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Performance Evaluation of Lateritic Soil Treated With Waste Marble Dust As a Suitable Landfill Liner Material

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Abstract: *This study evaluated the potential use of lateritic soil treated with waste marble dust (WMD) as a suitable material for landfill liners. The chemical analysis revealed that the WMD is rich in lime (CaO), imparting cementitious properties, while the lateritic soil exhibited a silica–sesquioxide ratio of 1.67, classifying it as lateritic. Laboratory tests assessed the effects of varying WMD content (0-12%) on the soil's Atterberg limits, compaction characteristics, hydraulic conductivity, unconfined compressive strength (UCS), and volumetric shrinkage strain (VSS). Results showed that liquid limit decreased from 36.4% to 30.2% and plastic limit increased from 12% to 24%, maintaining LL and PI values above the minimum thresholds recommended for landfill liners. Maximum dry density improved to 2.11 Mg/m³ under BSH compaction, while optimum moisture content reduced, indicating denser soil matrices. Hydraulic conductivity decreased significantly across compactive efforts, achieving values as low as 8.42×10^{-9} m/s, well within the $\leq1\times10^{-9}$ m/s requirement for liners. UCS values peaked at 340 kN/m², surpassing the 200 kN/m² benchmark, and VSS dropped below 4%, minimizing risks of excessive shrinkage. These findings demonstrate that 6 to 12% WMD-treated lateritic soil meets critical geotechnical criteria for landfill liners, offering a sustainable approach that simultaneously manages marble waste and enhances soil performance.*

Keywords: *Lateritic Soil, Waste Marble Dust, Landfill Liner, Hydraulic Conductivity, Unconfined Compressive Strength*

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1. INTRODUCTION

In many developing countries like Nigeria, open dumping remains the predominant method of municipal solid waste (MSW) disposal. Estimates indicate that over 250 metric tons of waste are deposited daily across numerous dumpsites in Nigeria (Sabat, 2012). These wastes often comprise diverse materials, including industrial, chemical, and biological contaminants (Geeta Rani *et al.*, 2014), with heavy metals such as chromium, nickel, zinc, and lead posing significant health risks (Singh *et al.*, 2014). Open dumps, commonly found in cities like Kano, are frequently located near residential areas, exposing communities to severe health and environmental hazards. Leachate from these sites percolates into the subsurface, contaminating groundwater resources. The World Health Organization (WHO) warns that prolonged exposure to such contaminated environments could adversely affect up to a quarter of the exposed population (Chen and Idusuyi, 2015). Additionally, methane gas generated from waste decomposition presents explosion hazards, while accumulated scrap tyres not only sustain dump fires but also serve as breeding grounds for disease vectors. Fires involving tyres release toxic dioxins, linked to cancer and reproductive disorders even at minimal concentrations. Moreover, scavenging birds at these sites can further spread diseases.

To mitigate these threats and protect groundwater, the construction of engineered landfills has become essential. Such landfills incorporate key components including liners, covers, leachate collection and treatment systems, gas management facilities, and monitoring mechanisms (Amadi and Eberemu, 2012). Liners—whether compacted clay liners (CCL), geomembranes, geosynthetic clay liners (GCL), or asphalt clay liners (ACL)—serve as critical barriers to prevent leachate migration. However, the adoption of synthetic liners like GCL often incurs high costs (Amadi and Eberemu, 2012), highlighting the need for more economical alternatives. Improving local soils with additives such as cement, lime, fly ash, quarry dust, or even polymers offers a promising approach. Traditionally, additives like bitumen, cement, and lime have been employed to enhance soil properties—bitumen for dust control, cement for strength, and lime for reducing clay plasticity (Osinubi, 1995).

A key criterion for landfill liners is low hydraulic conductivity, ideally not exceeding 1×10^{-9} m/s, alongside adequate liquid limit (≥30%), plasticity index (≥10%), fine fraction (≥50% passing 0.075 mm sieve), low volumetric shrinkage (≤ 4%), and sufficient strength (UCS ≥ 200 kN/m²) (CGRM, 2007; Frempong and Yanful, 2014; Amadi and Eberemu, 2012). However, natural lateritic soils, widely available in tropical regions, often exhibit relatively high hydraulic conductivity due to their mineralogical composition, limiting their direct use as liner material.

In parallel, the marble industry generates substantial waste during quarrying, cutting, and polishing, with marble dust constituting up to 20 - 30% of the original block weight (Alyamac and Ince, 2009). Improper disposal of this fine waste not only alters landscapes and reduces soil fertility by increasing alkalinity (Montero *et al.*, 2009) but also causes air and visual pollution. Utilizing waste marble dust as a stabilizing agent for lateritic soils presents an opportunity to enhance soil properties for landfill liner applications while simultaneously addressing environmental concerns associated with marble waste disposal. This study, therefore, evaluates the suitability of lateritic soil treated with waste marble dust as an economical and sustainable landfill liner material.

II. MATERIALS AND METHODS

2.1 Materials

The lateritic soil used in this study was sourced from Ungogo Local Government Area of Kano State, Nigeria, located at approximately 11°57'16.7"N and 8°27'16.4"E. Soil samples were collected from depths ranging between 0.5 m and 1.2 m using disturbed sampling techniques. To preserve their natural moisture content, the samples were immediately sealed in polythene bags and transported to the Soil Mechanics Laboratory of the Department of Civil Engineering, Bayero University, Kano. In the laboratory, the samples were spread out and air-dried under controlled conditions prior to testing.The waste marble dust (WMD) was obtained from the Dei-Dei building materials market in Abuja, where marble cutting and polishing activities generate significant quantities of marble waste. The WMD was collected in sacks and transported to the same laboratory for further processing. Before use, the WMD was sieved through a BS No. 200 sieve (75 µm) to ensure uniform particle size. For the study, the WMD was incorporated into the lateritic soil at proportions of 0, 3, 6, 9, and 12% by dry weight of the lateritic soil.

2.2 Experimental Work

A comprehensive laboratory program was undertaken to evaluate the suitability of lateritic soil treated with waste marble dust (WMD) as a landfill liner material. The WMD was incorporated into the lateritic soil at proportions of 0, 3, 6, 9, and 12% by dry weight.Tests performed included chemical analysis of the WMD and lateritic soil, mineralogical characterization of the soil, consistency limits, compaction (using British Standard Light (BSL), British Standard Heavy (BSH), and West African Standard (WAS) efforts), hydraulic conductivity, volumetric shrinkage strain, unconfined compressive strength (UCS), and batch equilibrium adsorption. All tests were carried out in line with relevant procedures in BS 1377 (1990) and BS 1924 (1990).

The index properties (liquid limit, plastic limit, and plasticity index) were determined for both the natural and treated soils. For compaction, samples were prepared by thoroughly mixing air-dried soil (passing the 4.76 mm BS No. 4 sieve) with the designated WMD content. The specimens were compacted at varying moisture contents using BSL, BSH (per BS 1377 and BS 1924), and WAS compaction (per Nigerian General Specification, 1997), to establish moisture–density relationships.

Hydraulic conductivity was assessed on compacted specimens using a rigid-wall permeameter under falling head conditions following Head (1992). UCS tests were performed on specimens compacted in plastic tube moulds at optimum moisture content, as well as wet and dry of optimum, for each compaction energy level. Testing followed clause 7.3 of BS 1377 (1990) and BS 1924 (1990). After static compaction, samples were sealed in plastic bags and cured for at least 24 hours before testing.

Volumetric shrinkage was monitored by compacting specimens at optimum and allowing them to air dry at 25 ± 2 °C. Dimensions and weights were recorded periodically over 30 days until changes ceased. This suite of tests provided the necessary data to evaluate improvements in geotechnical properties relevant to landfill liner performance.

III. RESULTS AND DISCUSSION

3.1 Chemical composition of Waste Marble Dust and Soil

The chemical composition of the waste marble dust (WMD) and the lateritic soil was determined using X-Ray Fluorescence (XRF), as presented in Tables 1(a) and 1(b). Results indicate that WMD is predominantly composed of lime (CaO), reflecting its cementitious nature, while the soil is rich in silica (SiO_2). The silica–sesquioxide ratio of the soil was calculated as 1.67, confirming its classification as lateritic according to ASTM C618-12a (2013).

Table 1: Percentage Oxide Composition of Lateritic Soil and WMD

Elemental Oxide	% Composition	
	Lateritic soil	WMD
SiO_2	51.20	15.39
$Al_2 O_2$	21.55	8.90
FeO_3	9.20	2.53
TiO_2	0.32	0.20
Cr_2O_3	0.65	0.56
MnO	0.70	0.60
MgO	4.30	2.8
CaO	6.99	59.07
Na_2O	0.56	0.47
K_2O	0.72	0.88
P_2O_5	0.83	0.90
LOI	5.04	7.78

3.2 IndexandEngineeringPropertiesoftheNaturalSoil

The basic index and engineering properties of the natural lateritic soil are summarized in Table 2, with its particle size distribution curve shown in Figure 9. The soil was classified as an A-6 material under the AASHTO system (AASHTO, 1986), indicating a clayey soil of fair to poor quality for subgrade support. According to the Unified Soil Classification System (USCS), the soil is categorized as clay of low plasticity (CL) (ASTM, 1992). This suggests a moderately plastic soil with the potential for improvement through stabilization.

Table 2: The Index and Engineering Properties of the natural lateritic Soil

Property	Quantity
NaturalMoistureContent(%)	7.10
SpecificGravity	2.69
Gravel(%)	19.34
Sand(%)	29.20

SiltorClay(%)	51.45
LiquidLimit(%)	36.00
PlasticLimit (%)	24.00
PlasticityIndex(%)	12.00
LinearShrinkage(%)	8.30
PercentagepassingBSNo200Sieve	51.45
FreeSwell(%)	58
AASHTOClassification	A-6
USCSClassification	CL
OMC(BritishStandardHeavy) (%)	12.70
MDD(BritishStandard Heavy) (Mg/m^3)	2.00
OMC(BritishStandardLight)(%)	14.84
MDD(British Standard Light)(Mg/m^3)	1.86
OMC(WestAfricanstandard)(%)	13.83
MDD(West African standard)(Mg/m^3)	1.92
UCS(British StandardHeavy) (kN/m^2)	220
UCS(British StandardLight) (kN/m^2)	80
UCS(West African standard)(kN/m^2)	130
pHValue	6.8
Colour	Reddishbrown
DominantclayMineral	Kaolinite

3.3 Effect of Waste Marble Dust (WMD) on Atterberge Limits

The influence of WMD on the Atterberg limits of the lateritic soil is depicted in Figure 10a, while the impact on linear shrinkage is shown in Figure 10b. As the WMD content increased from 0 to 12%, the liquid limit (LL) decreased from 36.4% to 30.2%. The reduction was gradual, with slight decreases up to 6% WMD, followed by a sharper decline at 9%, attributed to flocculation and agglomeration processes arising from cation exchange reactions between the calcium in WMD and the clay minerals. This behavior aligns with the findings of Osinubi*et al.* (2006).

Simultaneously, the plastic limit (PL) increased from 12.0% for the untreated soil to 24.0% at 12% WMD. The higher PL indicates increased water demand to achieve plastic consistency, likely due to the increased surface area and cementitious hydration reactions associated with the added WMD. Consequently, the plasticity index (PI) showed a consistent reduction with higher WMD content, reflecting lower clay activity and potential for volume change.

According to CGRM (2007) and recommendations by Frempong and Yanful (2014), suitable landfill liner soils should have LL > 30% and PI > 10%. The treated soils maintained LL values around the 30% threshold and PI values consistently above 10%, indicating that the mixtures still satisfy the Atterberg limits criteria for landfill liner materials.

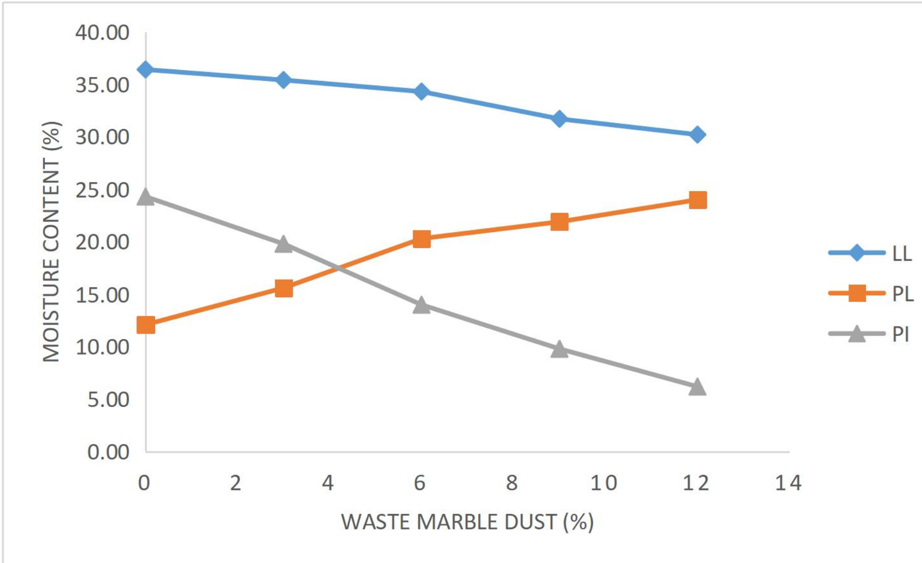

Fig. 1: Variation of Atterberge Limits with Waste Marble Dust Contents

3.4 Compaction Characteristic

Compaction tests under BSL, BSH, and WAS energy levels were conducted to establish moisture–density relationships, with results shown in Figures 2 and 3. For BSH and WAS compaction, the MDD increased from 2.00 and 1.92 Mg/m³ for the natural soil to peaks of 2.11 and 2.05 Mg/m³ respectively at 9% WMD. A slight decline in MDD was observed at 12% WMD, possibly due to the lower specific gravity of WMD compared to the soil matrix, partially replacing heavier soil particles (Osinubi*et al.*, 2011). In the BSL tests, MDD initially rose with 3% WMD, dipped slightly at 6%, and peaked again at 9%.

Meanwhile, OMC decreased across all compactive efforts, from 14.24% (BSL), 12.70% (BSH), and 13.83% (WAS) for untreated soil to 13.09%, 9.52%, and 11.58% at 9% WMD respectively. This trend reflects reduced water requirements due to flocculation and formation of denser aggregates (Moses and Osinubi, 2013). These compaction results suggest that the addition of WMD leads to better packing and reduced voids, improving the compacted soil's integrity.

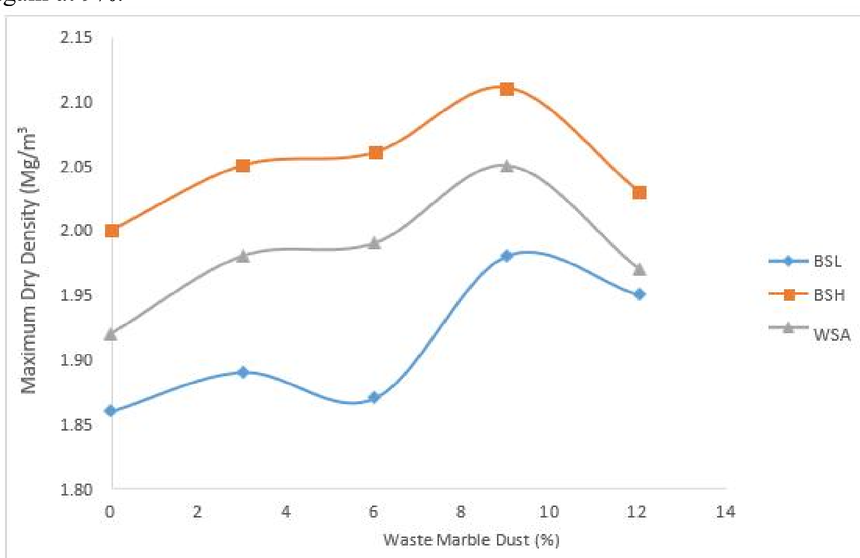

Fig. 2: Variation of Maximum Dry Density with Waste Marble Dust Treatment

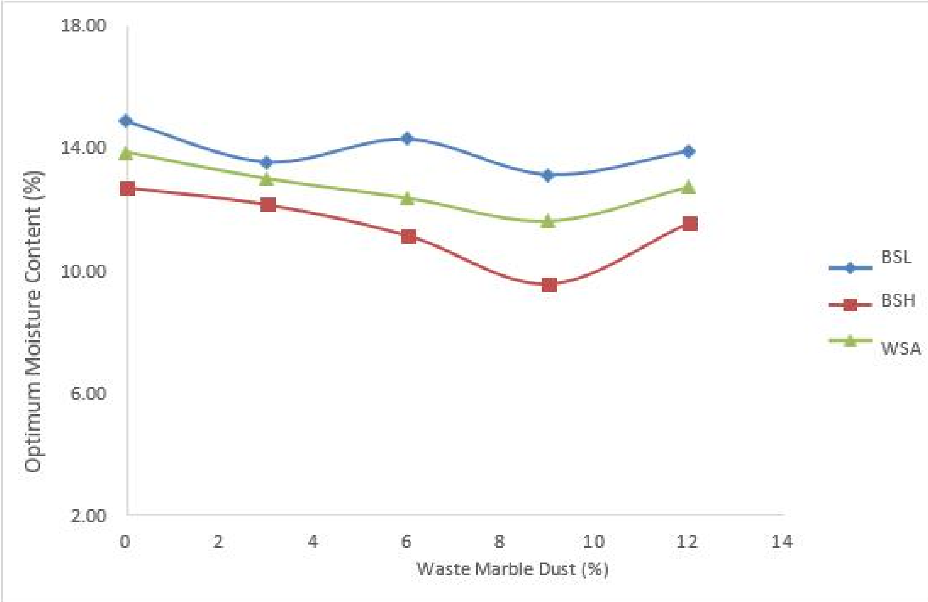

Fig. 3: Variation of Optimum Moisture Content with Waste Marble Dust Treatment

3.5 Effect of Waste Marble Dust on Hydraulic Conductivity

The hydraulic conductivity results are presented in Figure 4. For all compaction efforts, hydraulic conductivity decreased significantly with increasing WMD content, dropping from 1.75×10^{-7} to 1.74×10^{-8} m/s (BSL), 5.38×10^{-8} to 8.42×10^{-9} m/s (BSH), and 8.95×10^{-8} to 1.40×10^{-8} m/s (WAS). The marked reduction is primarily due to the fine WMD particles filling soil voids and promoting a tighter soil fabric, as also noted by Moses and Osinubi (2013).

Importantly, the minimum hydraulic conductivity of 1.0×10^{-9} m/s required for landfill liners (CGRM, 2007) was met at WMD contents ranging from 6% to 12%, particularly under the BSH efforts. This clearly demonstrates the potential of WMD-treated lateritic soil to function effectively as a hydraulic barrier.

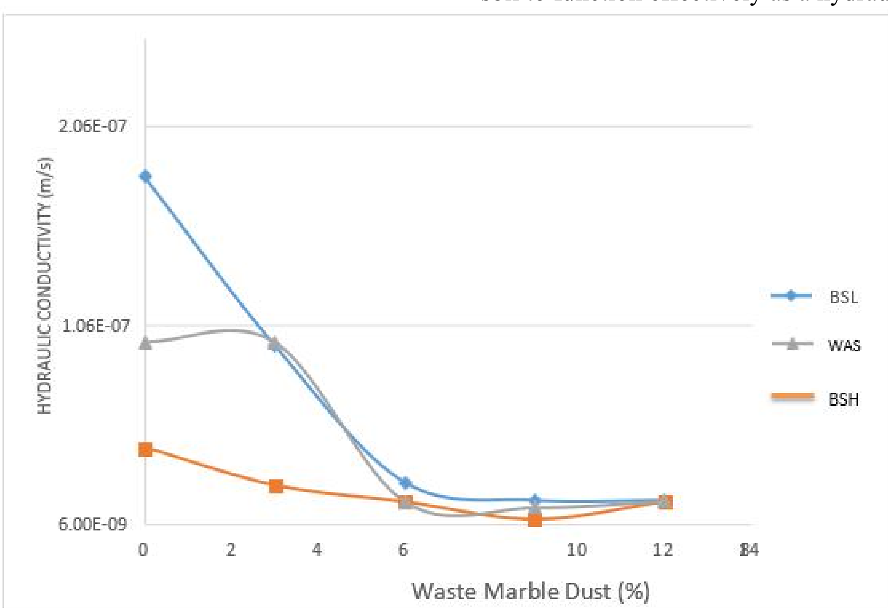

Fig.4: Variation of Hydraulic Conductivity with WMD Contents

3.6 Effect of Waste Marble Dust on Unconfined Compressive Strength

The UCS of the treated soils generally increased with WMD content, achieving ranges of 80–220 kN/m² (BSL), 220–340 kN/m² (BSH), and 80–240 kN/m² (WAS) as illustrated in Figure 5. Peak strengths of 220, 340, and 240 kN/m² were recorded for BSL, BSH, and WAS respectively. These values exceed the 200 kN/m² minimum suggested by Daniel and Wu (1993) for landfill liner applications. The strength gains are largely attributed to pozzolanic reactions resulting in the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which enhance the soil matrix (Negi*et al.*, 2013; Edeh*et al.*, 2014). However, at very high WMD content, UCS slightly declined, likely due to insufficient water to sustain complete pozzolanic reactions (Mohammed *et al.*, 2001).

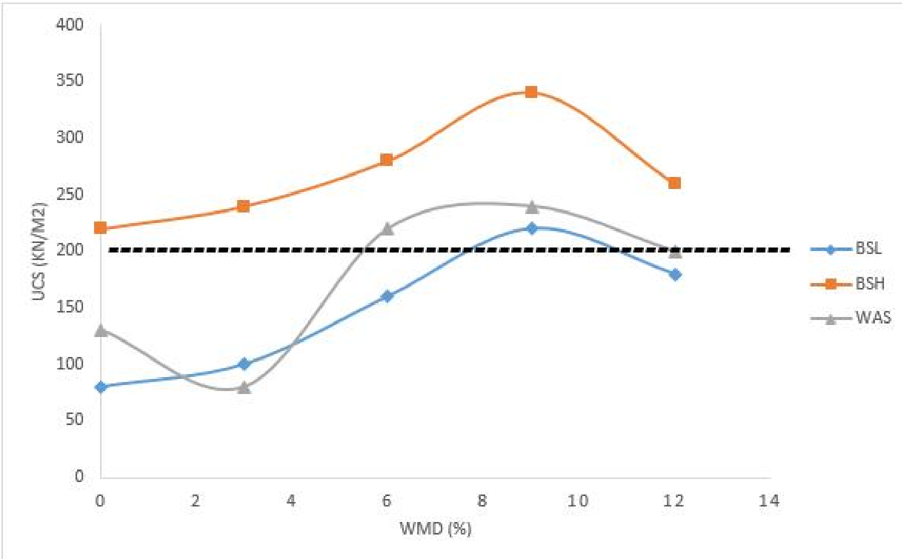

Fig. 5: Variation of Unconfined Compressive Strength with WMD Contents

3.7 Effect of Waste Marble dust on Volumetric Shrinkage Strain (VSS)

Fig.6 highlights the reduction in volumetric shrinkage strain with increased WMD. VSS dropped from 15.3% to 3.1% (BSL), 12.2% to 1.1% (BSH), and 10.7% to 2.7% (WAS) as WMD content increased up to 9%, staying well below the 4% maximum recommended for landfill liners (CGRM, 2007). This decline is attributed to stronger interparticle bonding and aggregation from ion exchange between Ca^{2+} in the WMD and clay minerals, resulting in a coarser, more stable soil structure (Osinubi and Eberemu, 2009; Liman, 2009).

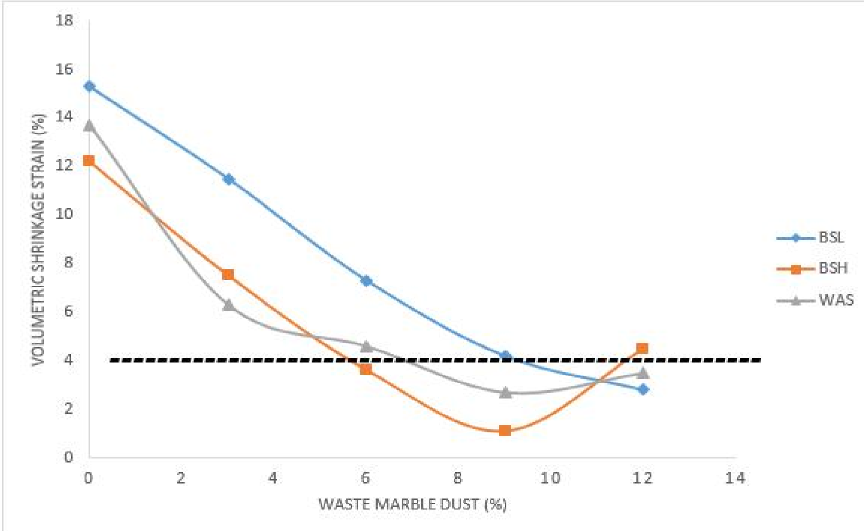

Fig. 6: Variation of Volumetric Shrinkage with WMD Contents

IV. CONCLUSIONAND RECOMMENDATIONS

The addition of waste marble dust (WMD) to lateritic soil significantly improved its geotechnical properties, enhancing its potential as a landfill liner material. XRF analysis confirmed that the WMD is predominantly composed of lime (CaO), enabling cementitious reactions, while the lateritic soil is silica-rich with a silica - sesquioxide ratio of 1.67, classifying it as lateritic. Incorporation of WMD led to reductions in liquid limit from 36.4% to 30.2% and consistent increases in plastic limit from 12% to 24%, resulting in lower plasticity indices - all within acceptable thresholds for landfill liners. The treated soils thus retained LL and PI values meeting recommended criteria (LL >30%, PI >10%), indicating reduced potential for excessive volume change. Compaction results revealed increases in maximum dry density up to 2.11 Mg/m³ (BSH) and reductions in optimum moisture content, suggesting denser, more efficiently packed soil-WMD matrices that require less water.

Equally important, the hydraulic conductivity of the mixtures decreased markedly with WMD addition, reaching values as low as 8.42×10^{-9} m/s (BSH), comfortably meeting the stringent 1.0×10^{-9} m/s standard required for landfill liners. Unconfined compressive strengths peaked at 220, 340, and 240 kN/m² for BSL, BSH, and WAS respectively, exceeding the 200 kN/m² benchmark and underscoring the structural integrity gained through pozzolanic activity. Volumetric shrinkage strain was also substantially reduced across compactive efforts, remaining well below the critical 4% threshold. Overall, these findings collectively demonstrate that lateritic soil treated with up 6 to 12% WMD satisfies essential index, strength, hydraulic, and shrinkage requirements, confirming its suitability as an effective, sustainable material for landfill liner applications.

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