventionnels. Décrit à partir d'une vaste littérature, l'étude met en évidence le double avantage de l'utilisation des déchets dans les barrières de décharge: la conservation des ressources naturelles et l'amélioration du recyclage des déchets. Bien que certains produits de déchets se soient montrés prometteurs en raison de leurs caractéristiques géotechniques et mécaniques améliorées, les préoccupations concernant la lixiviation des contaminants dangereux restent primordiales. Cette revue évalue l'utilisation optimale des déchets dans les barrières de décharge. Elle souligne la nécessité d'évaluations chimiques et bioessais complètes pour prédire avec précision le comportement de lixiviation à long terme et la compatibilité environnementale. La recherche indique l'utilité prospective des matériaux dérivés des déchets dans les applications de barrière de décharge, alignée avec les objectifs de durabilité environnementale. Cependant, cette approche exige un accent accru sur la sécurité, nécessitant des évaluations complètes et spécifiques au site.

Keywords: Landfill barriers; geotechnical characteristics; recycling.

1 INTRODUCTION

In recent decades, incineration, recycling, and composting have increasingly enhanced solid waste management strategies in contemporary societies. However, landfilling persists as a globally predominant method for waste disposal. A significant portion of industrialized nations, including numerous European Union (EU) member states and the United States of America (US), continue to incorporate landfilling as a fundamental component of their solid waste management systems.

The primary environmental concern with landfilling is the contamination of the surrounding environment due to landfill leachate. To prevent this, engineered landfills are equipped with impermeable multi layered barriers, including a cover and bottom liner systems, which consist of natural geological barriers, technical barriers, and drainage systems. These systems serve to reduce rainfall infiltration, control gas emissions, and protect soil and water contamination.

EU regulations stringently govern landfill specifications, mandating a combination of geological and artificial barriers along with bottom liners from the construction phase till the closure and post-closure phase. It should be mentioned that the affordability and technological feasibility of such landfill lining technologies is often beyond the reach of low-income countries. Consequently, a diverse range of alternative materials, both natural and waste-derived, have gained attention as potential substitutes.

The application of waste materials in landfill linings is believed to have economic benefits. It conserves natural resources and conforms to essential international environmental policies that emphasize waste reduction, the reuse of materials, and recycling efforts. Moreover, incorporating waste materials can potentially enhance liner characteristics and performance. However, the application of these unconventional materials is not without controversy.

Despite extensive research on the use of wastes material in landfill barrier construction, results still present poorly definitive conclusions on the suitability of each waste material for such applications. Therefore, this paper provides a comparative analysis of various waste materials suggested in literature publications for use in engineered hydraulic barriers within landfills. It discusses the geotechnical (Figure 1) and hydraulic conductivity (*k*)properties (Table 1), advantages, and disadvantages of these materials, with a focus on environmental protection issues, adhering to international global regulatory norms and guidelines.

2 RED MUD

In waste management, the application of Red Mud, a byproduct of alumina extraction from bauxite, has garnered significant interest for its potential in environmental remediation, particularly as a liner material for landfills. Several studies, demonstrated the Red Mud's efficacy in reducing contaminants like iron (Fe), sulphate (SO_4), cooper (Cu), Zinc (Zn), and bacteria in leachate (Duchesne and Doye, 2005; Çoruh and Ergun, 2010). Field investigation conducted by Ujaczki *et al.*, (2016) evaluated the use of red mud-soil mixtures as potential additives for landfill cover layers. Using a comprehensive set of chemical, biological, and ecotoxicity metrics, it was concluded that these mixtures could be safely used in poor-quality subsoils at concentrations up to 20% by weight without causing ecological toxicity. Based on these findings, red mud-soil mixtures were advocated to be incorporated into the surface layers of landfill cover systems.

Kalkan (2006) found that red mud improves the density and strength of compacted clay liners while reducing their expansibility and permeability (k<10-9m/s). Rubinos et al. (2015, 2016, 2017) studied red mud in landfill liners, examining its geotechnical qualities, low permeability, chemical stability, and environmental safety. They also noted its ability to capture mercury from leachates. Their findings show that red mud has a low permeability (10-9 m/s), high friction angle (38°), and cohesion (79.5 kPa), enhancing shear resistance on slopes. However, organic solvents and acids affect its properties, suggesting the need for more research on its chemical and environmental effects.

Nonetheless, the studies also highlighted that desiccation significantly affect red mud's permeability, raising concerns about its direct application in landfill cover systems. Panda et al., (2017) highlighted that red mud bioneutralization using microbial action with various carbohydrate sources could improve its geotechnical properties. While red mud's resistance to chemical attack and contaminant retention are notable, concerns about its alkalinity, the need for effluent management, and the potential release of radionuclides and trace metals under varying conditions necessitate careful consideration (Rubinos and Barral, 2013; Hegedűs et al., 2016). Field validation red mud liners remains essential. Given these factors, the use of red mud liners might be best suited for industrial or mining waste landfills. While red mud shows promise as a landfill liner material, its application should be carefully evaluated, considering its narrow operational range, potential environmental impacts, and the need for effective effluent management.

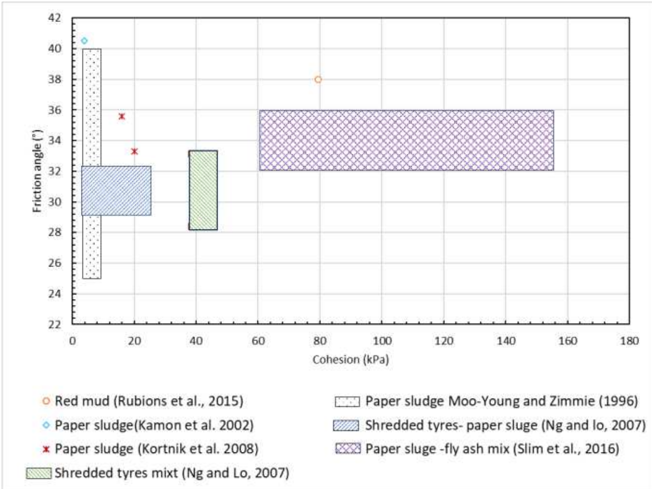

Figure 1. Shear parameter of wastes studied in the review.

3 PAPER SLUDGE

In recent decades, the utilization of waste materials from the paper industry, particularly paper sludges, gathered considerable consideration in the context of sustainable landfill engineering. These by-products, often described as paper sludge, have been increasingly recognized as viable alternatives to traditional clays for the construction of landfill liners.

Table 1. Waste material characteristics and its hydraulic Conductivity.

Material	Hydraulic Conductivity	Advantages	Limitation	Reference
Red Mud	9×10^{-10} to 5.13×10^{-10} m/s	- Good for reducing contaminants like Fe, SO4, Cu, Zn, and bacteria. - Enhances geotechnical properties when used in clay liners. - Can withstand shear forces on landfill slopes.	-Susceptible to desiccation affecting permeability. -Concerns about alkalinity, need for effluent management, and potential release of radionuclides and trace metals.	Rubinos et al. (2015); Panda et al. (2017)
Paper Sludge	3.4×10^{-10} to 5.3×10^{-8} m/s	- Effective as hydraulic barriers due to low *k*. - Contains organic fibers enhancing cohesion and friction angle. -Environmental compatibility confirmed for landfill applications.	-Susceptibility to desiccation and freeze-thaw cycles. - Requires high *w* during compaction.	Moo-Young and Zimmie (1996); Kamon et al. (2002); Kraus et al. (1997); Kortnik et al. (2008)
Paper Sludge - Wood Ash	5.0×10^{-9} m/s	-Potential enhancement of geotechnical properties.	-Requires further study for comprehensive understanding.	Kortnik et al. (2008)
Shredded Tyres - Paper Sludge	4.15×10^{-9} m/s	- Improves shear strength. - High ability of Pb retardation.	-Potential increase in *k*. -Variable concentrations of heavy metals in leachates.	Ng and Lo (2007)
Shredded Tyres Mixture	4.01×10^{-7} to 1.0×10^{-10} m/s	-Reduces dry density and compressive strength beneficially. -Enhances contaminant sorption capacity.	-May lead to an undesirable elevation in *k*.	Ng and Lo (2007)
Cement Kiln Dust - Black Cotton Soil	1.0×10^{-8} to 1.5×10^{-10} m/s	-Elevates maximum dry density and reduces optimum *w*. -Improves vertical strain and unconfined compressive strength.	-Concerns about caustic nature and potential leachates containing harmful compounds.	Oriola and Moses (2011)
Cement Kiln Dust - Lateritic Soil	9×10^{-9} to $<1.0 \times 10^{-10}$ m/s	-Reduction in plasticity index and vertical strain. -Notable increase in unconfined compressive strength.	-Concerns about caustic nature and potential leachates containing harmful compounds.	Amadi and Ebermu (2013)

Investigations identified the potential of paper sludge to achieve a state of low *k*, thereby serving effectively as hydraulic barriers (Rubinos and Spagnoli, 2018).Moo-Young and Zimmie, (1996) investigated the geotechnical characteristics of various paper mill sludges, revealing their high water content (*w*: 150 – 250%), plasticity index (77–191), and compressibility. These studies highlighted the impact of *w* on the compaction and hydraulic properties of paper sludge, noting the trade-off between water content and hydraulic performance although the shear strength varied based on the contents of organic matter and the fibres. However, challenges such as the susceptibility of the paper sludge to desiccation and freeze-thaw cycles, which can significantly influence its *k*, were also identified.

Further laboratory and field investigations focused on the long-term efficiency of paper sludge as an hydraulic barrier layer in landfill covers by Kraus *et al.*, (1997) and Moo-Young and Zimmie, (1997), demonstrated that paper sludge could maintain acceptable hydraulic barrier properties over extended periods ($k < 10^{-9}$ m/s). Kamon *et al.*, (2002), confirmed these results by conducting a comprehensive assessment of paper sludge for landfill cover applications, emphasizing its potential to maintain low *k* under a large range of *w* (50–200%) and for 10 years, and its high friction angle (40.5°) and cohesion of 3.9 kPa due to the presence of organic fibres.

The environmental compatibility of paper sludge has been the subject of studies by Boni *et al.* (2004) that have evaluated the leaching potential of heavy metals from paper sludge, finding concentrations to be within acceptable environmental thresholds. Zule *et al.* (2007) and Kortnik *et al.* (2008) extended these analyses to include chemical and biodegradability assessments, further validating the environmental suitability of paper sludge for landfill applications.

Studies by Slim *et al.*, (2016), have experimented with paper sludge mixtures and, incorporating class C fly ash to enhance their geotechnical properties while maintaining low *k*. These studies suggest that with appropriate modification, paper sludge could serve as an effective component in alternative landfill liner designs.

Paper sludge appears to be a viable option for landfill barrier construction as its primary benefits include its suitable *k* and geotechnical characteristics, which have been verified in operating municipal solid waste landfills across the United States, Finland, Canada, and Japan. It`s considered relatively safe regarding the leaching of trace metals (Rubinos and Spagnoli, 2018). However, its significant vulnerability to drying out and freeze-thaw cycles presents a notable drawback.

4 CEMENT KILN DUST

Cement kiln dust, a fine, alkaline material by-product captured through electrostatic precipitators during cement clinker manufacture, has been increasingly investigated for its potential as a soil stabilization agent, particularly in the construction of waste containment barriers(Kunal, et al., 2012). Research conducted by Mohamed (2002) in which cement kiln dust was utilized at an optimal ratio of 6% in soil barriers formulation specifically for hazardous waste in arid environments, led to a significant reduction in *k*, to below 10^{-9} m/s, and simultaneously improved the soil's shear strength. Parallel findings were reported by Oriola and Moses, (2011), who examined the effects of integrating 4 –16% cement kiln dust (by dry weight) into "black cotton" expansive soils. The research indicated that cement kiln dust generally elevates the maximum dry density and reduces the optimum *w*. Soils with 4–12% cement kiln dust content achieved satisfactory *k* levels below 10^{-9} m/s. However, it was noted that the 4% cement kiln dust concentration was particularly effective in improving soil *k*, while higher cement kiln dust proportions tended to be counterproductive. Additionally, significant improvements in vertical strain and unconfined compressive strength were observed, surpassing 200 kN/m^2, for up to 16% cement kiln dust treatment. This enhancement is attributed to the pozzolanic properties of cement kiln dust.

Amadi and Eberemu, (2013) extended this research to compacted lateritic soils derived residually, stabilized with up to 16% cement kiln dust. They reported a reduction in plasticity index (from 20 to 30%) and maximum unit weight, alongside a decrease in vertical strain (consistently below 4%) and a notable increase in unconfined compressive strength with rising cement kiln dust content. Osinubi *et al.* (2015) outlined the optimal zone for cement kiln dust cured lateritic soil, specifying 10% cement kiln dust content, prepared with *w* ranging between 13.5 and 21.3%, and compacted using British Standard Heavy (BSH) energy.

Collectively, these studies advocate for the potential application of cement kiln dust as a soil stabilizer in the construction of waste containment barriers, especially considering its geotechnical properties and influence on *k*. However, it is crucial to address concerns regarding the potential environmental hazards posed by cement kiln dust leachates, which may contain harmful compounds and exhibit a caustic nature. Hence, a definitive assessment of cement kiln dust's suitability for such applications necessitates a detailed understanding of these environmental implications.

5 SHREDDED TYRES

The integration of shredded tyres in landfill hydraulic barriers, either alone or in conjunction with natural soil or other waste materials, has been the focus of numerous research. Al-Tabbaa and Aravinthan, (1998) examined the engineering and leaching attributes of compacted clay mixed with up to 20% shredded tyres. The findings indicated that the addition of shredded tyres resulted in reduced dry density, unconfined compressive strength, and *k*. Natural clay-shredded tyres mixtures with varying percentages and particle sizes when permeated with different liquids such as paraffin, acidic water, and distilled water, exhibited interesting adhering dynamics between shredded tyres and clay. The study found that *k* increased when permeated with water or acidic water, but decreased significantly when permeated with paraffin by more than 50 times, attributed to the absorption by tyre particles and their consequent swelling (up to 600 kPa). This property was seen as beneficial, as it mitigated the negative impact of organic chemicals with low dielectric constants on clays. However, the leaching tests indicated variable concentrations of heavy metals, necessitating site-specific assessments.

Ng and Lo (2007) adopted a different approach by creating a combination of waste tyre aggregates with paper sludge for use as daily landfill covers. The research demonstrated that the mixed paste, being significantly lighter and less permeable than conventional soil covers, improved shear strength. Additionally, the paste displayed a high ability of Pb retardation (retardation factor D = 19.0–59.0), suggesting its effectiveness as a landfill cover system (Ng and Lo, 2010).

A study focusing on the geotechnical characteristics of sand-bentonite mixtures reinforced with tyre chips (5 - 15%) for a potential use as liner material, revealed a reduction in maximum dry density from 1.69 to 1.76 g/cm^3 with an increase in tire content from 0% to 15% (Mukherjee and Mishra, 2017). Up to 10% tyre content the consolidation coefficient exhibited a slight decrease, but then rose to 0.110 with further addition (15%). The optimum water content remained largely stable at approximately 16%. Additionally, the swelling index improved across all tire content levels (from 0.023 to 0.089), attributable to the tires elastic properties. The inclusion of tire material positively influenced the unconfined compressive strength, as evidenced by a growth in the Improvement factor. This enhancement was also seen in the cohesion (from 28.4 kPa to 49.1 kPa) up to 10% tire content, and in the friction angle (from 27.3° to 33.1°) for all tire contents. These findings suggest that the integration of tire chips into soil base can significantly reduce the probability of failure. Despite improving the shear strength, the addition of tyre chips adversely affected hydraulic conductivity, necessitating careful consideration of the tyre content to maintain desired permeability values.

Overall, these studies collectively indicate that shredded tyres can be an effective reinforcement additive for clay liners, mitigating issues like cracking due to desiccation and enhancing contaminant sorption capacity. Conversely, concerns regarding increased k and potential leaching of contaminants from the tyres remain.

6 COMPARATIVE CONCLUSION

The examination of the previously mentioned waste materials demonstrates that a significant proportion exhibit technical attributes appropriate for the landfill barriers. Nonetheless, it is imperative to acknowledge that every distinct waste type possesses unique properties, and its deployment offers both benefits and drawbacks relative to conventional materials employed in landfill liners and covers. These considerations predominantly pertain to geotechnical and hydraulic efficacy, economic implications, and environmental safety concerns.

Bauxite residue (red mud) is characterized by a suite of beneficial properties for application as a liner, predominantly due to its robust mechanical resistance, considerable capacity of acid neutralization, resilience to chemical degradation, and notably, its superior adsorption capabilities for a large spectrum of contaminants, comprising toxic trace metalloids, organic chemicals, phosphorus, and bacteria. Conversely, its limitations are marked by a restricted range of acceptable k, vulnerability to desiccation, inherently caustic nature, the presence of radionuclides and trace metalloids, its alkalinity leaching and its sensitivity to desiccation. These factors necessitate a cautious approach, recommending the use of red mud primarily for reactive bottom liners in industrial or mining wastes landfills.

Pulp and paper mill sludges present viable options for landfill cover system, attributed to their low k, acceptable slope stability, and controlled metal leaching during landfilling operations. The primary challenges associated with paper sludge include the necessity for high w during compaction and the risk of biodegradation. However, the most critical limitation of paper sludge is its heightened susceptibility to desiccation and freeze-thaw cycles and oxidative and microbiological degradation. This characteristic strongly suggests the implementation of a protective top layer to mitigate the risk of structural compromise due to cracking.

Cement Kiln Dust is beneficial as a conditioner for clays or clayey soils, enhancing the geotechnical properties, density, and vertical settlement properties of barrier materials. However, limitations exist in the permissible proportions of in the mixture, and its occasional adverse impact on k presents technical challenges. The most notable concerns with Cement Kiln dust use are its acidic properties and its leachate hazardous materials.

End-of-life shredded tires demonstrate functional efficacy in reinforcing liners, attributable to their swelling and elastic characteristics. The incorporation of such materials enhances the geotechnical characteristics and contaminant retention capabilities of the natural barriers. Significantly, their incorporation mitigate the detrimental effects of low dielectric constant organic chemicals on clays. However, this approach is not without weaknesses, as it may lead to an undesirable elevation in hydraulic conductivity and an increased risk of contaminant leaching.

The utilization of waste in engineering landfill barriers offers common advantages, such as reducing landfill space and environmental impacts, decreasing costs, and enhancing waste recycling rates. However, there is a necessity for more comprehensive research on the chemical compatibility and environmental impact of these wastes, particularly regarding their contaminant leaching characteristics.

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