EDSU Journal of Engineering and Technology (EDSUJET)

Geotechnical Enhancement of Sand-Bentonite Liners Using Bagasse Ash: A Sustainable Approach to Landfill Barrier Systems

Amedu Lawal Makhu*, **John Wasiu**

Department of Civil Engineering, Edo State University, Uzairue, Nigeria.
Email address: amedulawal13@gmail.com[1]; johnwasiu@gmail.com[2]

Received: 16th August, 2025, Accepted: 27th September, 2025, Published: 30 November 2025

K E Y W O R D S

Bagasse
Stabilization
Bentonite
Landfill
Pozzolans
Compaction

A B S T R A C T

This research investigates the geotechnical enhancement of bagasse ash modified sand-bentonite mixtures (SBMs) for application as sustainable landfill liner materials. With increasing concern over the environmental degradation caused by leachate migration from landfills and the limitations of conventional liner systems under heavy metal exposure, the study explores the potential of incorporating sugarcane bagasse ash a pozzolanic agro-industrial by-product into SBMs to enhance their geotechnical performance. Laboratory tests were conducted to assess index properties, compaction characteristics, shear strength, and bearing capacity. Results indicated that the specific gravity of the mixtures generally decreased from 2.64 to 2.54 with increasing bagasse ash content, although minor intermediate fluctuations were observed. Atterberg limits showed a progressive increase in plasticity index, suggesting improved sealing and moisture retention. Compaction tests revealed increasing optimum moisture content (9.44–25.80%) and a decrease in maximum dry density from 1.85 to 1.51 Mg/m³, reflecting lighter but more moisture-demanding materials. Shear strength parameters demonstrated a non-linear response: initial additions of bentonite and bagasse ash reduced shear resistance, but higher proportions promoted recovery and stabilization due to pozzolanic gel formation. The CBR values decreased from 11.95% to 1.20%, indicating a functional shift from structural support to hydraulic barrier The optimum balance between shear resistance, deformability, and low bearing capacity suitable for landfill barriers was observed at a mix containing 10% bentonite and 12.5% bagasse ash. The findings highlight bagasse ash as a viable, eco-friendly additive that improves contaminant retention, reduces permeability, and enhances the integrity of engineered barrier systems.

1. INTRODUCTION

Municipal solid waste (MSW) is increasing worldwide due to rapid urbanization, industrialization, and population growth. Global waste generation is projected to exceed 2.2 billion tonnes per year by 2025 (Hoornweg & Bhada-Tata, 2012). Landfilling remains the most common disposal method, especially in developing countries, because it is practical and cost-effective (Zhang, Tan, & Gersberg, 2010). However, poorly engineered landfills produce leachates that often contaminate surrounding soil and groundwater, creating serious environmental and public health concerns (Rowe, 2017). To reduce these risks, sand–bentonite mixtures (SBMs) are frequently used as liners, as bentonite provides low permeability and swelling capacity that limit leachate migration (Joseph & Varghese, 2017). Bentonite liners, however, are associated with certain limitations. Their relatively high cost makes arge-scale use challenging in resource-constrained settings, while exposure to heavy metals and other chemical contaminants can increase hydraulic conductivity and compromise sealing performance (Ajitha & Sheela Evangeline, 2019; Wang et al., 2019). These challenges have led to growing interest in supplementary stabilizers that are both affordable and environmentally sustainable, with industrial and agricultural by-products showing considerable promise in recent research (Chowdhury, Mani, & Rahman, 2019).

Sugarcane bagasse ash (BA), a by-product of sugarcane processing, is one such material. Rich in silica and alumina, it possesses pozzolanic properties that improve soil plasticity, reduce permeability, and enhance long-term stability through cementitious reactions (Latifi et al., 2019; Jha & Sivapullaiah, 2021). Prior studies have confirmed its potential in soil stabilization and landfill liner applications (Amu, Ogunniyi, & Oladeji, 2011; Afolayan, Oyekanmi, & Ogundele, 2021). This study evaluates the effect of BA on the geotechnical characteristics of SBMs, with the aim of establishing its suitability as a sustainable additive for landfill liner design and promoting the beneficial reuse of agricultural waste in civil engineering.

2. MATERIALS AND METHODS

2.1 Materials

Sand: The sand used in this study was collected from Ekhei Girls Road in Auchi, Etsako West Local Government Area of Edo State, Nigeria, located between latitude 7°07'N and longitude 6°16'E. The tools used for the collection of samples for the purpose of this project was shovel, hand auger, sample bag/sack and measuring tape.

Bentonite: The bentonite used in this study was in powdered form, representing the typical type commonly available for construction works. Its fine texture, swelling ability, and ease of mixing make it suitable for various engineering applications such as soil stabilization and barrier formation, ensuring consistency in laboratory testing and practical use.

Bagasse Ash (BA): The bagasse ash used in this study was obtained from sugarcane residue collected at local processing centers in Auchi. This ash, produced as a byproduct of sugarcane milling and combustion, is lightweight, rich in silica, and has potential pozzolanic properties, making it useful for construction-related applications and laboratory investigations.

2.2 Methods

Sample Preparation

To study the effect of varying BA content, six SBM mixtures were prepared with constant sand content (100%) and varying bentonite (0–10%) and bagasse ash content (0–12.5%). All mixtures were homogenized manually in the laboratory to ensure uniform distribution of components before geotechnical testing.

This study employed a series of geotechnical tests to characterize the index, compaction, and strength properties of sand–bentonite mixtures (SBMs) stabilized with bagasse ash (BA). All procedures were carried out in accordance with **BS 1377 (1990)** standards unless otherwise specified.

Index Property Tests

Particle Size Distribution (Sieve Analysis): This test was carried out to determine the gradation of the sand samples and to provide a basis for soil classification. It gives insight into the proportions of different particle sizes, which influence soil behavior and suitability for construction purposes.

Specific Gravity: The specific gravity of the soil solids was determined using the pycnometer method. This parameter provides information on the relative density of the soil particles, which is essential in understanding soil strength and stability.

Atterberg Limits: The liquid limit, plastic limit, and plasticity index were measured to assess the consistency and plasticity characteristics of the soil. These limits help define the soil's behavior under varying moisture conditions, which is critical for engineering applications.

Linear Shrinkage: The linear shrinkage test was conducted to evaluate the soil's volumetric stability when dried. This property indicates the potential for cracking and shrinkage, which affects soil performance in construction works

Compaction Characteristics

The Standard Proctor Compaction Test was carried out to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the soil mixtures. These parameters are essential for evaluating soil compaction behavior and ensuring stability in engineering applications.

Strength Tests

The Direct Shear Test was performed to establish the shear strength parameters of the soil, specifically cohesion (c) and angle of internal friction (φ), under different normal stresses. In addition, the California Bearing Ratio (CBR) test was conducted to assess the load-bearing capacity of the soil and its overall suitability for use in landfill barrier systems and related geotechnical works.

3. RESULTS AND DISCUSSION

The results encompass index properties, compaction behavior, shear strength parameters and California Bearing Ratio (CBR),

Index Properties

The index properties of the sand and its modified mixtures are critical for understanding the soil's behavior, workability, and potential application in landfill liners. The properties evaluated include Particle size Distribution, Specific gravity, liquid limit, plastic limit, plasticity index, and linear shrinkage.

Particle Size Distribution (PSD): The soil was classified as A–3 under AASHTO and as SP (poorly graded sand) under USCS, indicating silty or fine sands with low plasticity and poor binding qualities. The gradation curve confirmed poor particle distribution, high permeability, and weak cohesiveness, making the soil unsuitable for landfill liners. The effective particle size range (0.07–2.00 mm) aligns with natural sandy soils found in riverine and aeolian environments, but the absence of fines and clay prevents water retention and plastic behavior required for low-permeability barriers.

Particle Size Distribution- Sieving

PROJECT: Research Project

JOB REF; Student

Sample Description: Soil

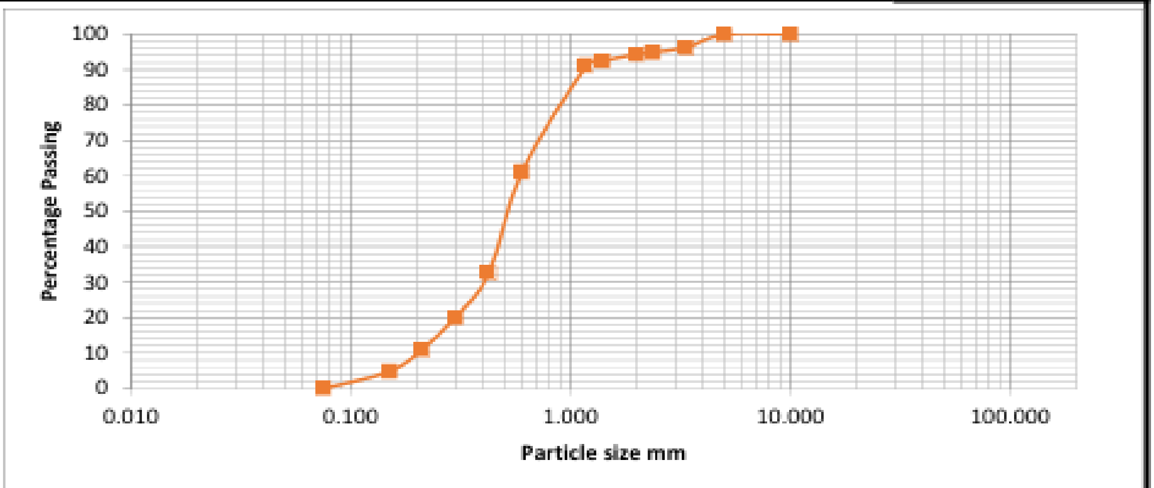
Date 25/4/2025

Test Method BS 1377: Part 2: 1990: 9.5

Sample

Total mass of dry sample g 300.6

BS test sieve size (mm)	Mass Retained g	Cumulative Mass Retained g	Percentage Retained %	Percentage Passing %
10	0	0	0.00	100.00
5	0	0	0.00	100.00
3.35	11.1	11.1	3.69	96.31
2.36	4.1	15.2	1.36	94.94
2	1.5	16.7	0.50	94.44
1.4	5.8	22.5	1.93	92.51
1.18	3.8	26.3	1.26	91.25
0.6	90.4	116.7	30.07	61.18
0.425	86.1	202.8	28.64	32.53
0.3	37.3	240.1	12.41	20.13
0.212	27	267.1	8.98	11.14
0.15	19.1	286.2	6.35	4.79
0.075	14.4	300.6	4.79	0.00
pan				



Conducted By: S.O

Checked By:

Table 2: Summary of the Index Properties Results of Soil and Its Mixtures

	SAMPLES					
TEST	**I**	**II**	**III**	**IV**	**V**	**VI**
Specific Gravity	2.64	2.58	2.57	2.60	2.51	2.54
Liquid Limit	17.60	19.09	22.05	24.51	26.87	31.04
Plastic Limit	12.29	16.72	15.76	19.75	18.32	19.48
Plasticity Index	5.31	2.37	6.29	4.76	8.55	11.56
Linear Shrinkage	4.00	2.50	4.00	3.00	4.50	6.50

The results presented in Table 2 show clear variations in the index properties of the sand and its mixtures. The specific gravity decreased from 2.64 to 2.54, indicating lighter mixtures, while the plasticity index increased from 5.31 to 11.56 and linear shrinkage from 4.00% to 6.50%, showing improved consistency, moisture retention, and sealing capacity. These findings confirm the effectiveness of bagasse ash and bentonite in enhancing soil properties for landfill liner applications.

Compaction Characteristics

The compaction characteristics of the mixtures were determined using the Standard Proctor Test in line with BS 1377: Part 4 (1990).

Table 3: Summary Table for Trend Analysis

Sample	%Bentonite	%Bagasse Ash	OMC (%)	MDD (Mg/m^3)
I	0	0	9.44	1.85
II	2	2.5	14.80	1.80
III	4	5.0	15.50	1.75
IV	6	7.5	18.63	1.67
V	8	10.0	22.07	1.58
VI	10	12.5	25.80	1.50

The results presented in Table 3 show clear variations in the compaction properties of the sand and its mixtures. The Optimum Moisture Content (OMC) increased from 19.44% to 25.80% with higher bagasse ash content, while the Maximum Dry Density (MDD) decreased from 1.85 Mg/m^3 to 1.50 Mg/m^3. This trend indicates reduced soil density and greater moisture demand, which is consistent with the findings of Komine (2004).

Shear Strength: Direct shear tests were conducted to assess the strength parameters of the mixtures, particularly cohesion (c) and internal friction angle (φ).

Table 4: Direct Shear Box Test Result

Sample	%B + %BA	Cohesion (kN/m^2)	Angle of Internal Friction (°)
I	0 + 0	0.95	43.73
II	2 + 2.5	0.77	37.83
III	4 + 5.0	0.79	38.38
IV	6 + 7.5	0.61	31.36
V	8 + 10.0	0.91	42.38
VI	10 + 12.5	0.91	42.38

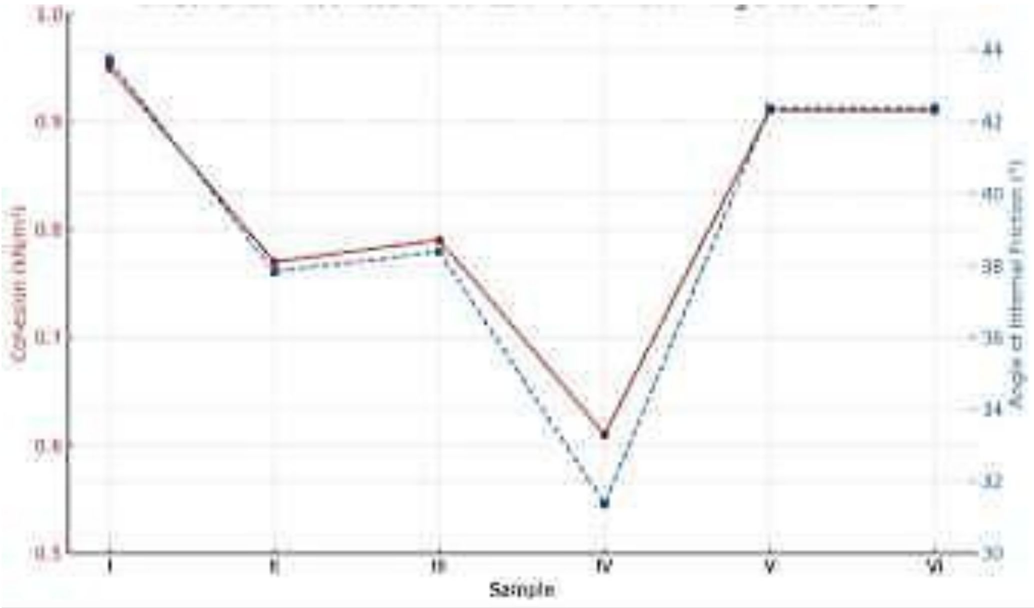


Fig 1: Variation of Cohesion and angle of internal friction with sample composition

The results in Table 4 and Figure 1 show that adding 2–5% B + BA (Samples II and III) reduced cohesion and friction angle due to bentonite's lubricating effect, consistent with Mitchell and Soga (2005). At higher contents (Samples V and VI), both parameters improved, reflecting pozzolanic reactions and soil densification. The overall trend indicates an initial strength loss followed by recovery, underscoring the importance of proper mix proportions and curing in achieving effective landfill liner materials.

California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test is a penetration test used to evaluate the **strength of subgrade soils** and their suitability for use in **pavement and foundation applications.**

Table 5: California Bearing Ratio (CBR) Test Results of Sand and Its Mixtures

Sample	% Bentonite	% Bagasse Ash	CBR Value (%)
I	0	0	11.95
II	2	2.5	8.70
III	4	5.0	2.20
IV	6	7.5	1.85
V	8	10.0	1.35
VI	10	12.5	1.20

-

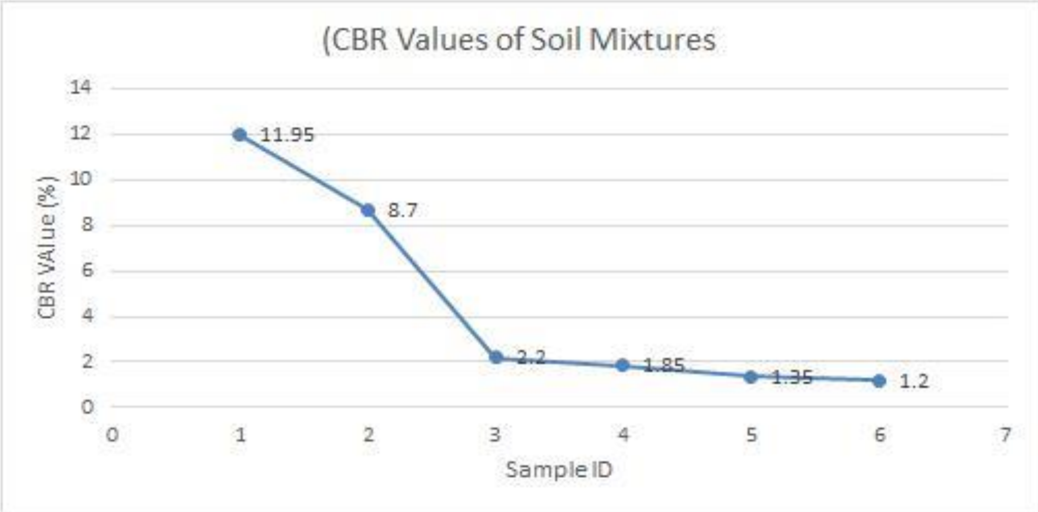


Fig 2: Variation of California bearing ratio (CBR) values with sample ID in sand mixture

The CBR results (Table 5) show a steady decline from 11.95% in the natural soil to 1.20% at 10% B + 12.5% BA. This reduction reflects the weakening effect of bentonite and bagasse ash, shifting the soil from load-bearing to compressible behavior. Mixtures with CBR of 2% or less (Samples IV–VI) are most suitable for landfill liners, with Sample VI performing best. These findings are consistent with Komine (2004), who highlighted the suitability of bentonite-based mixtures for barrier systems, and with Latifi et al. (2019), who observed that pozzolanic additives enhance sealing properties at higher replacement levels.

4 CONCLUSION

This study investigated the geotechnical characteristic of sand-bentonite mixtures (SBMs) stabilized with bagasse ash (BA) for use in engineered landfill barrier systems. Based on laboratory evaluations of index properties, compaction, shear strength, and CBR, the following conclusions are drawn:

i. The incorporation of bagasse ash (BA) into sand–bentonite mixtures (SBMs) significantly modified the soil's geotechnical properties in ways favorable for landfill liner applications.
ii. **Index properties** showed a slight reduction in specific gravity (2.64–2.54), with increases in plasticity index and linear shrinkage, indicating improved consistency, sealing capacity, and moisture retention.
iii. **Compaction results** revealed higher Optimum Moisture Content (OMC) (19.44–25.80%) and lower Maximum Dry Density (MDD) (1.85–1.50 Mg/m^3), reflecting lighter, more moisture-demanding mixtures.
iv. **Direct shear tests** indicated a non-linear strength response: initial reductions in cohesion and friction angle at low BA contents, followed by recovery at higher contents due to pozzolanic gel formation and densification.
v. **CBR values** dropped from 11.95% (control) to 1.20% (10% B + 12.5% BA), confirming a transition from load-bearing to compressible barrier behavior, with mixtures containing ≥6% bentonite and ≥7.5% BA most suitable.
vi. The study validates BA as an effective and sustainable additive that enhances SBM performance, reduces reliance on expensive conventional liners, and supports waste valorization in line with sustainable engineering practices.

NOMENCLATURE

OMC – Optimum Moisture Content
MDD – Maximum Dry Density

CBR – California Bearing Ratio
SBM – Sand-Bentonite Mixture
BA – Bagasse Ash

ABBREVIATIONS

MSW – Municipal Solid Waste
BS – British Standard
USCS – Unified Soil Classification System
AASHTO – American Association of State Highway and Transportation Officials

ACKNOWLEDGEMENT

The author sincerely acknowledges the invaluable supervision and guidance of Prof. John Wasiu throughout this research work. Special thanks go to Ighiegwe Emmanuel Irudunoghena for his editorial assistance and critical review of the manuscript. The author also appreciates Modestus Temidayo Ebiniyi for his technical support and expertise in conducting the basic laboratory analysis that contributed significantly to this study.

REFERENCES

Adewuyi, A. P., & Adegoke, T. (2008). Exploratory study of bagasse ash as partial replacement for cement in concrete. Leonardo Electronic Journal of Practices and Technologies, 12, 47–58.

Afolayan, A. J., Oyekanmi, A. A., & Ogundele, D. T. (2021). Improving lateritic soil properties using bagasse ash. International Journal of Civil Engineering and Technology, 12(4), 345–356.

Ajitha, K. V., & Sheela Evangeline, M. (2019). Impact of heavy metal concentration on the hydraulic conductivity of clay-bentonite liners. Environmental Geotechnics, 6(2), 113–124. https://doi.org/10.1680/jenge.16.00068

Amu, O. O., Ogunniyi, S. A., & Oladeji, O. O. (2011). Geotechnical properties of lateritic soil stabilized with sugarcane straw ash. American Journal of Scientific and Industrial Research, 2(2), 323–331. https://doi.org/10.5251/ajsir.2011.2.2.323.331

BS 1377. (1990). Methods of test for soils for civil engineering purposes. British Standards Institution.

Cheah, C. B., & Ramli, M. (2011). The implementation of effective microstructural development in modified clay liners. Materials and Structures, 44(3), 703–715.

Chindaprasirt, P., Homwuttiwong, S., & Sirivivatnanon, V. (2008). Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar. Cement and Concrete Research, 34(7), 1087–1092. https://doi.org/10.1016/j.cemconres.2003.11.021

Chowdhury, S., Mani, A., & Rahman, M. (2019). Utilization of bagasse ash as a soil stabilizer in geotechnical applications. Journal of Geotechnical and Geoenvironmental Engineering, 145(3), 04019012. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002019

Dang, L. C., Fatahi, B., & Khabbaz, H. (2015). Soil stabilization using bagasse ash and hydrated lime. Procedia Engineering, 111, 640–647. https://doi.org/10.1016/j.proeng.2015.07.114

Elinwa, A. U., & Ejeh, S. P. (2004). Characteristics of bamboo leaf ash blended cement concrete. Journal of Civil Engineering and Environmental Systems, 21(2), 71–78.

Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: A global review of solid waste management (Vol. 15). World Bank.

Jha, A. K., & Sivapullaiah, P. V. (2021). Role of bagasse ash in improving the strength of soil-bentonite mixtures. Geotechnical and Geological Engineering, 39, 2341–2354. https://doi.org/10.1007/s10706-020-01603-y

Joseph, A., & Varghese, S. (2017). Effectiveness of bentonite as a soil liner material. International Journal of Civil Engineering and Technology, 8(10), 1508–1516.

Komine, H. (2004). Simplified evaluation on hydraulic conductivity of bentonite-based buffer materials. Applied Clay Science, 26(1–4), 13–19. https://doi.org/10.1016/j.clay.2003.11.002

Latifi, N., Marto, A., Rashid, A. S. A., & Kassim, K. (2019). Engineering behavior of lateritic soil stabilized with bagasse ash and hydrated lime. Soils and Foundations, 59(1), 1–12. https://doi.org/10.1016/j.sandf.2018.12.002

Latifi, N., Rashid, A. S. A., Siddiqua, S., & Horpibulsuk, S. (2019). Strength and microstructural characteristics of bagasse ash stabilized soil. Applied Clay Science, 152, 340–347. https://doi.org/10.1016/j.clay.2017.11.030

Mitchell, R. J., & Soga, K. (2005). Fundamentals of soil behavior (3rd ed.). John Wiley & Sons.

Oliveira, F. S., Bicalho, K. V., Rezende, L. R., & Soares, J. P. (2022). Evaluation of the geotechnical performance of sand–bentonite mixtures with alternative additives. Construction and Building Materials, 340, 127701. https://doi.org/10.1016/j.conbuildmat.2022.127701

Osinubi, K. J., Eberemu, A. O., & Amadi, A. A. (2020). Engineering behavior of soils stabilized with bagasse ash and bentonite mixtures. Soils and Foundations, 60(2), 335–345. https://doi.org/10.1016/j.sandf.2020.02.005

Pokhrel, D. (2006). Review of landfill leachate treatment technologies. Waste Management, 26(3), 327–336. https://doi.org/10.1016/j.wasman.2005.09.005

Qian, X., Koerner, R. M., & Gray, D. H. (2016). Geotechnical aspects of landfill design and construction. Pearson Education.

Rahman, M. A., Hossain, M. K., & Islam, M. M. (2020). Environmental implications of bagasse ash as a construction material. Renewable Materials and Engineering, 12(2), 110–121.

Rowe, R. K. (2017). Advances and remaining challenges for geosynthetics in geoenvironmental engineering applications. Geotextiles and Geomembranes, 45(3), 258–288. https://doi.org/10.1016/j.geotexmem.2017.01.004

Tchobanoglous, G., & Kreith, F. (2002). Handbook of solid waste management (2nd ed.). McGraw-Hill.

Wang, F., Zhang, L., Wang, H., & Li, X. (2019). Effect of heavy metal contaminants on the permeability of compacted bentonite. Applied Clay Science, 183, 105299. https://doi.org/10.1016/j.clay.2019.105299

Wang, Y., Zhang, Y., Chen, H., & Sun, H. (2019). Influence of heavy metals on hydraulic conductivity of bentonite-sand liners. Environmental Earth Sciences, 78(1), 27. https://doi.org/10.1007/s12665-019-8009-7

Zhang, D., Tan, S. K., & Gersberg, R. M. (2010). Municipal solid waste management in China: Status, problems and challenges. Journal of Environmental Management, 91(8), 1623–1633. https://doi.org/10.1016/j.jenvman.2010.03.012