Stability Evaluation of Landfill Liners Using Compacted Waste Foundry Sand and Bentonite

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Abstract: The construction of secure landfill liners consumes vast quantities of high-quality natural clay, leading to resource depletion and environmental concerns. Concurrently, the foundry industry generates significant amounts of Waste Foundry Sand (WFS), a by-product that poses disposal challenges. This study investigates the feasibility of utilizing WFS stabilized with bentonite as a sustainable material for landfill liner applications. WFS was mixed with bentonite (0% to 10% by weight) and compacted using British Standard Heavy (BSH) energy. Index properties, compaction characteristics, and Unconfined Compressive Strength (UCS) at 7, 14, and 28-day curing periods were evaluated. Results indicate that the addition of bentonite transformed the non-plastic WFS into a plastic material at 8% bentonite content and above. The Maximum Dry Density (MDD) decreased from 1.96 Mg/m³ to 1.6 Mg/m³, while the Optimum Moisture Content (OMC) increased from 17% to 21% as bentonite content increased from 0% to 10%. The UCS increased with both bentonite content and curing period, peaking at 383.61 kN/m² for the 8% bentonite mixture after 28 days of curing. This value significantly surpasses the common regulatory benchmark of 200 kN/m² for liner stability. The study concludes that an optimum mix of 92% WFS and 8% bentonite, compacted at BSH energy, provides a technically viable, sustainable, and economically beneficial alternative to conventional clay liners, effectively valorizing industrial waste while meeting critical geotechnical requirements for waste containment.

Keywords: *Waste Foundry Sand, Bentonite, Landfill Liner, Unconfined Compressive Strength.*

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I. INTRODUCTION

The safe containment of municipal and industrial solid waste remains a paramount challenge of modern civilization. Engineered landfill barrier systems, particularly compacted clay liners (CCLs), are critical for preventing leachate migration and safeguarding groundwater resources [1, 2]. Traditionally, these liners are constructed from high-quality natural clay soils. However, the large-scale extraction of such clays contributes to resource depletion, landscape degradation, and a considerable environmental footprint [3]. This underscores the need for alternative liner materials that are both technically effective and environmentally sustainable.

In modern days, industrial activities generate vast quantities of by-products that require proper management. The metal casting industry alone produces millions of tons of Waste Foundry Sand (WFS) annually [4]. While part of this material is reused in secondary applications, the majority is disposed of in landfills, creating an economic burden for foundries and an ecological concern for the environment [5]. Consequently, the utilization of WFS to help reduce the problem associated with waste disposal management for recycling purposes aligns with the principles of sustainable waste management and the circular economy.

Foundry sand is primarily a clean, high-quality silica sand used for moulding in metal casting. The most common type, “green sand,” consists of silica sand mixed with 5–10% bentonite clay (as a binder), 2–5% water, and carbonaceous additives [8]. After repeated use, the sand loses its binding properties and is discarded as WFS. Physically, WFS is typically sub-angular to rounded, with a uniform grain size distribution where 85–95% falls between 0.6 mm and 0.15 mm [8]. It is non-plastic, with a specific gravity of 2.39–2.55, and is predominantly composed of silica (SiO_2 >85%), although traces of metals and organics may remain from the casting process [9]. Mechanically, WFS exhibits good shear strength with reported unconfined compressive strengths between 482–3968 kN/m² and internal friction angles of 33°–43° [10]. However, its free-draining nature and high permeability render it unsuitable as a separate hydraulic barrier.

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Bentonite, on the other hand is some natural clay rich in montmorillonite, valued for its high cation exchange capacity, swelling potential and very low hydraulic conductivity. Sodium bentonite, in particular can swell 12–15 times its dry volume upon hydration forming an impermeable gel that effectively seals soil pores [11]. When blended with granular soils, bentonite fills voids between sand grains, reduces permeability and imparts cohesion. This not only improves hydraulic sealing capacity but also enhances undrained shear strength making the mixture more suitable for landfill liner applications [7].

While WFS has been studied for use in low-value applications such as road bases and embankments, its utilization in landfill liner systems where both hydraulic and mechanical performance remains underexplored. This study addresses this gap by systematically investigating compacted WFS–bentonite mixtures as landfill liner materials. Specifically, the study evaluates the index and compaction characteristics of the mixtures, examines the influence of bentonite content and curing time on UCS capable of meeting regulatory standards.

II. OBJECTIVES OF THE STUDY

The development of alternative landfill liner materials requires a balance between technical performance, environmental safety, and sustainable resource use. Since Waste Foundry Sand (WFS) alone lacks the low permeability and cohesion necessary for hydraulic barriers, its modification with bentonite offers a promising solution. To evaluate this potential, the present study was designed with the following specific objectives:

- To determine the index properties of Waste Foundry Sand (WFS) and bentonite.
- To investigate the compaction characteristics (optimum moisture content and maximum dry density) of WFS mixed with bentonite at various percentages.
- To examine the effect of bentonite content and curing period on the Unconfined Compressive Strength (UCS) of the mixtures.
- These properties help predict soil behaviour under varying moisture conditions and indicate its sealing potential.

III. MATERIALS AND METHODS

➢ *Materials*

- *Waste Foundry Sand (WFS):*

The WFS used was a dark brown, fine sand obtained from the Defence Industries Corporation of Nigeria (DICON), Kaduna. It was air-dried, crushed, and passed through a BS No. 4 (4.75 mm) sieve before testing.

- *Bentonite:*

A light brown, commercially available sodium bentonite was procured from a market in Kano, Nigeria. It exhibited very fine particles and a greasy feel, characteristic of high-quality bentonite.

➢ *Sample Preparation*

The untreated WFS was tested to establish baseline properties. Subsequently, mixtures were prepared with bentonite contents of 2%, 4%, 6%, 8%, and 10% by dry weight. The materials were mixed thoroughly to ensure that the bentonite particles were well-dispersed to achieve homogeneity. All laboratory tests were conducted for treated and untreated samples in accordance with BS 1377 (1990)**:** Methods of Test for Soils for Civil Engineering Purposes, to ensure accuracy, reliability and comparability of results.

➢ *Experimental Procedure*

Laboratory tests were conducted to evaluate the physical and mechanical properties of the untreated Waste Foundry Sand (WFS) and the treated WFS–bentonite mixtures. All procedures were performed in accordance with BS 1377 (1990) and related standard test methods, as outlined below:

- *Moisture content*

The natural moisture content of the samples was determined using the oven-drying method. It was conducted to determine the natural water content of WFS and bentonite to assess the workability, compaction and strength behaviour. The soil samples were weighed and placed in a thermostatically controlled oven at a temperature of 105 ± 5 °C for 24 hours. The samples were then reweighed, and the moisture content was calculated as the percentage loss in weight relative to the dry mass.

- *Specific gravity*

This test was conducted to provide insight to the relative density of WFS mixed with bentonite. The specific gravity of WFS and bentonite was determined using a density bottle. Oven-dried soil samples were carefully placed in the bottle, and the displacement method with distilled water was used to compute the specific gravity, ensuring correction for the water temperature.

- *Particle size distribution*

The test was conducted to classify the WFS-bentonite mixtures and identify its gradation, which influences permeability, compaction behavior and suitability for liner applications. The gradation of WFS was obtained through dry sieve analysis. Wet sieving was initially carried out to wash out fine particles passing through the 75 µm sieve. The retained material was then oven-dried and subjected to mechanical dry sieving through a set of standard sieves. The results were used to plot the particle size distribution curve.

- *Atterberg limits*

The Atterberg limits was conducted to predict soil behaviour under varying moisture conditions and indicate its binding potential. The consistency limits of the WFS and bentonite mixtures were determined to assess their plasticity characteristics. The Liquid Limit (LL) was obtained using the Casagrande apparatus, while the Plastic Limit (PL) was determined by rolling soil threads to a 3 mm diameter. The Plasticity Index (PI) was calculated as the difference between LL and PL. In addition, Linear Shrinkage (LS) was measured by drying soil bars in an oven and recording the reduction in length.

- *Compaction characteristics*

The compaction properties of the untreated WFS and WFS–bentonite mixtures were determined using the British Standard Heavy (BSH) compaction method equivalent to the Modified Proctor test. Samples were compacted in a standard mould in five layers, each receiving 27 blows from a 4.5 kg rammer dropped from a height of 450 mm. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were obtained from the compaction curves.

- *Unconfined Compressive Strength (UCS)*

This test measures the undrained shear strength of the WFS-bentonite mixtures at different curing times (7, 14, and 28 days). It provides insight into the stability of landfill liners under load and ensures compliance with regulatory strength requirements (≥200 kN/m²). Cylindrical specimens measuring 38 mm in diameter and 76 mm in height were prepared by statically compacting the WFS–bentonite mixtures at their respective OMC and MDD, using BSH compaction energy. The specimens were extruded from the moulds and cured in airtight plastic wraps to prevent moisture loss. Curing was carried out for 7, 14, and 28 days to evaluate the effect of curing time on strength development. After curing, specimens were tested under axial loading at a constant strain rate of 0.10 mm/min until failure. The UCS was determined as the maximum axial stress sustained by the specimen.

IV. RESULTS AND DISCUSSION

➢ *Properties of the Materials*

- *Waste Foundry Sand*

The index properties of the natural WFS are summarized in Table 1. The WFS is classified as A-3(0) according to AASHTO and SM (silty sand) according to the Unified Soil Classification System (USCS). This classification signifies poorly graded sandy materials with limited fines for both classification methods and is characterized by high permeability. The natural moisture content recorded a very low value (0.36%), consistent with its free-draining behaviour and storage in dry conditions. The Atterberg limit tests reveal that WFS is essentially non-plastic as it exhibits no measurable plastic limit or plasticity index. A liquid limit of 29% was obtained and very low linear shrinkage value (0.31%). The particle size distribution curve (Figure 1) confirms it is a fine sand, with 62.5% passing the No. 200 sieve.

Table 1 Properties of Waste Foundry Sand

Property	**Value**
% Passing Sieve No. 200	62.5
Natural Moisture Content (%)	0.36
Liquid Limit (%)	29.0
Plastic Limit	Non-plastic
Plasticity Index	Non-plastic
Linear Shrinkage (%)	0.31
Specific Gravity	2.58
AASHTO Classification	A-3(0)
USCS Classification	SM
OMC (%)	17
MDD (Mg/m³)	1.96
Colour	Dark Brown

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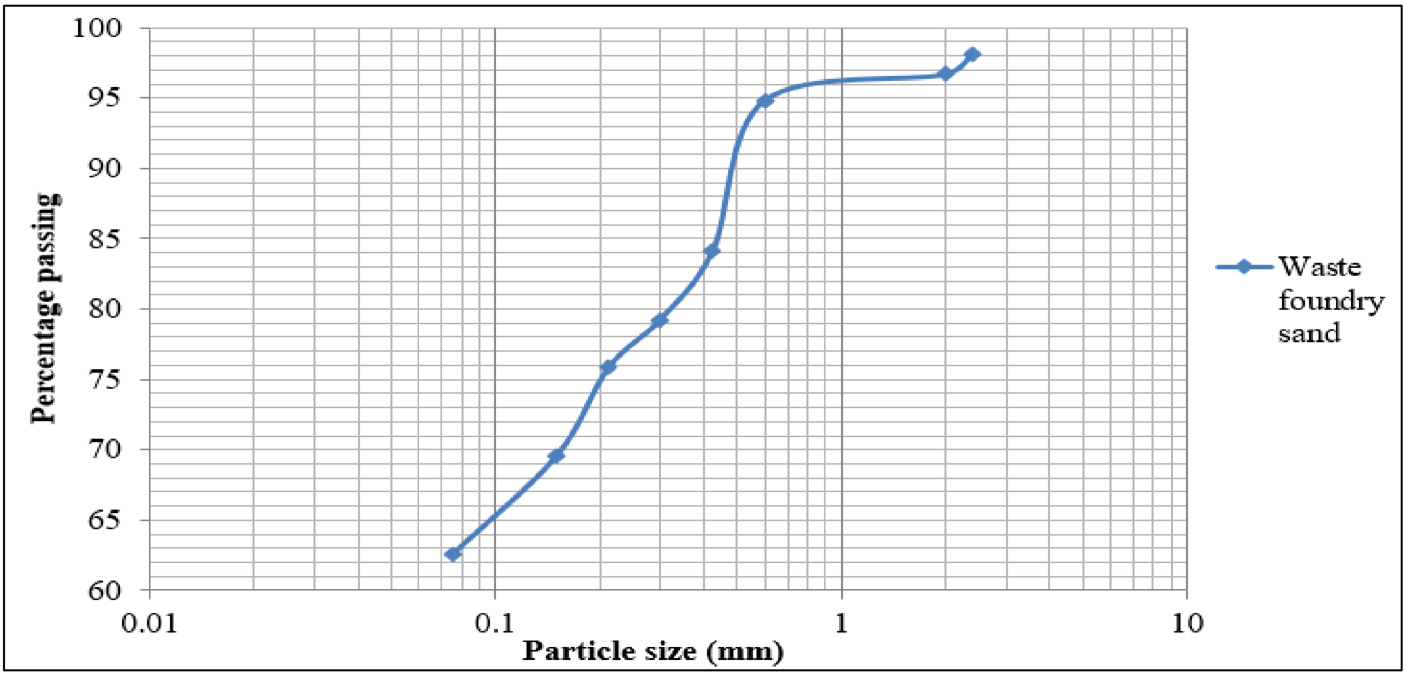

Fig 1 Particle Size Distribution Curve of WFS.

- *Bentonite*

The bentonite was classified as A-3(0) and SM, similar to the WFS. However, its fine texture, greasy feel and strong cohesion are indicative of its high clay content mineral dominated by montmorillonite. When mixed with WFS, the clay fraction of bentonite can fill the voids between the WFS particles imparting cohesion and significantly reducing permeability of the material.

➢ *Properties of WFS-Bentonite Mixtures*

The index properties of the WFS-Bentonite mixtures are summarized in Table 2. The addition of bentonite progressively modified the physical and engineering properties of the Waste Foundry Sand. The increased bentonite content from 0% to 10%, highlights changes which were observed in parameters such as liquid limit, linear shrinkage, specific gravity, optimum moisture content (OMC) and maximum dry density (MDD).

Table 2 Properties of WFS-Bentonite Mixtures

Property	0%	2%	4%	6%	8%	10%
% Passing No. 200	62.5	62.3	62.9	60.5	62.05	65.39
Liquid Limit, LL (%)	29.0	29.8	31.0	31.5	32.7	33.5
Plastic Limit, PL (%)	-	-	-	-	29.1	31.5
Plasticity Index, PI (%)	-	-	-	-	3.6	2.0
Linear Shrinkage, LS (%)	0.31	1.97	2.36	3.93	4.33	4.72
Specific Gravity, Gs	2.58	2.53	2.46	2.41	2.38	2.29
OMC (%)	17	18	19	19	20	21
MDD (Mg/m³)	1.96	1.89	1.78	1.72	1.68	1.60

➢ *Discussion of Index Properties for WFS-Bentonite mixtures*

- *Atterberg Limits*

The variation of Atterberg limits with bentonite content is shown in Figure 2. The Liquid Limit (LL) showed a progressive increase from 29.0% to 33.5%. A more significant change was observed in plastic behavior. The WFS was non-plastic with up to 6% bentonite content. However, at 8% and 10% bentonite content, the mixtures exhibited plasticity, with Plasticity Indices (PI) of 3.6% and 2.0%, respectively. This transition is critical, as it indicates the development of cohesive forces within the soil matrix necessary for a liner material that must maintain integrity upon cracking.

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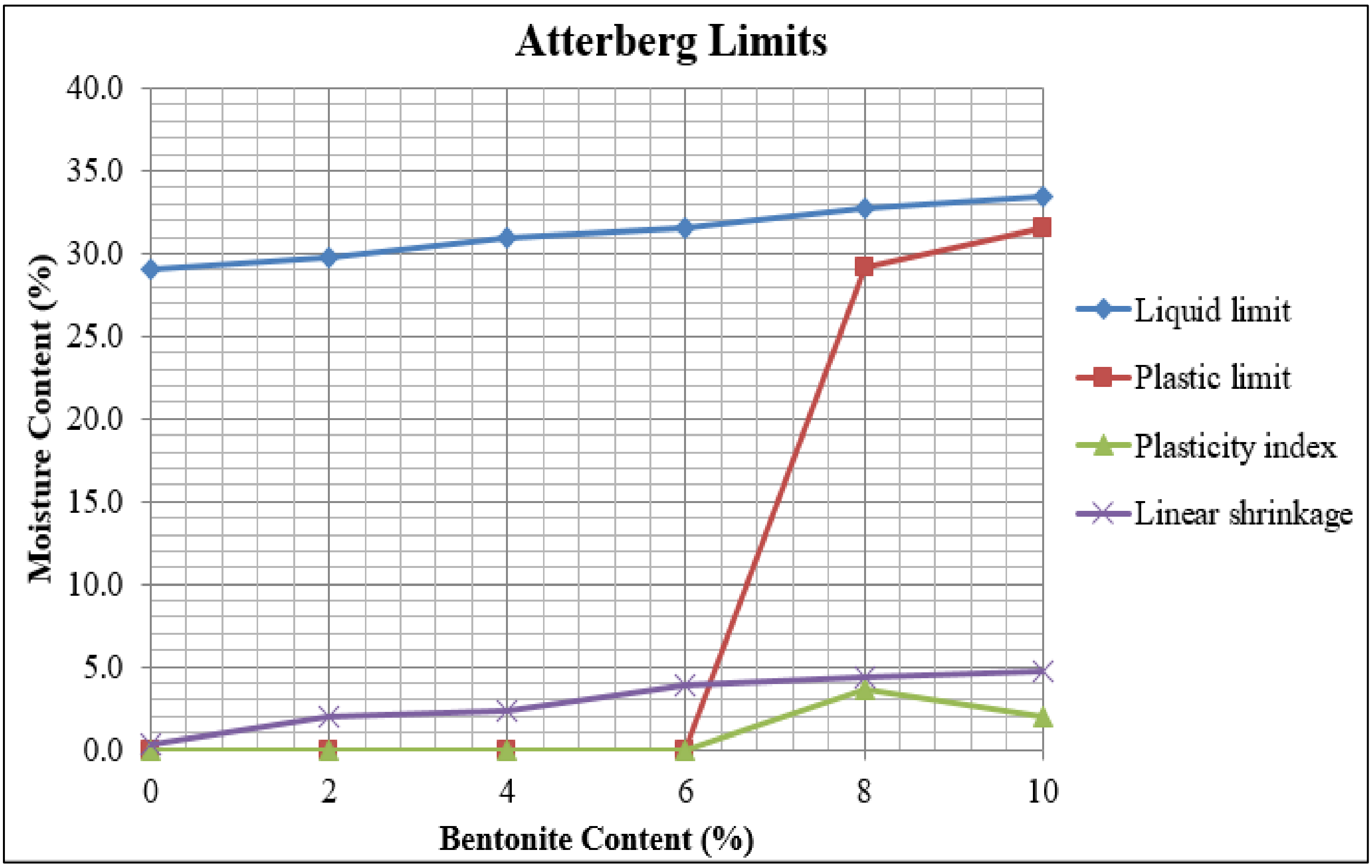

Fig 2 Variation of Atterberg Limits with Bentonite Content.

- *Specific Gravity*

The specific gravity of the mixtures decreased linearly from 2.58 to 2.29 as bentonite content increased from 0% to 10% as presented in Figure 3. This is attributed to the lower specific gravity of bentonite clay minerals compared to the silica sand particles of the WFS.

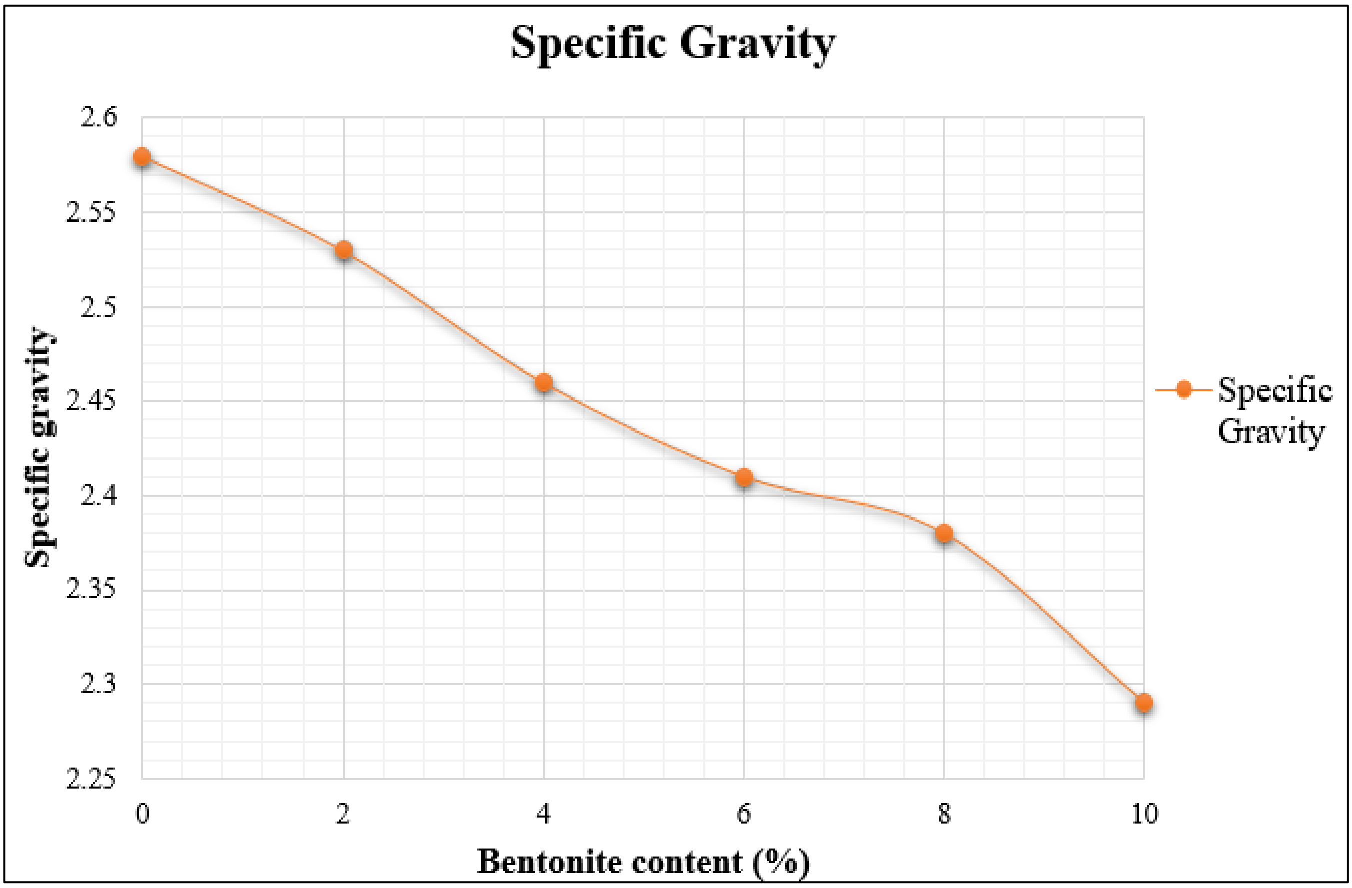

Fig 3 Variation of Specific Gravity with Bentonite Content.

- *Linear Shrinkage*

Linear Shrinkage (LS) increased significantly from 0.31% to 4.72% with the addition of bentonite in Figure 2. According to the classification by Murthy [13], LS values greater than 8% are considered "critical" for expansion. While the values here are below this threshold, the increasing trend indicates a growing tendency for volume change with drying, which should be considered in the design to manage desiccation cracking.

➢ *Compaction Characteristics*

- *Maximum Dry Density (MDD) and Optimum Moisture Content (OMC)*

The compaction characteristics were significantly influenced by bentonite content. As shown in Figures 4 and 5, the MDD decreased from 1.96 Mg/m³ to 1.60 Mg/m³ while the OMC increased from 17% to 21%. This is due to the high-water absorption and swelling tendency of bentonite, which requires more water to achieve compaction. Conversely, the MDD decreased from 1.96 Mg/m³ (0% bentonite) to 1.60 Mg/m³ (10% bentonite). The reduction is attributed to the replacement of dense sand particles with lighter bentonite particles and the increased voids created by swelling clays, which reduce the overall packing density.

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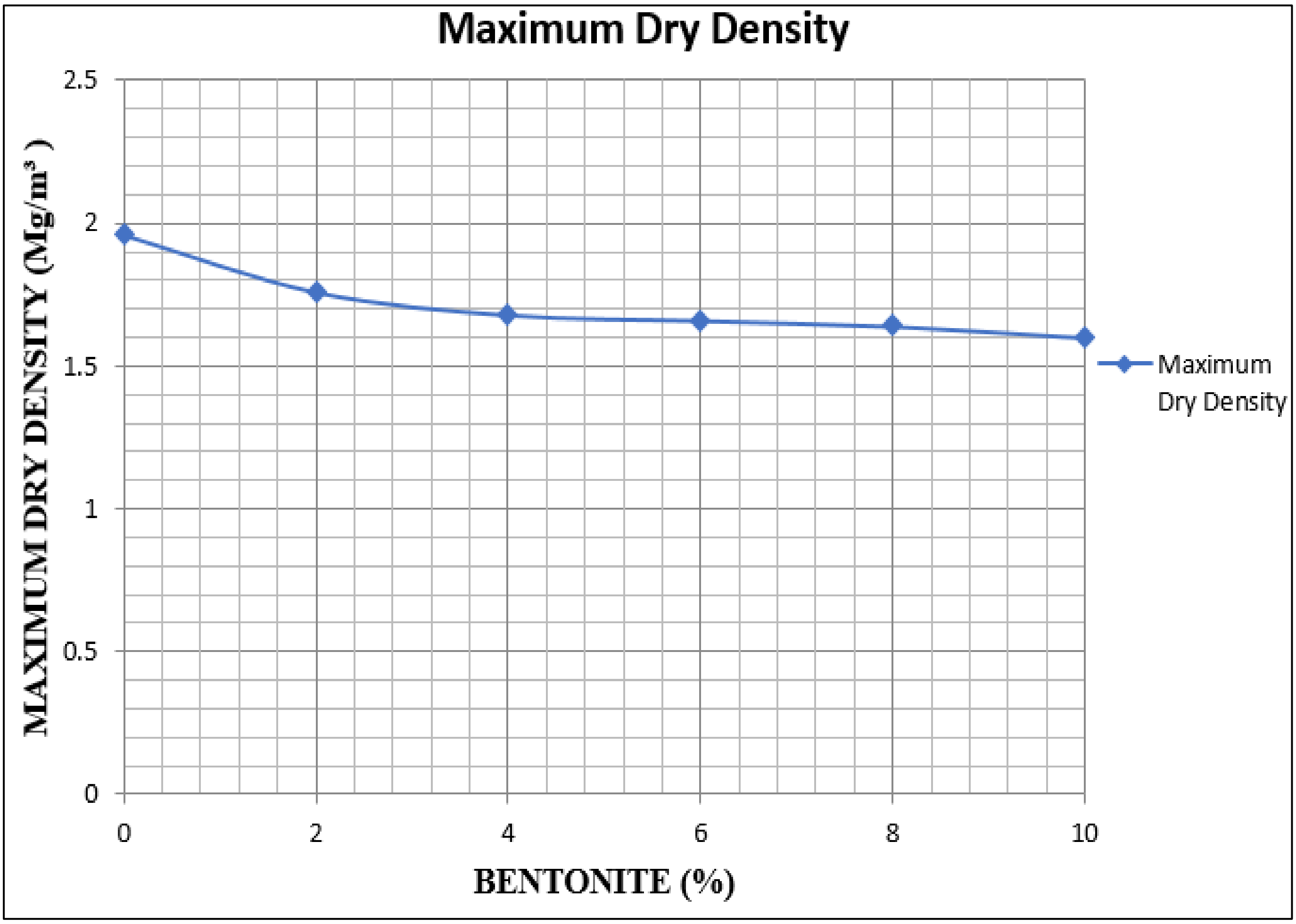

Fig 4 Variation of Maximum Dry Density (MDD) with Bentonite Content.

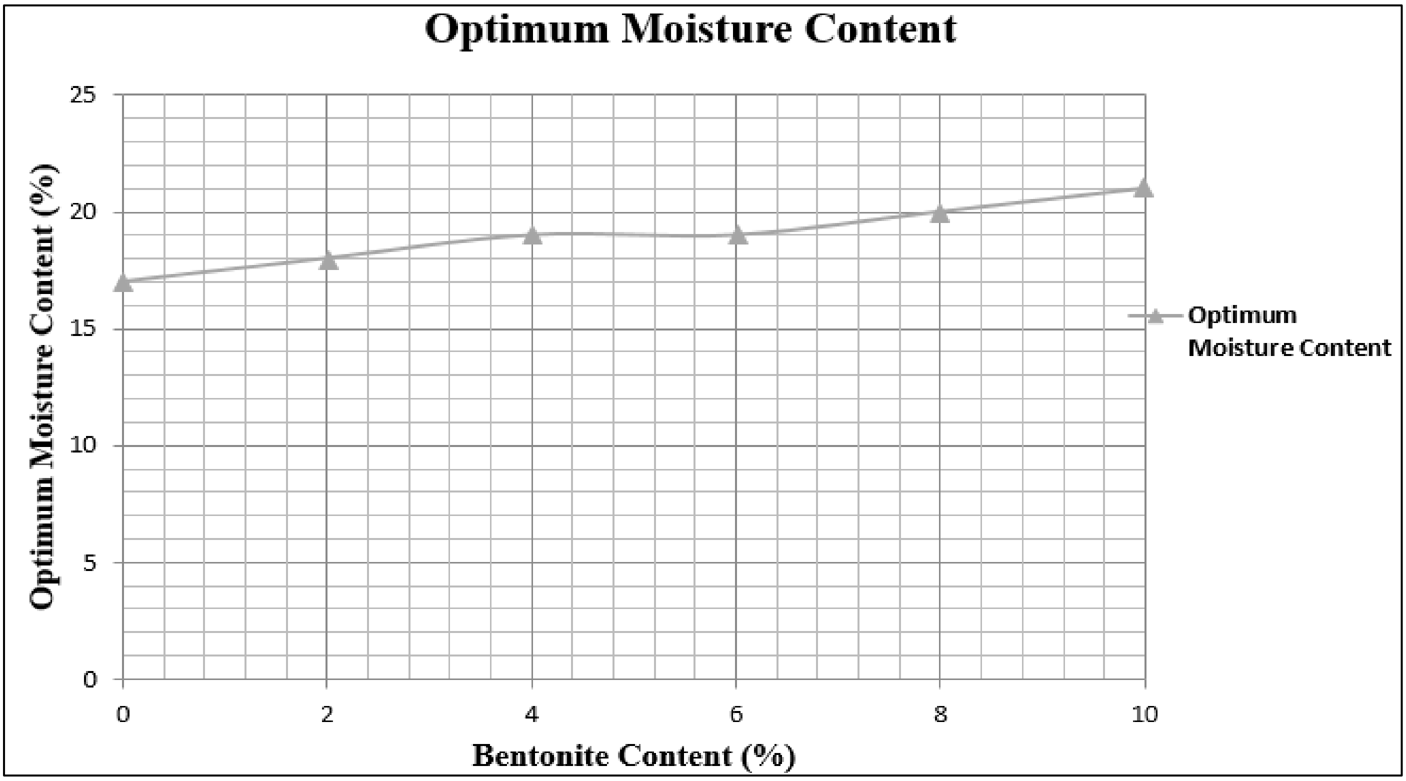

Fig 5 Variation of Optimum Moisture Content (OMC) with Bentonite Content

➢ *Unconfined Compressive Strength (UCS) and Stability Analysis*

The Unconfined Compressive Strength (UCS) values for WFS–bentonite mixtures at curing periods of 7, 14, and 28 days are presented in Table 3 and illustrated in Figure 6. The results illustrate the trends with respect to both bentonite content and curing duration.

Table 3 Unconfined Compressive Strength (kN/m²) at different Curing Periods

Bentonite Content (%)	7 days	14 days	28 days
0	138.34	161.48	171.27
2	130.94	144.88	160.56
4	255.92	273.72	295.34
6	288.29	300.66	341.56
8	314.32	345.18	383.61
10	298.59	317.94	335.63

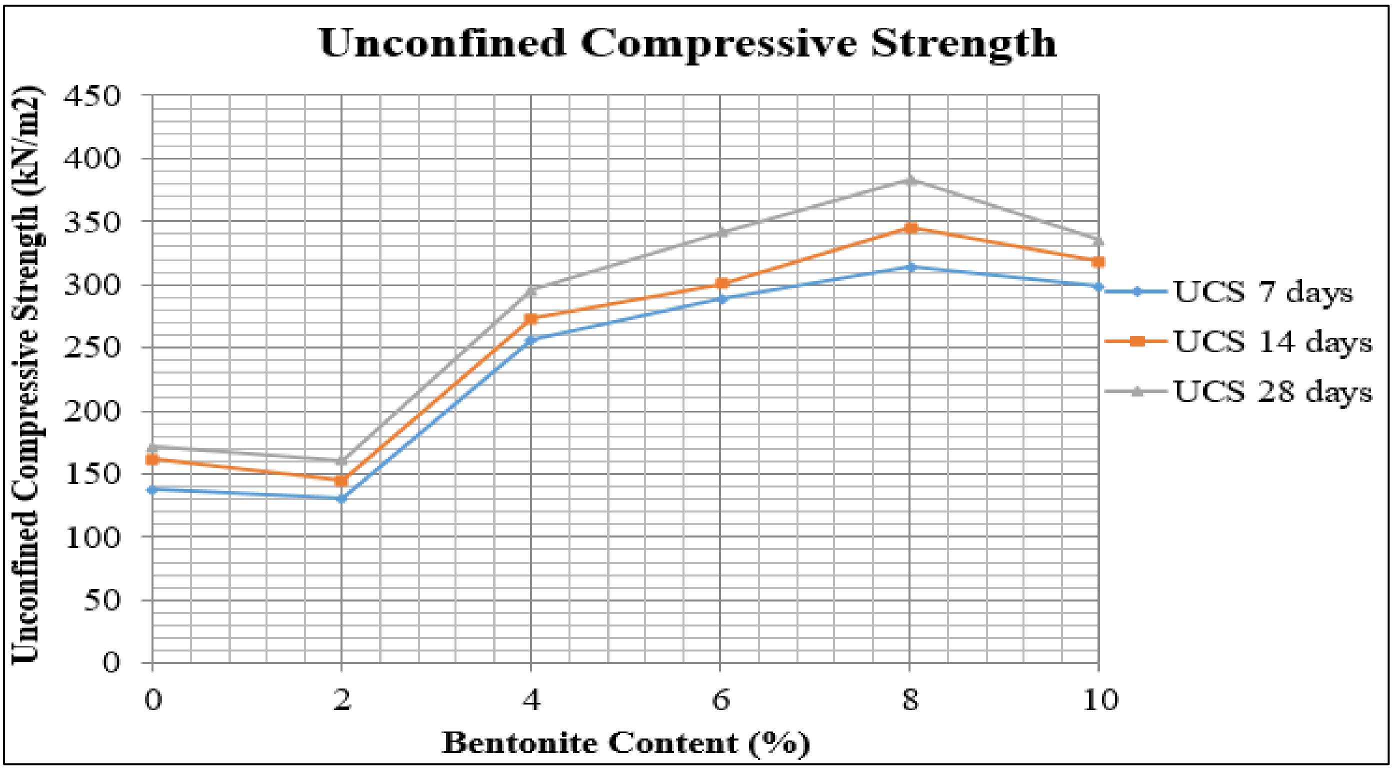

Fig 6 Variation of UCS with Bentonite Content and Curing Period

- *Effect of Bentonite content*

The UCS values for untreated WFS (0% bentonite) were relatively low with slight increase slightly from 138.34 kN/m² at 7 days to 171.27 kN/m² at 28 days. These values fall below the specification of 200 kN/m² for landfill liner stability [12], confirming that unmodified WFS lacks adequate strength for such applications.

At 2% bentonite content, the UCS values remained lower than the control across all curing periods (130.94–160.56 kN/m²), suggesting that small bentonite additions initially disrupted the sand matrix without contributing sufficient cohesion to offset the effect. However, with increase in bentonite content, a significant improvement in strength was observed. At 4% bentonite content, UCS values increased significantly to 255.92 kN/m² (7 days) and reached 295.34 kN/m² at 28 days exceeding the minimum regulatory requirement. Further increments to 6% and 8% bentonite content yielded the highest strength gains, with peak UCS values of 341.56 kN/m² and 383.61 kN/m² respectively after 28 days. The 10% bentonite content values for UCS decreased slightly relative to 8% (335.63 kN/m² at 28 days), suggesting that excessive bentonite may lead to reduced particle interlock and weaker structural integrity.

- *Effect of curing period*

The UCS values increased consistently with curing time for all percentages of bentonite content. This strength gain can be attributed to improved particle bonding and gradual hydration of bentonite which enhances cohesion within the mixture. For example, at 8% bentonite, UCS improved from 314.32 kN/m² (7 days) to 383.61 kN/m² (28 days), reflecting a 22% increase. The trend signifies the importance of curing in the development of shear strength and long-term liner stability.

- *Effect on Stability*

The addition bentonite contents of 4, 6 and 8**%** appear optimal, producing UCS values well above the regulatory benchmark and ensuring liner stability for application. Ina addition, the increase in bentonite content beyond 8% is counterproductive, as the excessive clay fraction reduces the structural contribution of sand leading to lower strength despite higher plasticity.

- *Implications for Landfill Liner Design*

The UCS value of 383.61 kN/m² for the 8% bentonite mix at 28 days far exceeds the specification of 200 kN/m² for landfill liner stability [12]. This confirms that the WFS-bentonite mixture possesses adequate undrained shear strength to resist internal slope failure under its own weight and the weight of overlying waste.

The use of British Standard Heavy (BSH) compaction energy ensures that the laboratory results are directly transferable to field compaction practices, making the proposed mix design practically implementable. The transition to a plastic soil at 8% bentonite also suggests improved workability and self-healing capacity, which are beneficial properties for a liner material.

- *Sustainability and Economic Benefits*

The use of 92% WFS in the optimum liner mix marks a significant step toward sustainable waste management by providing a high-volume reuse pathway that diverts WFS from landfills while reducing reliance on virgin clay soils. This dual benefit not only lessens environmental burdens but also conserves natural resources, offering a practical “win–win” solution that aligns with global circular economy goals in construction and geotechnics.

V. CONCLUSION

This study comprehensively evaluated the feasibility of using Waste Foundry Sand (WFS) stabilized with bentonite as a sustainable material for landfill liner construction. Based on the laboratory investigation using British Standard Heavy compaction energy, the following conclusions are drawn:

- The addition of bentonite alters the properties of WFS, transforming it from a non-plastic, granular material into a cohesive soil with measurable plasticity at contents of 8% and above.
- The addition of bentonite from 4% to 8% significantly increased strength for UCS values. This is due to the development of strong cohesive bonds from the bentonite, which effectively binds the WFS particles together. The mixture transforms from a purely frictional material to a cohesive-frictional one.
- The compaction characteristics are modified, with Maximum Dry Density (MDD) decreasing and Optimum Moisture Content (OMC) increasing with higher bentonite content.
- The Unconfined Compressive Strength (UCS) is highly dependent on both bentonite content and curing period. This suggests ongoing pozzolanic reactions or thixotropic hardening within the bentonite-clay matrix, leading to long-term strength gain.
- An optimum mix of 92% WFS and 8% bentonite is recommended when compacted at BSH energy and cured for 28 days which achieved a UCS value of 383.61 kN/m², which comfortably surpasses the regulatory strength requirement of 200 kN/m² for landfill liner stability. This represents a 124% increase in strength compared to the untreated WFS.
- Beyond the optimum of 8%, the UCS decreased at 10% bentonite. This is likely due to the excess bentonite retaining too much water at OMC, creating a more plastic and less stiff matrix that reduces the frictional resistance between the sand particles
- This research demonstrates that a liner material composed predominantly of an industrial by-product can not only meet but exceed the mechanical performance criteria for safe waste containment which can be environmentally sustainable and economically advantageous.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

- The optimum mix of 92% WFS and 8% bentonite, compacted at BSH energy can be adopted for landfill liner construction to ensure regulatory compliance and long-term stability.
- Large-scale field trials can be conducted to confirm laboratory findings under real landfill conditions, including variability in moisture, load, and environmental factors.
- The long-term hydraulic conductivity, chemical compatibility with leachates, and durability can be explored under cyclic wetting/drying to strengthen confidence in field application.

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➢ *List of Figures*

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