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Research Article

Microstructural Evaluation of Bagasse Ash Stabilized Sand-Bentonite Mixtures Using XRD SEM, and EDX Techniques

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Abstract

The microstructure of compacted sand–bentonite mixtures (SBMs) modified with sugarcane bagasse ash (SBA) was investigated to evaluate the mechanisms responsible for improving their suitability as sustainable landfill liner materials. SBA was incorporated at replacement levels of 0%, 2.5%, 5%, 7.5%, 10%, and 12.5%, while the mixtures were characterized using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), and X-ray Diffraction (XRD). XRD analysis of the control sand revealed quartz, kaolinite, and metahalloysite as the dominant mineral phases, with minor quantities of gibbsite and vermiculite. The mixture containing 10% bentonite and 12.5% SBA exhibited new diffraction peaks and peak broadening, indicating the formation of calcium silicate hydrate (C–S–H) and confirming the occurrence of pozzolanic reactions. SEM images demonstrated a progressive transformation from the loose, porous granular structure of the untreated sand to a dense, compact, and well-cemented matrix in the SBA-modified mixtures. EDX analysis of the optimum mixture recorded oxygen (61.40 wt%), silicon (17.37 wt%), aluminum (6.52 wt%), and iron (6.42 wt%), confirming the development of a silica–alumina-rich cementitious matrix. These microstructural modifications enhanced particle bonding, reduced pore spaces, and improved contaminant retention capacity. The findings demonstrate that SBA effectively induces pozzolanic reactions and pore refinement, making SBA-modified SBMs a sustainable and environmentally friendly material for engineered landfill liner systems.

Keywords

Bagasse Ash, Bentonite, Landfill Liner, Calcium Silicate Hydrate, X-Ray Diffraction

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 [6]. Landfilling remains the most common disposal method, especially in developing countries, because it is practical and cost-effective [13]. However, poorly engineered landfills produce leachates that often contaminate surrounding soil and groundwater, creating serious environmental and public health concerns [12]. To reduce these risks, sand bentonite mixtures (SBMs) are frequently

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used as liners, as bentonite provides low permeability and swelling capacity that limit leachate migration [9]. Bentonite liners, however, are associated with certain limitations. Their relatively high cost makes large-scale use challenging in resource-constrained settings, while exposure to heavy metals and other chemical contaminants can increase hydraulic conductivity and compromise sealing performance [2]. 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 [3]. 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 [10]. Prior studies have confirmed its potential in soil stabilization and landfill liner applications [8]. This work uses SEM/EDX and XRD to characterize fabric, elemental and mineralogical changes in SBM with 0-12.5% of BA.

2. Materials and Methods

2.1. Materials

2.1.1. 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 soil was classified as being in the A–3 group, which is generally linked to fine or silty sands with low plasticity and poor binding qualities, according to the American Association of State Highway and Transportation Officials (AASHTO) soil classification system.

2.1.2. Bentonite

The bentonite sample used was sourced from a private construction firm in Auchi.

2.1.3. Bagasse Ash (BA)

Bagasse ash was derived from sugarcane residue collected from local processing centers in Auchi.

2.2. Methods

2.2.1. Sample Preparation

Sand from Ekhei was mixed with bentonite and SBA. Six formulations were prepared: 0%, 2.5%, 5%, 7.5%, 10%, and 12.5% SBA, with bentonite 2–10%. Samples were compacted at OMC and cured.

2.2.2. Microsturctural Analysis

Microsturtural analysis was carried out using X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray (EDX) in accordance with BS 1377 (1990) standards. The microstructural test was performed at the National Institute of Building and Road Research (NIBRR), Abuja. XRD identify crystalline phases and mineral transformations. SEM was used to examine particle morphology, bonding, and aggregation. EDX analysis was conducted to determine the elemental composition of the samples. The analysis compare the control mix (100% sand, 0% bentonite, 0% BA) and the optimum mix (100% sand, 10% bentonite, 12.5% SBA) to evaluate structural changes due to stabilization.

3. Results and Discussion

3.1. X-ray Diffraction (XRD) Results

3.1.1. Sample 1

The XRD analysis of the untreated (control) soil indicates that quartz is the dominant mineral phase, with the highest diffraction peak occurring at 31.0° (2θ) and additional characteristic peaks at 14.4°, 24.3°, 42.7°, 46.2°, and 58.9°. The predominance of crystalline quartz confirms that the soil is mainly composed of silica-rich, chemically inert minerals with low pozzolanic reactivity. Although minor iron-bearing minerals are present, their contribution is insignificant compared to quartz. Consequently, the untreated soil has limited potential to develop cementitious bonds or improve its engineering properties without stabilization. The absence of reactive mineral phases also suggests high permeability and poor contaminant containment capacity, making the natural soil unsuitable for landfill liner applications unless modified with suitable stabilizing materials. This observation is consistent with findings by [5] and [11].

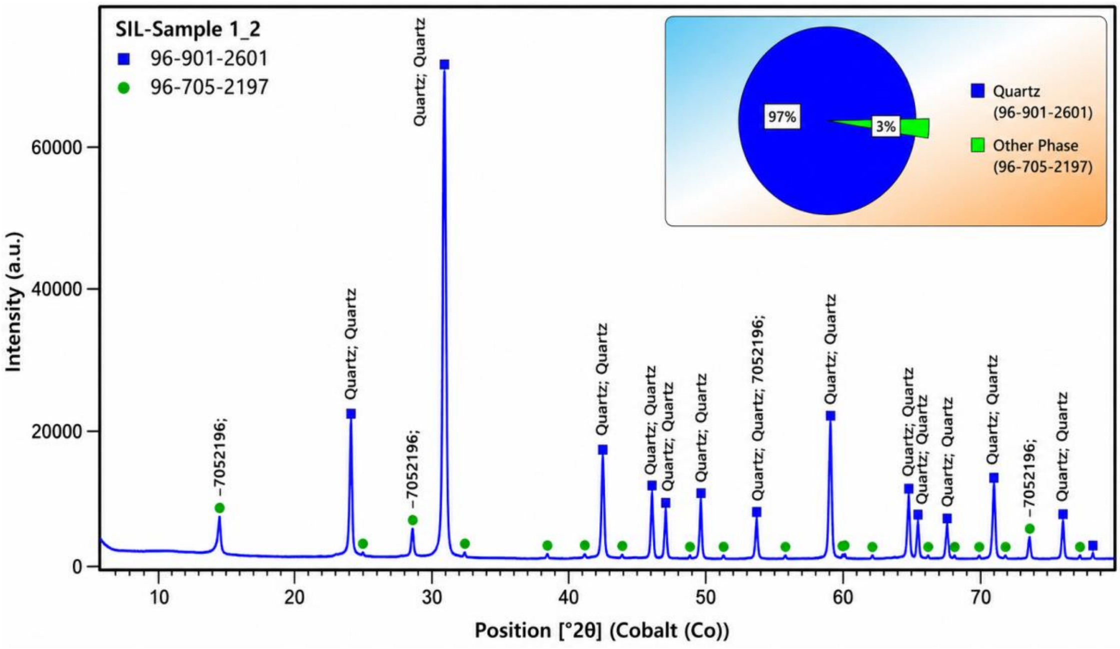

Figure 1. X-ray Diffraction Pattern of untreated Soil Sample 1 (100%Sand, 0% Bentonite, 0%, Bagasse Ash).

3.1.2. Sample 2

The XRD analysis of Sample 2 indicates that quartz remains the dominant crystalline mineral, with the strongest diffraction peak observed at 31.1° (2θ). However, compared with the untreated soil, the addition of 2.5% bagasse ash and 2% bentonite caused a slight reduction in quartz peak intensities, reflecting the incorporation of amorphous materials from the additives. The presence of amorphous silica in bagasse ash is expected to promote pozzolanic reactions, leading to the gradual formation of cementitious compounds such as calcium silicate hydrate (C-S-H) gels. Minor changes in peak distribution and slight peak broadening suggest the early stages of microstructural modification, although no significant new crystalline phases were identified. Trace nitrogenous organic compounds originating from the bagasse ash were also detected. Overall, the results demonstrate that the additives have initiated mineralogical changes that are expected to improve the soil's density, reduce permeability, and enhance its performance as a landfill liner or other geotechnical barrier material. This observation is consistent with findings by [5] and [11].

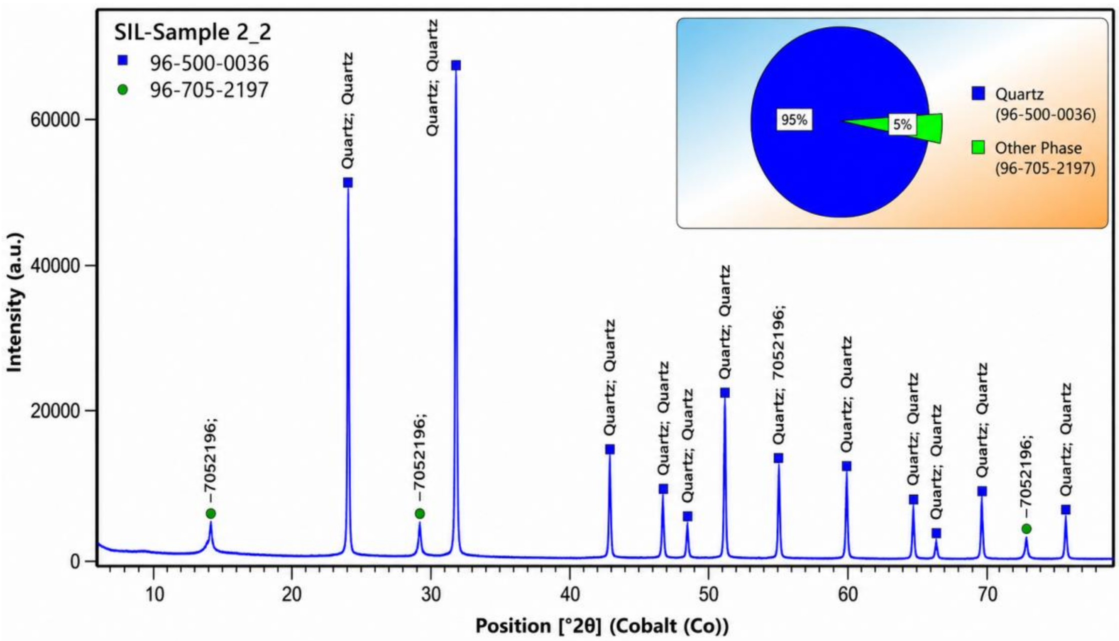

Figure 2. X-ray Diffraction Pattern of Soil Sample 2 (100%Sand, 2% Bentonite, 2.5%, Bagasse Ash).

3.1.3. Sample 3

Sample 3 shows continued mineralogical modification following the addition of 4% bentonite and 5% bagasse ash. Quartz remains the dominant crystalline mineral, with its strongest diffraction peak occurring at approximately 31.1 ° (2θ). However, compared with the previous samples, the quartz peaks exhibit reduced intensity and slight broadening, indicating a decrease in crystallinity and an increase in amorphous reaction products. The appearance of a new low-angle peak around 6.0° (2θ) suggests the presence of layered clay minerals introduced by the bentonite. In addition, the increased bagasse ash content contributes amorphous silica that promotes pozzolanic reactions, leading to the gradual formation of poorly crystalline cementitious products such as calcium silicate hydrate (C-S-H). Although these products are not directly detected by XRD, the reduction in quartz intensity and the increase in amorphous phases provide indirect evidence of their formation. Minor carbon-rich phases associated with the bagasse ash are also present, potentially enhancing the soil's contaminant adsorption capacity. Overall, the XRD results indicate that the combined effects of bentonite and bagasse ash produce a more refined and less crystalline soil structure, which is expected to improve permeability control and contaminant containment. These findings agree with the observations of [5] and [11].

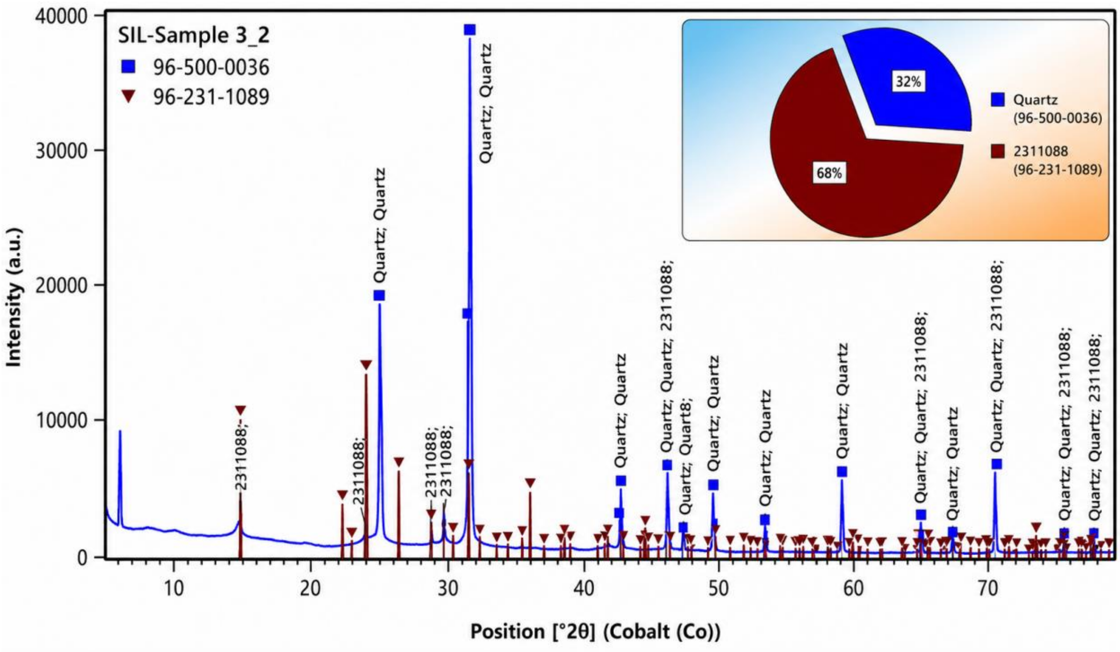

Figure 3. X-ray Diffraction Pattern of Soil Sample 3 (100%Sand, 4% Bentonite, 5%, Bagasse Ash).

3.1.4. Sample 4

The XRD analysis of Sample 4 indicates that quartz remains the dominant mineral phase, with the strongest diffraction peak observed at 31.1 °(2θ), corresponding to a d-spacing of 3.34 Å. Additional quartz peaks at 24.3 °, 42.7 °, 49.8 °, and 58.9° (2θ) confirm the continued predominance of silica-based minerals. However, compared with the untreated soil and earlier modified samples, the reduced intensity and slight broadening of the quartz peaks suggest a gradual decrease in quartz crystallinity due to the increased incorporation of bentonite and bagasse ash. Low-intensity peaks are associated with layered clay minerals from bentonite and residual organic phases introduced by bagasse ash. The presence of amorphous silica and other poorly crystalline reaction products contributes to soil densification and pore refinement, although these phases are not distinctly visible in the XRD pattern. Overall, the results indicate progressive microstructural refinement and the development of a denser soil matrix, enhancing the material's suitability as a low-permeability landfill barrier through the combined physical sealing effect of bentonite and the pozzolanic contribution of bagasse ash. This observation is consistent with findings by [5] and [11].

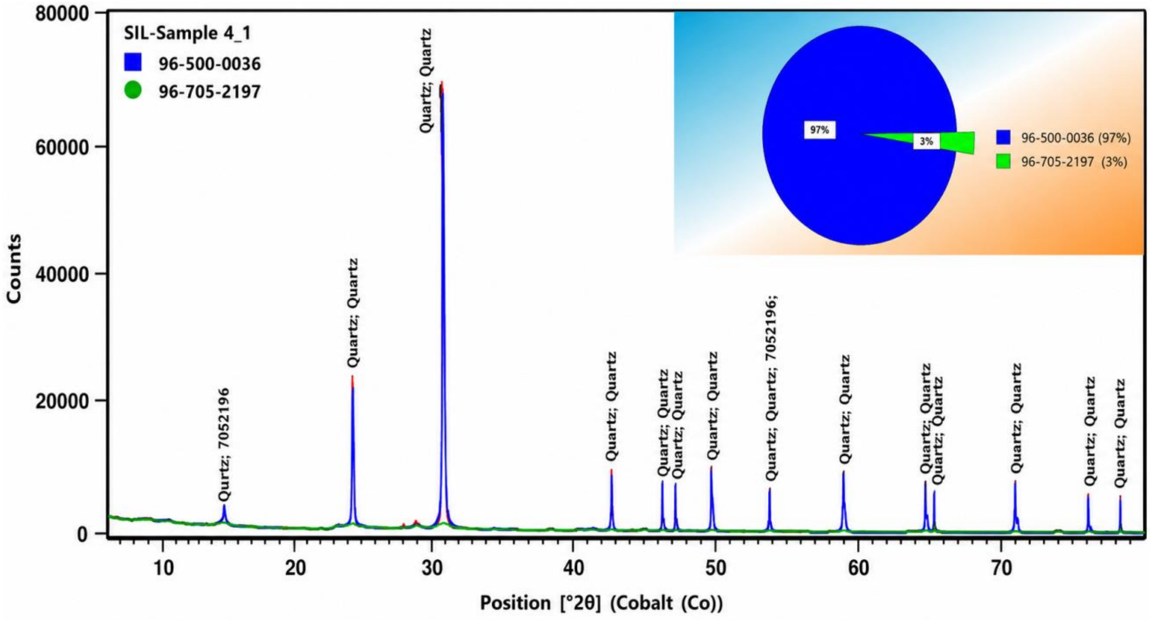

Figure 4. X-ray Diffraction Pattern of Soil Sample 4 (100%Sand, 6% Bentonite, 7.5%, Bagasse Ash).

3.1.5. Sample 5

The mineralogical changes seen in the previous sample are continued in Sample5'sXRDpattern, which contains 10% bagasse ash and 8% bentonite. With its most noticeable peak occurring at 31.1°2θ, orad-spacing of 3.33Å, quartz continues to be the predominant crystalline ephase. Additional noteworthy quartz peaks can be found at 24.4°,42.8°,49.8°, and 59.0°2θ, suggesting that silica-based minerals continue to be the foundation of the soil's crystalline structure. When compared to the control and previously modified samples, the diffraction pattern shows a further decrease in the relative intensity of the quartz peaks, despite the quartz's continued dominance. Due to continuous pozzolanic reactions between the bagasse ash and calcium- containing species in the soil, this attenuation indicates that the soil matrixis becoming more and more enriched with amorphous phases. This interpretation is corroborated by the widening of the peaks, especially at the major quartz positions. This is consistent with microstructural densification and the partial consumption of crystalline silica during cementitious gel formation. The presence of other minor peaks in the diffraction pattern is probably related to the organic components of the bagasse ash, which add carbonaceous and nitrogen-rich residues to the soil system. Low levels of quartz and organic phases are among the reference compounds found in the pattern, which is in line with bagasse ash's slow incorporation into the soil matrix. By physically sealing pores and reducing pathways for contaminant migration, Sample 5's increasing bentonite dosage helps to create a more compact microstructure. According to [5] and [11], bentonite's swelling qualities are well known for being very successful in lowering soil permeability. At the same time, the bagasse ash supplies more amorphous silica that can react with the available calcium to form calcium silicate hydrate (C-S-H) gels. However, because these gels are usually amorphous, they are not readily visible in the diffraction pattern. The soil is changing toward a multi-barrier system that incorporates chemical adsorption, physical densification, and possible pozzolanic stabilization, according to Sample 5's XRD analysis. The broadening of peaks and the decrease in crystalline quartz intensity show that the soil is becoming more refined and less permeable, which is necessary for its intended use as a barrier.

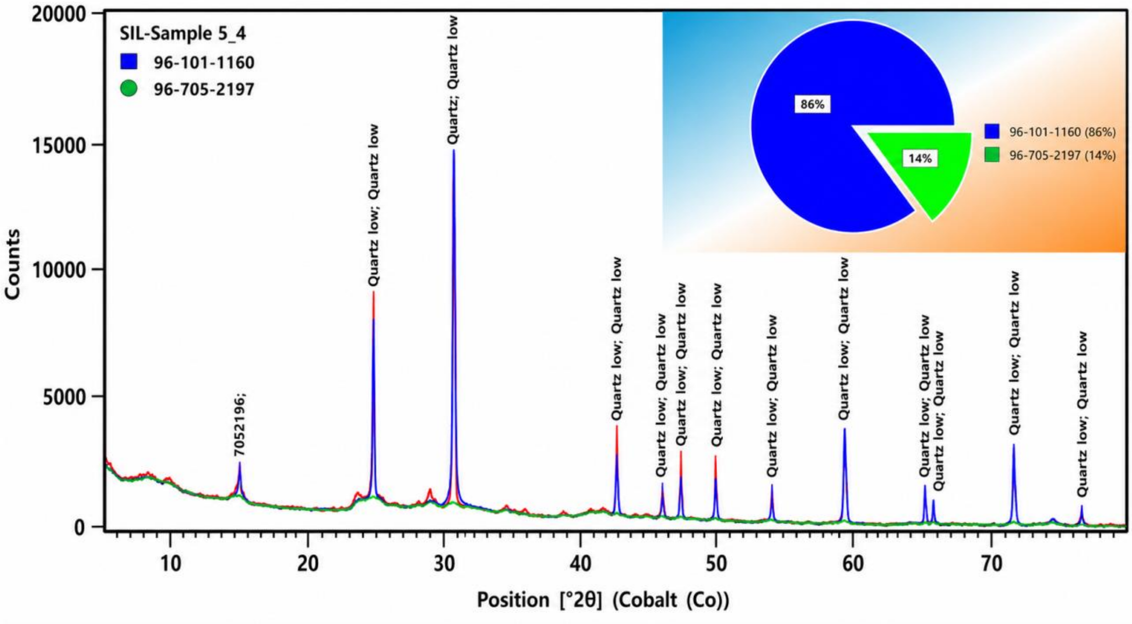

Figure 5. X-ray Diffraction Pattern of Soil Sample 5 (100%Sand, 8% Bentonite, 10%, Bagasse Ash).

3.1.6. Sample 6

A further evolution in the mineralogical structure of the soil is revealed by the XRD analysis of Sample 6, which is the soil modified with the highest dosage of 10% bentonite and 12.5% bagasse ash. The dominant peak at 31.1° 2θ with a d-spacing of 3.33 Å indicates that quartz is still the principal crystalline phase; however, its relative intensity has been declining in comparison to all other samples. Although they are still visible, the quartz peaks at 24.4°, 42.8°, 49.8°, and 59.0° 2θ are less intense than in previous samples, indicating that the soil's amorphous and less crystalline phases are becoming more and more dominant. At 29.1°, 34.8°, 36.0°, 38.8°, and 40.9° 2θ, new minor peaks that were not as noticeable in the previous samples emerge. The persistent interaction between the components of bagasse ash and soil minerals may be the cause of these peaks, which could be linked to secondary minerals or poorly crystalline reaction products. At this higher level of modification, the existence of these extra peaks indicates that the soil matrix is going through more intricate chemical changes. A broadening of the quartz reflections in the diffraction pattern also suggests increased structural disorder and the probable formation of cementitious products like calcium silicate hydrates. Although XRD cannot readily detect these products, which usually form in an amorphous or poorly crystalline state, their presence can be deduced from the observed decrease in quartz crystallinity and the broadening of diffraction peaks. Low quartz and nitrogen-rich organic residues, which are indicative of bagasse ash modification, are confirmed by the identified reference compounds. In landfill environments, the nitrogenous phases help the soil's chemical adsorption capacity, which improves its ability to immobilize both organic and inorganic contaminants. Because of its expansive qualities and capacity for microstructural sealing, the higher bentonite content in Sample 6 continues to be essential in lowering soil permeability. A soil system that provides both chemical and physical barriers to contaminant migration is produced by the combined effects of bagasse ash-induced pozzolanic activity and bentonite swelling. [5] and [11] highlighted the significance of densification and gel formation in enhancing the performance of stabilized soils, and this dual mechanism is consistent with his findings.

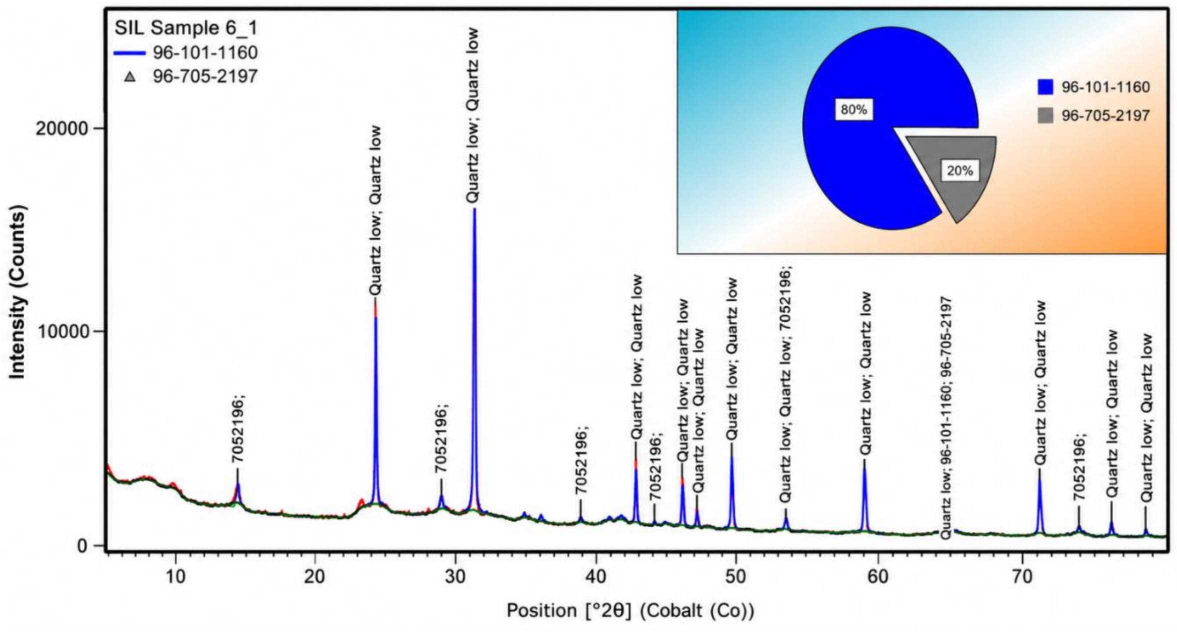

Figure 6. X-ray Diffraction Pattern of Soil Sample 6 (100%Sand, 10% Bentonite, 12.5%, Bagasse Ash).

3.2. SEM Results

3.2.1. Sample 1

The SEM micrograph reveals that the untreated soil possesses a loose and porous microstructure with weak inter-particle bonding and numerous interconnected voids.

The soil particles appear poorly packed, with little evidence of cementitious products or particle agglomeration. This open fabric promotes the easy movement of water and contaminants through the soil, resulting in high permeability. The absence of reaction products further indicates that no significant microstructural densification has occurred. Consequently, the untreated soil exhibits poor engineering performance as a landfill liner material due to its inability to effectively restrict contaminant migration. These observations are consistent with previous studies, which reported that untreated sandy soils generally require stabilization to achieve the low permeability and improved structural integrity needed for landfill containment applications. This observation is consistent with findings by [7] and [4].

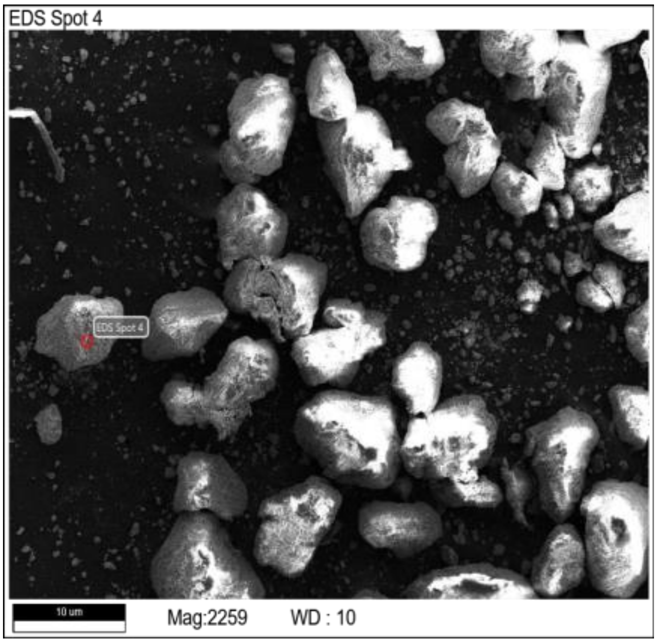

Figure 7. Scanning Electron Microscopy Micrograph of Untreated Soil Sample 1 (100% of Sand, 0% Bentonite, 0%, Bagasse Ash).

3.2.2. Sample 2

The SEM analysis indicates that the addition of 2% bentonite and 2.5% bagasse ash produced noticeable improvements in the soil microstructure compared with the untreated sample. The modified soil exhibits a denser and more compact particle arrangement due to the combined effects of bentonite swelling and the void-filling ability of fine bagasse ash particles. Bentonite effectively blocks pore spaces through its expansive nature, while bagasse ash promotes particle bonding and pore refinement through the formation of cementitious products. These microstructural changes reduce pore connectivity, decrease permeability, and improve the soil's capacity to retain contaminants, making the material more suitable for landfill liner applications. This observation is consistent with findings by [7] and [4].

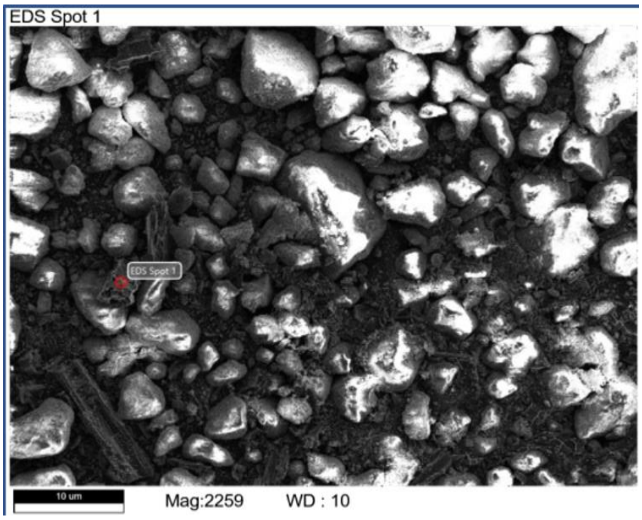

Figure 8. *Scanning Electron Microscopy Micrograph of Soil Sample 2 (100% of Sand, 2% Bentonite, 2.5%, Bagasse Ash).*

3.2.3. Sample 3

The SEM analysis of Sample 3 reveals that the incorporation of 4% bentonite and 5% bagasse ash produces a denser and more compact soil microstructure than the unmodified soil and the lower-dosage samples. The combined effects of bentonite swelling, pore filling by bagasse ash particles, and the formation of cementitious products through pozzolanic reactions improve particle bonding and reduce the number of visible voids within the soil matrix. However, some localized heterogeneity is still observed, indicating that certain regions contain higher concentrations of bagasse ash particles than others. This heterogeneous distribution creates distinct microstructural zones, comprising a well-integrated, stabilized matrix and localized ash-rich regions. Such a microstructure is beneficial for landfill liner applications because it enhances both structural integrity and contaminant retention. These observations agree with the findings of [5] and [11].

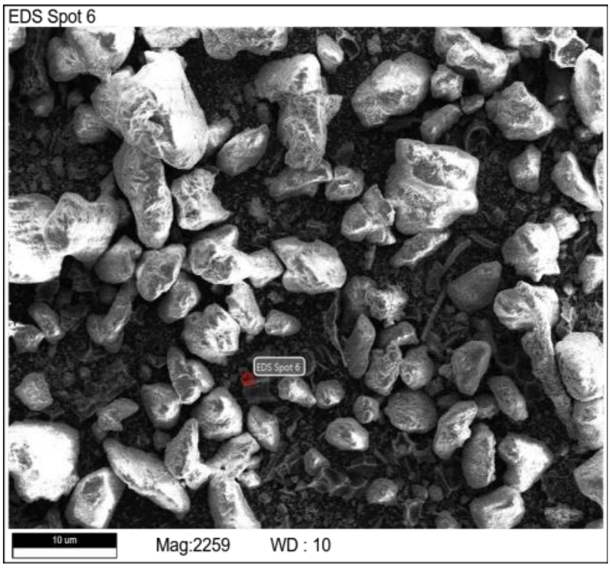

Figure 9. *Scanning Electron Microscopy Micrograph of Soil Sample 3 (100% of Sand, 4% Bentonite, 5%, Bagasse Ash).*

3.2.4. Sample 4

Sample 4's SEM analysis shows notable microstructural and chemical changes that improve its suitability for landfill containment. Sample 4 is soil modified with 6% bentonite and 7.5% bagasse ash. With a weight percentage of 81.70% and an atomic percentage of 86.89%, the first analysis point in Sample 4 demonstrates the overwhelming dominance of carbon. This high carbon content makes it evident that there is a sizable amount of carbonaceous material in the bagasse ash, most likely from unburned organic residues. According to research by [1], a high carbon concentration helps control contaminants because it creates a lot of adsorptive sites that can hold organic pollutants in the soil matrix.

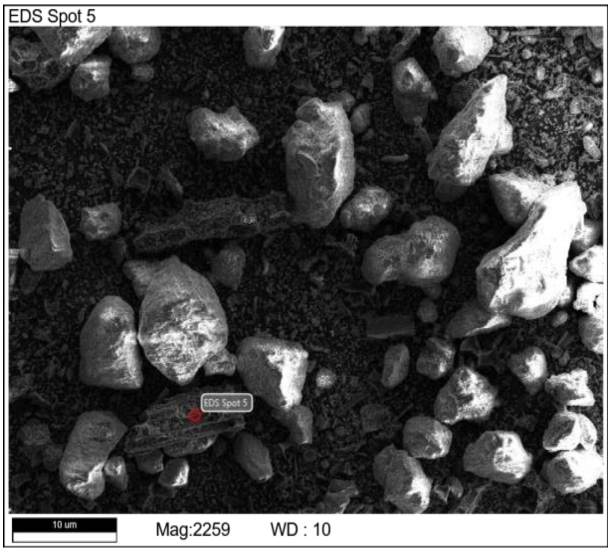

Figure 10. *Scanning Electron Microscopy Micrograph of Soil Sample 4 (100% of Sand, 6% Bentonite, 7.5%, Bagasse Ash).*

3.2.5. Sample 5

The SEM micrograph of Sample 5 shows that increasing the bentonite content to 8% and bagasse ash to 10% resulted in a more advanced stage of soil stabilization. The soil matrix appears denser and more compact, with fewer interconnected pores than the lower-dosage samples. Bentonite fills the voids between sand particles, while bagasse ash contributes additional fine particles that enhance particle packing. The microstructure also exhibits some localized ash-rich regions alongside well-blended bentonite-rich areas, indicating a heterogeneous but well-stabilized matrix. This combination promotes improved soil sealing, increased densification, and enhanced contaminant retention, making the material more suitable for landfill liner applications. This observation is consistent with findings by [7] and [4].

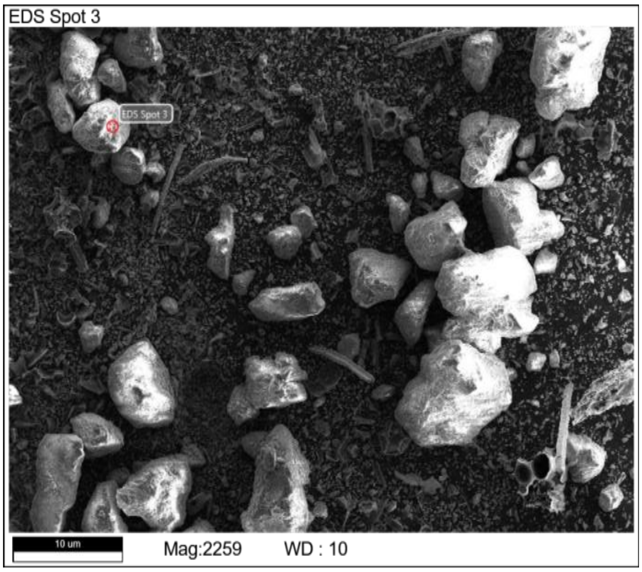

Figure 11. *Scanning Electron Microscopy Micrograph of Soil Sample 5 (100% of Sand, 8% Bentonite, 10%, Bagasse Ash).*

3.2.6. Sample 6

The SEM analysis of Sample 6 (10% bentonite + 12.5% bagasse ash) revealed a well-developed, dense, and stable microstructure with a compact matrix. The high oxygen, silicon, and aluminum contents indicate the formation of abundant oxide phases and silicate minerals, which contributed to pore filling, improved particle bonding, reduced permeability, and enhanced structural stability. Bentonite played a significant role in sealing pore spaces and increasing matrix densification, while bagasse ash was uniformly incorporated into the stabilized soil. The analysis also identified localized ash-rich regions with high carbon content, representing adsorption sites capable of immobilizing contaminants without compromising the overall integrity of the soil matrix. This observation is consistent with findings by [7] and [4]. Overall, the SEM observations demonstrate that Sample 6 achieved the highest degree of microstructural densification and stabilization, providing an effective combination of physical barrier performance (through bentonite) and chemical contaminant retention (through bagasse ash). This makes Sample 6 the optimum mixture for improving engineering performance and landfill liner applications.

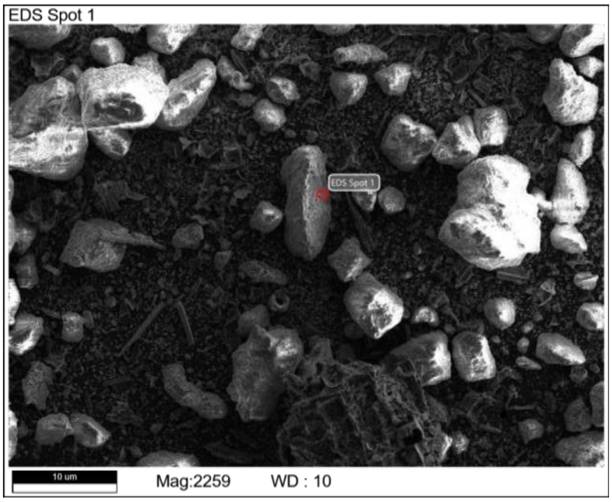

Figure 12. *Scanning Electron Microscopy Micrograph of Soil Sample 6 (100% of Sand, 10% Bentonite, 12.5%, Bagasse Ash).*

3.3. EDX Results

3.3.1. Sample 1

The EDX analysis indicates that the untreated soil is dominated by oxygen (63.86 wt%, 71.94 at%) and silicon (24.43 wt%, 15.68 at%), confirming that the soil mainly consists of silica-rich minerals, particularly quartz. Aluminum is present at a relatively low concentration (3.58 wt%), suggesting a limited amount of aluminosilicate clay minerals and, consequently, low natural pozzolanic reactivity. Minor amounts of iron (1.42 wt%) and titanium (0.48 wt%) represent accessory oxide minerals commonly found in natural soils, while the carbon content (6.23 wt%) indicates a low level of organic matter. Overall, the elemental composition confirms that the untreated soil is predominantly composed of chemically inert minerals with limited binding capacity, making it unsuitable for contaminant containment without stabilization.

3.3.2. Sample 2

The EDX analysis reveals significant changes in the elemental composition of the modified soil. The first analysis point is dominated by carbon (73.98 wt.%), indicating the contribution of carbonaceous materials from bagasse ash, which enhance the soil's adsorption capacity for organic contaminants. Oxygen remains abundant (23.11 wt.%), while the presence of calcium confirms the potential for pozzolanic reactions leading to calcium silicate hydrate (C–S–H) gel formation. Potassium and sulphur further reflect the chemical contribution of bagasse ash. At the second analysis point, oxygen (54.33 wt.%), silicon (21.12 wt.%), and aluminum (12.19 wt.%) become dominant, highlighting the influence of bentonite and the silicate mineral matrix. The elevated aluminum content confirms the incorporation of bentonite, while minor amounts of iron and titanium indicate the presence of accessory minerals. Overall, the EDX results demonstrate that the combined addition of bentonite and bagasse ash promotes both chemical stabilization through pozzolanic reactions and enhanced adsorption capacity, supporting improved contaminant immobilization and long-term landfill barrier performance.

3.3.3. Sample 3

The EDX analysis confirms significant changes in the elemental composition of Sample 3 following stabilization with bentonite and bagasse ash. At the first analysis point, oxygen (56.12 wt.%, 64.36 at.%) and silicon (18.33 wt.%) remain the dominant elements, indicating the continued presence of oxide and silicate phases. Aluminum (8.94 wt.%) increases due to the addition of bentonite, while carbon (10.01 wt.%) reflects the contribution of bagasse ash. Iron (5.50 wt.%), together with small amounts of potassium (0.70 wt.%) and titanium (0.40 wt.%), further contributes to the complex mineral composition and suggests the development of stronger particle bonding. The second analysis point exhibits a markedly different elemental distribution, with carbon becoming the dominant element (81.19 wt.%, 86.82 at.%), accompanied by lower oxygen (14.40 wt.%), silicon (0.87 wt.%), and aluminum (0.42 wt.%) contents, while potassium increases to 3.11 wt.%. This indicates the presence of localized bagasse ash-rich regions or carbonaceous residues within the soil matrix. The variation between the two analysis points demonstrates the heterogeneous distribution of bentonite and bagasse ash, resulting in both oxide-rich stabilized zones and carbon-rich adsorption zones. This dual chemical composition enhances the barrier performance of the modified soil by providing improved structural stability together with increased contaminant adsorption capacity, making the material suitable for landfill liner applications.

3.3.4. Sample 4

The EDX analysis of Sample 4 reveals a heterogeneous but well-developed chemical composition resulting from the combined effects of 6% bentonite and 7.5% bagasse ash. The first analysis point is dominated by carbon (81.70 wt%), indicating a high concentration of carbonaceous material from bagasse ash, which enhances the soil's capacity to adsorb organic contaminants. Trace amounts of magnesium, silicon, phosphorus, sulfur, potassium, and calcium further confirm the contribution of bagasse ash. In contrast, the second analysis point is characterized by high oxygen (63.15 wt%), aluminum (13.81 wt%), and silicon (12.96 wt%) contents, reflecting the dominance of oxide-rich aluminosilicate phases associated with bentonite and the natural soil minerals. The presence of iron (3.96 wt%) and titanium (0.47 wt%) indicates the development of a chemically stable and reinforced mineral matrix. Overall, the EDX results demonstrate the formation of a dual-phase system consisting of carbon-rich zones that enhance contaminant adsorption and oxide-rich aluminosilicate zones that improve microstructural sealing and reduce permeability. This synergistic interaction between bagasse ash and bentonite enhances the engineering performance of the soil, making Sample 4 a suitable material for landfill liner applications due to its improved adsorption capacity, compactness, and contaminant containment potential.

3.3.5. Sample 5

The EDX analysis confirms the chemical modifications produced by the addition of bentonite and bagasse ash. At the first analysis point, oxygen is the dominant element (62.21 wt%), followed by carbon (16.09 wt%), silicon (9.16 wt%), and aluminum (9.07 wt%), reflecting the presence of oxide minerals and aluminosilicate phases supplied mainly by bentonite. Minor amounts of iron (2.44 wt%), potassium (0.67 wt%), and titanium (0.35 wt%) further contribute to soil stabilization through additional mineral binding. At the second analysis point, carbon becomes dominant (78.91 wt%), while oxygen decreases to 18.80 wt%, indicating localized ash-rich regions. Silicon and aluminum are present only in trace amounts, while potassium (1.78 wt%) and traces of chlorine are detected, confirming the contribution of bagasse ash. Overall, the EDX results indicate a heterogeneous distribution of bentonite- and ash-rich zones, supporting both physical densification and chemical immobilization of contaminants in the stabilized soil.

3.3.6. Sample 6

The EDX analysis of Sample 6 (10% bentonite and 12.5% bagasse ash) indicates a well-developed and chemically stable soil matrix. Oxygen is the dominant element (61.40 wt%), confirming the abundance of oxide minerals such as silicates and aluminates that enhance structural stability and reduce permeability. Silicon (17.37 wt%) and aluminum (6.52 wt%) demonstrate the continued contribution of bentonite to pore filling, densification, and improved barrier performance, while iron (6.42 wt%) may contribute to increased mechanical strength. Carbon is present at a moderate level (7.75 wt%) in the first analysis point, indicating a well-dispersed contribution from bagasse ash. The second analysis point is characterized by a very high carbon content (86.74 wt%), with lower oxygen (12.04 wt%) and a small amount of potassium (1.22 wt%), representing localized ash-rich regions. These carbon-rich zones provide additional adsorption sites for contaminant immobilization without compromising the integrity of the stabilized matrix. Overall, the EDX results demonstrate that Sample 6 achieved an optimal combination of bentonite-induced physical sealing and bagasse ash-assisted chemical adsorption, resulting in a dense, low-permeability, and chemically active barrier material with enhanced contaminant retention capacity.

4. Conclusion

This study investigated the microstructural performance of sand-bentonite mixtures (SBMs) stabilized with bagasse ash (BA) for use in engineered landfill barrier systems. Based on laboratory evaluations of microstructural characteristics, the following conclusions are drawn:

1) The XRD, SEM, and EDX analyses confirmed that increasing bentonite and bagasse ash contents progressively modified the soil from a loose, quartz dominated structure to a denser and more stable matrix with enhanced engineering properties.
2) Bentonite primarily improved the soil through pore filling and sealing, while bagasse ash contributed amorphous silica and carbon-rich phases that promoted pozzolanic reactions and enhanced contaminant adsorption.
3) Progressive reductions in quartz peak intensity, increased amorphous phases, and improved particle bonding demonstrated effective microstructural densification and lower permeability of the stabilized soils.
4) The combined use of bentonite and bagasse ash significantly enhanced the soil's suitability as a landfill liner by improving contaminant retention, structural stability, and barrier performance.
5) Among all the mixtures investigated, the sample containing 10% bentonite and 12.5% bagasse ash (Sample 6) exhibited the highest degree of stabilization and is therefore the optimum composition for landfill liner applications.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
at%	Atomic Percentage
BA	Bagasse Ash
BS	British Standard
C–S–H	Calcium Silicate Hydrate
EDX	Energy Dispersive X-ray Spectroscopy
MSW	Municipal Solid Waste
NIBRR	National Institute of Building and Road Research
OMC	Optimum Moisture Content
SBA	Sugarcane Bagasse Ash
SBMs	Sand–Bentonite Mixtures
SEM	Scanning Electron Microscopy
wt%	Weight Percentage
XRD	X-ray Diffraction
2θ	Two-Theta (X-ray Diffraction Angle)

Author Contributions

Amedu Lawal Makhu: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft

Zekeri Jafaru: Project administration, Supervision, Validation

Ahmed Alhassan: Writing – original draft

Ifabiyi Stephen Olugbemniga: Visualization

Conflicts of Interest

The authors declare no conflicts of interest.

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